МИНИСТЕРСТВО НАУКИ И ВЫСШЕГО ОБРАЗОВАНИЯ
РОССИЙСКОЙ ФЕДЕРАЦИИ
ФЕДЕРАЛЬНОЕ ГОСУДАРСТВЕННОЕ БЮДЖЕТНОЕ
ОБРАЗОВАТЕЛЬНОЕ УЧРЕЖДЕНИЕ ВЫСШЕГО ОБРАЗОВАНИЯ
ПЕРМСКИЙ ГОСУДАРСТВЕННЫЙ
НАЦИОНАЛЬНЫЙ ИССЛЕДОВАТЕЛЬСКИЙ УНИВЕРСИТЕТ

АКАДЕМИЧЕСКАЯ И ПРОФЕССИОНАЛЬНАЯ КОММУНИКАЦИЯ НА ИНОСТРАННОМ ЯЗЫКЕ

English Reader for Students of Nanophysics

Допущено методическим советом
Пермского государственного
национального исследовательского университета
в качестве учебного пособия для студентов,
обучающихся по направлению подготовки магистров
«Нанотехнологии и микросистемная техника»

ИЗДАТЕЛЬСКИЙ ЦЕНТР
“Perm University Press”

Пермь 2018

УДК 811.111:53(075.8)
ББК 81.2
Б12

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Б12 Академическая и профессиональная коммуникация на иностранном языке. English Reader for Students of Nanophysics: [Электронный ресурс]: учеб. пособие / сост. С. С. Бабаджан, А. Ф. Корлякова. Перм. гос. нац. исслед. ун-т. – Электрон. дан. – Пермь, 2018. – 5 Мб; 152 с. – Режим доступа: http://www.psu.ru/files/docs/science/books/uchebnie-posobiya/English-Reader-for-Students-of-Nanophysics.pdf. – Загл. с экрана.

ISBN 978-5-7944-3228-2

Данное пособие предназначено для студентов магистратуры физического факультета, обучающихся по направлению подготовки магистров «Нанотехнологии и микросистемная техника». Пособие содержит аутентичные тексты, связанные с различными областями нанофизики. Каждый текст сопровождается лексико-грамматическими упражнениями, направленными на расширение потенциального словаря и развитие навыков чтения. Основная цель пособия − развитие навыков чтения научно-технической литературы и подготовка студентов физико-технического профиля к чтению оригинальной литературы по специальности.

УДК 811.111:53(075.8)
ББК 81.2

Издается по решению ученого совета
факультета современных иностранных языков и литератур
Пермского государственного национального исследовательского университета

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ISBN 978-5-7944-3228-2

1. NEW RESEARCH ADVANCES SPINTRONICS TECHNOLOGY

Discoveries will help realize the promise of faster, energy-efficient spintronic computers and ultra-high-capacity data storage.

Summary:

Engineers have reported advances in so-called ‘spintronic’ devices that will help lead to a new technology for computing and data storage. They have developed methods to detect signals from spintronic components made of low-cost metals and silicon, which overcomes a major barrier to wide application of spintronics.

Engineers at the University of California, Riverside, have reported advances in so-called “spintronic” devices that will help lead to a new technology for computing and data storage. They have developed methods to detect signals from spintronic components made of low-cost metals and silicon, which overcomes a major barrier to wide application of spintronics. Previously such devices depended on complex structures that used rare and expensive metals such as platinum. The researchers were led by Sandeep Kumar, an assistant professor of mechanical engineering.

Spintronic devices promise to solve major problems in today’s electronic computers, in that the computers use massive amounts of electricity and generate heat that requires expending even more energy for cooling. By contrast, spintronic devices generate little heat and use relatively minuscule amounts of electricity. Spintronic computers would require no energy to maintain data in memory. They would also start instantly and have the potential to be far more powerful than today’s computers.

While electronics depends on the charge of electrons to generate the binary ones or zeroes of computer data, spintronics depends on the property of electrons called spin. Spintronic materials register binary data via the “up” or “down” spin orientation of electrons – like the north and south of bar magnets – in the materials. A major barrier to development of spintronics devices is generating and detecting the infinitesimal electric spin signals in spintronic materials.

In one paper published in the January issue of the scientific journal Applied Physics Letters, Kumar and colleagues reported an efficient technique of detecting the spin currents in a simple two-layer sandwich of silicon and a nickel-iron alloy called Permalloy. All three of the components are both inexpensive and abundant and could provide the basis for commercial spintronic devices. They also operate at room temperature. The layers were created with the widely used electronics manufacturing processes called sputtering. Co-authors of the paper were graduate students Ravindra Bhardwaj and Paul Lou.

In their experiments, the researchers heated one side of the Permalloy-silicon bi-layer sandwich to create a temperature gradient, which generated an electrical voltage in the bi-layer. The voltage was due to phenomenon known as the spin-Seebeck effect. The engineers found that they could detect the resulting “spin current” in the bi-layer due to another phenomenon known as the “inverse spin-Hall effect.”

The researchers said their findings will have application to efficient magnetic switching in computer memories, and “these scientific breakthroughs may give impetus” to development of such devices. More broadly, they concluded, “These results bring the ubiquitous Si (silicon) to forefront of spintronics research and will lay the foundation of energy efficient Si spintronics and Si spin caloritronics devices.”

In two other scientific papers, the researchers demonstrated that they could generate a key property for spintronics materials, called antiferromagnetism, in silicon. The achievement opens an important pathway to commercial spintronics, said the researchers, given that silicon is inexpensive and can be manufactured using a mature technology with a long history of application in electronics.

Ferromagnetism is the property of magnetic materials in which the magnetic poles of the atoms are aligned in the same direction. In contrast, antiferromagnetism is a property in which the neighboring atoms are magnetically oriented in opposite directions. These "magnetic moments" are due to the spin of electrons in the atoms, and are central to the application of the materials in spintronics.

In the two papers, Kumar and Lou reported detecting antiferromagnetism in the two types of silicon – called n-type and p-type – used in transistors and other electronic components. N-type semiconductor silicon is "doped" with substances that cause it to have an abundance of negatively-charged electrons; and p-type silicon is doped to have a large concentration of positively charged "holes." Combining the two types enables switching of current in such devices as transistors used in computer memories and other electronics.

In the paper in the Journal of Magnetism and Magnetic Materials, Lou and Kumar reported detecting the spin-Hall effect and antiferromagnetism in n-silicon. Their experiments used a multilayer thin film comprising palladium, nickel-iron Permalloy, manganese oxide and n-silicon.

And in the second paper they reported detecting in p-silicon spin-driven antiferromagnetism and a transition of silicon between metal and insulator properties. Those experiments used a thin film similar to those with the n-silicon.

The researchers wrote in the latter paper that "The observed emergent antiferromagnetic behavior may lay the foundation of Si (silicon) spintronics and may change every field involving Si thin films. These experiments also present potential electric control of magnetic behavior using simple semiconductor electronics physics. The observed large change in resistance and doping dependence of phase transformation encourages the development of antiferromagnetic and phase change spintronics devices."

In further studies, Kumar and his colleagues are developing technology to switch spin currents on and off in the materials, with the ultimate goal of creating a spin transistor. They are also working to generate larger, higher-voltage spintronic chips. The result of their work could be extremely low-power, compact transmitters and sensors, as well as energy-efficient data storage and computer memories, said Kumar.

Task 1. *Find words or expressions meaning the following:*

1. very small;
2. to keep in existence;
3. immeasurably small;
4. present in large quantities;
5. a great success;
6. impulse;
7. found everywhere;
8. to be placed in a straight line;
9. analogous to.

Task 2. *Find sentences in support or against the following:*

1. New devices will address the major problems of modern computers: heat generation and reat power consumption.

2. Spintronic computers memory is volatile and needs power to store information.

3. Spintronic materials represent binary one and zero through individual electrons quantum spins.

4. By increasing the temperature of one side of the Fe- Ni- Si alloy and cooling the other side the researchers created a potential difference.

5. Scientists revealed it was possible to reproduce the most important property of spintronics: the ability to magnetically orient the neighbouring atoms in opposite directions.

6. This effect exists only in spintronic materials.

7. The new effect can lead to the emergence of Si spintronics and can cause transformations wherever thin Si films are used.

8. Electron-spin qubits interact with the environment surrounding them, principally through magnetic fields and can be effectively shielded.

Task 3. *Answer the following questions*:

1. What can University of Riverside engineers ‘discovery result in?
2. What’s the difference between spintronic devices and conventional devices?
3. Why are spintronic computers better than electronic ones?
4. How are binary one and zero represented in spintronics?
5. What makes Permmalloy so good?
6. What effect was found in P- type and N- type silicon?
7. Why is it so important?
8. Can we say that this effect was observed in conventional semiconductors? Why? Why not?
9. What’s the reason scientists want to be able to turn spin currents on and off?

2. COULD HOLEY SILICON BE THE HOLY GRAIL OF ELECTRONICS?

Part 1

Electronics miniaturization has put high-powered computing capability into the hands of ordinary people, but the ongoing downsizing of integrated circuits is challenging engineers to come up with new ways to thwart component overheating.

Scientists at the University of California, Irvine made a breakthrough recently in verifying a new material configuration to facilitate cooling. In a study in the journal Nanotechnology, members of UCI's Nano Thermal Energy Research Group highlight the attributes of holey silicon, a computer chip wafer with tiny, vertically etched orifices that work to shuttle heat to desired locations.

"We found that heat prefers to travel vertically through but not laterally across holey silicon, which means the material can effectively move the heat from local hot spots to on-chip cooling systems in the vertical direction while sustaining the necessary temperature gradient for thermoelectric junctions in the lateral direction," said corresponding author Jaeho Lee, UCI assistant professor of mechanical & aerospace engineering.

"This innovation could potentially be ideal for keeping electronic devices such as smartphones cool during operation," said lead author Zongqing Ren, a graduate student researcher in the NTERG.

He said that lab simulations demonstrated that the cooling effectiveness of holey silicon is at least 400 percent better than chalcogenides, compounds commonly used in thermoelectric cooling devices.

The lab's holey silicon research is a follow-on to a study published in Nature Communications in early 2017 in which Lee, as lead author, and his UC Berkeley-based collaborators employed nanometer-scale silicon mesh material to investigate properties of phonons, quasiparticles that give scientists insight into thermal transport mechanisms.

“We know that phonons can show wave-like as well as particle-like behavior during thermal transport,” Lee said. “Using meshes with different hole sizes and spacing, we were able to clarify complex thermal transport mechanisms at the nanoscale.”

Knowledge gained from the earlier study helped his team understand how small, neck-shaped structures created by the etched holes in holey silicon cause phonon backscattering, a particle effect leading to low in-plane thermal conductivity. High cross-plane thermal conductivity was caused by long-wavelength phonons that help to move heat away.

Lee said the temperature problem in electronics has grown in the past few years as microchip designers seem to have reached a size boundary. With larger components, manufacturers can use heat sinks, fins and even fans to funnel warmth away from critical hardware. On today’s densely packed chips with billions of nanoscale transistors – often sandwiched in slim, pocketable consumer products – there’s no room for such cooling technologies.

Other key issues are longevity and reliability. Semiconductor chips are being embedded in many new places – acting as sensors and actuators in cars and appliances and as nodes along the internet of things. These devices are expected to run continuously for years and even decades. Prolonged exposure to heat could cause the failure of such infrastructure.

“On the one hand, nanotechnology has opened up a whole new world of possibilities, but on the other, it’s created a host of challenges,” Lee said. “It’s important that we continue to develop a better understanding of the fundamentals of thermal transport and find ways to control heat transfer at the nanoscale.”

Part 2. High-speed and on-silicon-chip graphene blackbody emitters

Square graphene sheet is connected to source and drain electrodes. Modulated blackbody emission is obtained from graphene by applying input signal.

High-speed light emitters integrated on silicon chips can enable novel architectures for silicon-based optoelectronics. However, 1 face major challenges for their integration with a silicon-based platform because of their difficulty of direct fabrication on a silicon substrate. Here, high-speed, highly-integrated graphene-based on-silicon-chip blackbody emitters in the near-infrared (NIR) region including telecommunication wavelength were developed.

Graphene is a two-dimensional nanocarbon material, having unique electronic, optical and thermal properties that can be applied for optoelectronic devices. Graphene-based blackbody emitters are also promising light emitters on silicon chip in NIR and mid-infrared region. However, although graphene-based blackbody emitters have been demonstrated under steady-state conditions or relatively slow modulation (100 kHz), the transient properties of these emitters under high-speed modulation have not been reported to date. Also, optical communications with graphene-based emitters have never been demonstrated.

Here, the researchers demonstrated a highly integrated, high-speed and on-chip blackbody emitter based on graphene in NIR region including telecommunication wavelength. A fast response time of ~ 100 picoseconds has been experimentally demonstrated for single and few-layer graphene. The emission responses can be controlled by the graphene contact with the substrate depending on the number of graphene layers. The mechanisms of the high-speed emission are elucidated by performing theoretical calculations of the heat conduction equations considering the thermal model of emitters including graphene and a substrate.

The simulated results indicate that the fast response properties can be understood not only by the classical thermal transport of in-plane heat conduction in graphene and heat dissipation to the substrate but also by the remote quantum thermal transport via the surface polar phonons (SPoPhs) of the substrates. In addition, the first real-time optical communication with graphene-based light emitters was experimentally demonstrated, indicating that graphene emitters are novel light sources for optical communication. Furthermore, we fabricated integrated two-dimensional array emitters with large-scale graphene grown by chemical vapour deposition (CVD) method and capped emitters operable in air, and carried out the direct coupling of optical fibers to the emitters owing to their small footprint and planar device structure.

Graphene light emitters are greatly advantageous over conventional compound semiconductor emitters because they can be highly integrated on silicon chip due to simple fabrication processes of graphene emitters and direct coupling with silicon waveguide through an evanescent field. Because graphene can realize high-speed, small footprint and on-Si-chip light emitters, which are still challenges for compound semiconductors, the graphene-based light emitters can open new routes to highly integrated optoelectronics and silicon photonics.

Could holey silicon be the holy grail of electronics?

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Tasks. Part 1

Task 1. *Find words meaning the following*:

1. To dispute the truth of;
2. To suggest (an idea);
3. To make easy or easier;
4. Cause to continue for an extended period or without interruption;
5. An accurate and deep understanding of;
6. To put firmly and deeply into an object;
7. The state of having no protection from something harmful.

Task 2. *Say whether the following is true, false or not mentioned:*

1. Minituarization of integrated circuits is the main problem facing engineers today.
2. Changing the direction of holes in silicon will contribute to a more efficient heat dissipation.
3. This discovery could result in more effective cooling of electronic gadgets.
4. Phonons are quasiparticles which are responsible for heat transfer.
5. The dual nature of phonons during thermal transport can give us insight into complex heat transport mechanisms.
6. Since modern chips consist of billions of nanotransistors ,scientists are thinking of creating cooling nanoheat sinks , nanofins ,and other cooling nanodevices.
7. The new invention could play a crucial part in the internet of things making it more durable and reliable, and enabling it to last for dozens of years or more.

Task 3. *Answer the following questions*:

1. What discovery did Irvine scientists make?
2. Why is it a breakthrough?

3. What are its possible applications?
4. Was the discovery absolutely original? Why? Why not?
5. What is the physical mechanism behind the holey silicon effect?
6. Why is this effect so important?
7. How are chips affected by heat?

Tasks. Part 2 (from High-speed and on-silicon-chip graphene blackbody emitters).

Task 1. *Find words meaning the following:*

1. To make it possible for something to happen;
2. Make (something) clear; explain;
3. The process of disappearing or making something disappear;
4. Thanks to (2);
5. Good or useful in a particular situation;
6. Gradually disappearing from sight.

Task 2. *Say whether the following is true, false or not mentioned:*

1. Since it is hard to produce compound compound-semiconductor-based light emitters directly on a silicon substrate it is impossible to integrate them with a silicon based platform.
2. We still do not know the properties of graphene-based light emitters under high-speed modulation.
3. There have been a lot of successful experiments with graphene-based emitters optical communication
4. Graphene is not the best material for optical electronics.
5. The emission responses are proportional to the number of graphene layers.
6. How and why the high-speed emission happens is explained in terms of the heat conduction equations.
7. Graphene light emitters are only marginally superior to ordinary compound semiconductor emitters.

8. As graphene light emitters are very fast, this technology is extremely promising and has great prospects in optoelectronics and silicon photonics.

Task 3. *Answer the following questions:*

1. Why is it so hard to integrate high-speed light emitters with a silicon-based platform?
2. Why do scientists still doubt whether graphene light emitters can be used in optical communication?
3. What helps us to explain the causes of the high-speed emission?
4. What did the heat conduction equations mentioned demonstrate?
5. What makes graphene light emitters better tnan ordinary compound semiconductor ones?
6. Can we say that this technology has a great future? Why? Why not?

3. COMPUTERS: ADDING CARBON GIVES IRON–PLATINUM NANOCRYSTALS IDEAL OPTICAL PROPERTIES FOR HEAT-ASSISTED MAGNETIC RECORDING

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Now, Zhanhong Cen and co□workers at the A*STAR Data Storage Institute in Singapore have experimentally and theoretically investigated the properties of iron-platinum (FePt) nanocrystals for use in ultrahigh-density magnetic recording media. They show that, as well as having the appropriate magnetic characteristics, the optical response of FePt is suitable for high-performance data-storage applications and that the use of pulses of laser light improves the magnetic recording process1.

“Decreasing the size of magnetic particles makes the magnetic information become thermally unstable due to an effect called superparamagnetism,” explains Cen. “FePt nanoparticles are very promising, because for these nanoparticles, superparamagnetism is suppressed at room temperature.”

But FePt nanoparticles also have a drawback – the magnetic field required for writing data is much higher than that produced by present disk drives. While the magnetic-field intensity necessary for a change of state could potentially be reduced by locally heating the material with a pulse of light – a process called heat-assisted magnetic recording, little was known about the optical response of FePt until now.

Cen and the team created thin-film samples using a process known as sputtering, which involves firing a beam of particles at a FePt alloy to release iron and platinum atoms. The atoms land on a glass substrate covered with a layer of magnesium oxide where they form crystals. The team sputtered carbon at the same time to form a single layer of FePt nanocrystals 15 nanometers in diameter and 9.1 nanometers tall embedded in a film of carbon.

For comparison, the team also created a nanocrystal sample without carbon and probed the refractive index and absorption of the two samples with both visible and near-infrared light. The researchers used these values in a computer model to simulate the performance of the material in a heat-assisted magnetic recording device. The sample doped with carbon came out on top.

“Our simulations show that introducing carbon into a FePt nanocomposite can improve optical performance,” says Cen. “Ultimately, a FePt-carbon recording medium will perform better than current storage options, because it will use a smaller optical spot on the recording media and enable more energy-efficient writing and reading of data.”

Task 1. *Find words which mean the following:*

1. Very small;
2. Likely to be affected by a particular problem;
3. To make better;
4. Disadvantage;
5. To include;
6. To prevent or inhibit.

Task 2. *Say whether the following is true, false or is not mentioned.*

1. The optical properties of iron-platinum make it good for a high capacity storage device.

2. In contrast to magnetic particles nanoparticles do not need low temperatures.
3. Superparamagnetism is suppressed for nanoparticles as they are zapped with high intensity laser pulses.
4. Iron-platinum nanoparticles are ideal for creating high capacity disk drives.
5. Nanocrystal particles reveal the same optical properties whether they have carbon or not.
6. Since iron- platinum carbon nanoparticles are more efficient, it is possible to read and write more data, more densely.

Task 3. *Answer the following questions.*

1. What makes the disk drive in a computer tick?
2. Why are nanocrystals suitable for a high density storage?
3. How does superparamagnetism affect the magnetic information?
4. What makes nanoparticles different?
5. How does sputtering work?
6. Have iron-platinum nanoparticles any disadvantages?
7. How can the drawbacks be coped with?
8. What are better FePt nanoparticles’ properties due to?

4. NANOWIRE TRANSISTORS COULD KEEP MOORE'S LAW ALIVE

Researchers are perfecting ways to produce gate-all-around devices

By Alexander Hellemans

Illustration: Emily Cooper Gate-All-Around Transistors: In a new design, the transistor channel is made up of an array of vertical nanowires. The gate surrounds all the nanowires, which improves its ability to control the flow of current. Platinum-based source and drain contacts sit at the top and bottom of the nanowires.

The end of Moore's Law has been predicted again and again. And again and again, new technologies, most recently FinFETs, have dispelled these fears. Engineers may already have come up with the technology that will fend off the next set of naysayers: nanowire FETs (field-effect transistors).

In these nanodevices, current flows through the nanowire or is pinched off under the control of the voltage on the gate electrode, which surrounds the nanowire. Hence, nanowire FETs' other name: "gate-all-around" transistors. However, because of their small size, single nanowires can't carry enough current to make an efficient transistor.

The solution, recent research shows, is to make a transistor that consists of a small forest of nanowires that are under the control of the same gate and so act as a single transistor. For example, researchers at Hokkaido University and from the Japan Science and Technology Agency reported last year in Nature a gate-all-around nanowire transistor consisting of 10 vertical indium gallium arsenide nanowires grown on a silicon substrate. Although the device's electrical properties were good, the gate length – a critical dimension – was 200 nanometers, much too large for the tiny transistors needed to power the microprocessors of the 2020s.

Now two researchers working in France, Guilhem Larrieu of the Laboratory for Analysis and Architecture of Systems, in Toulouse, and Xiang Lei Han of the Institute for Electronics, Microelectronics, and Nanotechnology, in Lille, report the creation of a nanowire transistor that could be scaled down to do the job. It consists of an array of 225 doped-silicon nanowires, each 30 nm wide and 200 nm tall, vertically linking the two platinum contact planes that form the source and drain of the transistor. Besides their narrowness, what's new is the gate: A single 14-nm-thick chromium layer surrounds each nanowire midway up its length.

That thickness, the gate length, is the key. "The advantage of an all-around gate allows the creation of shorter gates, without loss of control on the current through the channel," explains Larrieu. "We demonstrated the first vertical nanowire transistor with such a short gate." An all-around gate will be a must if gate lengths are to get smaller than 10 nm, he says. In that scheme, "the size of the gate depends only on the thickness of the deposited layer; there is no complicated lithography involved," he adds.

The nanowires were of an unusual construction. Unlike with most vertical nanowire transistor prototypes, in which the nano wires are grown upward from a substrate, the French duo created their nanowires by starting out with a block of doped silicon and then etching away material to leave nano pillars. In between the pillars, they deposited an insulating layer to about half the pillars' height. Then they deposited the 14 nm of chromium and filled the remaining space with another insulating layer. "We tried to make the process completely compatible with current technology used in electronics. No new machines will have to be invented," says Larrieu. The researchers have plans to try to go below 10-nm gate length, and also to use indium gallium arsenide nanowires because of the better electron mobility.

Kelin Kuhn, director of advanced device technology at Intel's Hillsboro, Ore., location, agrees that all-around gate structures have some key advantages. Of all the CMOS-style advanced devices, they're generally expected to provide the best gate control for very short channels, she says.

Davide Sacchetto, a researcher at the École Polytechnique Fédérale de Lausanne, agrees: "The fabrication of the gate is interesting, and you get a small gate length." However, the advantage is lost if the nanowires are too long – 200 nm in this case – and the channel is only a small part of the total length of the nanowire, he says. "Even a difference of 5 nm would make a huge difference in the drain current."

According to Judy Hoyt, a researcher at the Microsystems Technology Laboratories at MIT, gate-all-around technology is now under study at a number of university labs worldwide. But as the nanowire transistors are more complex than the FinFETs, will this effort allow Moore's Law to live longer and fit even more transistors on a chip? "The jury is still out," says Hoyt. It depends on what the fabrication process and the structure will be, she says. "You really have to get the physics right, and that is what all these efforts are based on."

Task 1. *Find words meaning the following:*

1. To suggest an idea;
2. To make something go away;
3. To reduce;
4. In addition to;
5. Included, connected with;
6. Able to exist or be used without causing problems.

Task 2. *Say whether the following is true, false or not mentioned:*

1. One nanochip is enough to make a good transistor.
2. The new idea is to make a lot of nanowire work as a single transistor.
3. The new device's gate length should not be greater than 200 nm.

4. You can’t scale down a nanowire transistor endlessly.
5. An all- around gate allows gates to be shorter.
6. The size of the gate is directly proportional to the thickness of the deposited layer.
7. These new devices mean a complete change of technology and equipment.
8. Whether they mean the end of Moore’s law is still unclear.

Task 3. *Answer the following questions:*

1. Why cannot single nanowires make a good transistor?
2. What is the way out?
3. What was a great drawback of the new device?
4. What is the most important factor of an all-around transistor?
5. What is the difference between ordinary nanowires and the ones mentioned above?

5. THE FIRST NANOCHIPS

As scientists and engineers continue to push back the limits of chipmaking technology, they have quietly entered into the nanometer realm

By G. Dan Hutcheson

For most people, the notion of harnessing nanotechnology for electronic circuitry suggests something wildly futuristic. In fact, if you have used a personal computer made in the past few years, your work was most likely processed by semiconductors built with nanometer-scale features. These immensely sophisticated microchips or rather, nanochips are now manufactured by the millions, yet the scientists and engineers responsible for their development receive little recognition. You might say that these people are the Rodney Dangerfields of nanotechnology. So here I would like to trumpet their accomplishments and explain how their efforts have maintained the steady advance in circuit performance to which consumers have grown accustomed.

The recent strides are certainly impressive, but, you might ask, is semiconductor manufacture really nanotechnology? Indeed it is. After all, the most widely accepted definition of that word applies to something with dimensions smaller than 100 nanometers, and the first transistor gates under this mark went into production in 2000. Integrated circuits coming to market now have gates that are a scant 50 nanometers wide. That's 50 billionths of a meter, about a thousandth the width of a human hair.

Having such minuscule components conveniently allows one to stuff a lot into a compact package, but saving space per se is not the impetus behind the push for extreme miniaturization. The reason to make things small is that it lowers the unit cost for each transistor. As a bonus, this overall miniaturization shrinks the size of the gates, which are the parts of the transistors that switch between blocking electric current and allowing it to pass. The more narrow the gates, the faster the transistors can turn on and off, thereby raising the speed limits for the circuits using them. So as microprocessors gain more transistors, they also gain more speed.

The desire for boosting the number of transistors on a chip and for running it faster explains why the semiconductor industry, just as it crossed into the new millennium, shifted from manufacturing microchips to making nanochips. How it quietly passed this milestone, and how it continues to advance, is an amazing story of people overcoming some of the greatest engineering challenges of our time--challenges every bit as formidable as those encountered in building the first atomic bomb or sending a person to the moon.

Straining to Accelerate

The best way to get a flavor for the technical innovations that helped to usher in the current era of nanochips is to survey improvements that have been made in each of the stages required to manufacture a modern semiconductor--say, the microprocessor that powers the computer on which I typed this text. That chip, a Pentium 4, contains some 42 million transistors intricately wired together. How in the world was this marvel of engineering constructed? Let us survey the steps.

Before the chipmaking process even begins, one needs to obtain a large crystal of pure silicon. The traditional method for doing so is to grow it from a small seed crystal that is immersed in a batch of molten silicon. This process yields a cylindrical ingot--a massive gem-quality crystal--from which many thin wafers are then cut.

It turns out that such single-crystal ingots are no longer good enough for the job: they have too many "defects," dislocations in the atomic lattice that hamper the silicon's ability to conduct and otherwise cause trouble during chip manufacture. So chipmakers now routinely deposit a thin, defect-free layer of single-crystal silicon on top of each wafer by exposing it to a gas containing silicon. This technique improves the speed of the transistors, but engineers have been pushing hard to do even better using something called silicon-on-insulator technology, which involves putting a thin layer of insulating oxide slightly below the surface of the wafer. Doing so lowers the capacitance (the ability to store electrical charge) between parts of the transistors and the underlying silicon substrate, capacitance that would otherwise sap speed and waste power. Adopting a silicon-on-insulator geometry can boost the rate at which the transistors can be made to switch on and off (or, alternatively, reduce the power needed) by up to 30 percent. The gain is equivalent to what one gets in moving one generation ahead in feature size.

IBM pioneered this technology and has been selling integrated circuits made with it for the past five years. The process IBM developed, dubbed SIMOX, short for separation by implantation of oxygen, was to bombard the silicon with oxygen atoms (or rather, oxygen ions, which have electrical charge and can thus be readily accelerated to high speeds). These ions implant themselves deep down, relatively speaking, where they combine with atoms in the wafer and form a layer of silicon dioxide. One difficulty with this approach is that the passage of oxygen ions through the silicon creates many defects, so the surface has to be carefully heated afterward to mend disruptions to the crystal lattice. The greater problem is that oxygen implantation is inherently slow, which makes it costly. Hence, IBM reserved its silicon-on-insulator technology for its most expensive chips.

A new, faster method for accomplishing the same thing is, however, gaining ground. The idea is to first form an insulating oxide layer directly on top of a silicon wafer. One then flips the oxidized surface over and attaches it onto another, untreated wafer. After cleverly pruning off most of the silicon above the oxide layer, one ends up with the desired arrangement: a thin stratum of silicon on top of the insulating oxide layer on top of a bulk piece of silicon, which just provides physical support.

The key was in developing a precision slicing method. The French company that did so, Soitec, aptly trademarked the name Smart Cut for this technique, which requires shooting hydrogen ions through the oxidized surface of the first wafer so that they implant themselves at a prescribed depth within the underlying silicon. (Implanting hydrogen can be done more rapidly than implanting oxygen, making this process relatively inexpensive.) Because the hydrogen ions do most of their damage right where they stop, they produce a level within the silicon that is quite fragile. So after flipping this treated wafer over and attaching it to a wafer of bulk silicon, one can readily cleave the top off at the weakened plane. Any residual roughness in the surface can be easily polished smooth. Even IBM now employs Smart Cut for making some of its high-performance chips, and AMD (Advanced Micro Devices in Sunnyvale, Calif.) will use it in its upcoming generation of microprocessors.

The never-ending push to boost the switching speed of transistors has also brought another very basic change to the foundations of chip manufacture, something called strained silicon. It turns out that forcing the crystal lattice of silicon to stretch slightly (by about 1 percent) increases the mobility of electrons passing through it considerably, which in turn allows the transistors built on it to operate faster. Chipmakers induce strain in silicon by bonding it to another crystalline material--in this case, a silicon-germanium blend--for which the lattice spacing is greater. Although the technical details of how this strategy is being employed remain closely held, it is well known that many manufacturers are adopting this approach. Intel, for example, is using strained silicon in an advanced version of its Pentium 4 processor called Prescott, which began selling late last year.

Honey, I Shrunk the Features

Advances in the engineering of the silicon substrate are only part of the story: the design of the transistors constructed atop the silicon has also improved tremendously in recent years. One of the first steps in the fabrication of transistors on a digital chip is growing a thin layer of silicon dioxide on the surface of a wafer, which is done by exposing it to oxygen and water vapor, allowing the silicon, in a sense, to rust (oxidize). But unlike what happens to the steel body of an old car, the oxide does not crumble away from the surface. Instead it clings firmly, and oxygen atoms required for further oxidization must diffuse through the oxide coating to reach fresh silicon underneath. The regularity of this diffusion provides chipmakers with a way to control the thickness of the oxide layers they create.

For example, the thin oxide layers required to insulate the gates of today's tiny transistors can be made by allowing oxygen to diffuse for only a short time. The problem is that the gate oxide, which in modern chips is just several atoms thick, is becoming too slim to lay down reliably. One fix, of course, is to make this layer thicker. The rub here is that as the thickness of the oxide increases, the capacitance of the gate decreases. You might ask: Isn't that a good thing? Isn't capacitance bad? Often capacitance is indeed something to be avoided, but the gate of a transistor operates by inducing electrical charge in the silicon below it, which provides a channel for current to flow. If the capacitance of the gate is too low, not enough charge will be present in this channel for it to conduct.

The solution is to use something other than the usual silicon dioxide to insulate the gate. In particular, semiconductor manufacturers have been looking hard at what are known as high-K (high-dielectric-constant) materials, such as hafnium oxide and strontium titanate, ones that allow the oxide layer to be made thicker, and thus more robust, without compromising the ability of the gate to act as a tiny electrical switch.

Placing a high-K insulator on top of silicon is, however, not nearly as straightforward as just allowing it to oxidize. The task is best accomplished with a technique called atomic-layer deposition, which employs a gas made of small molecules that naturally stick to the surface but do not bond to one another. A single-molecule-thick film can be laid down simply by exposing the wafer to this gas long enough so that every spot becomes covered. Treatment with a second gas, one that reacts with the first to form the material in the coating, creates the molecule-thin veneer. Repeated applications of these two gases, one after the next, deposit layer over layer of this substance until the desired thickness is built up.

After the gate insulator is put in place, parts of it must be selectively removed to achieve the appropriate pattern on the wafer. The procedure for doing so (lithography) constitutes a key part of the technology needed to create transistors and their interconnections. Semiconductor lithography employs a photographic mask to generate a pattern of light and shadows, which is projected on a wafer after it is coated with a light-sensitive substance called photoresist. Chemical processing and baking harden the unexposed photoresist, which protects those places in shadow from later stages of chemical etching.

Practitioners once believed it impossible to use lithography to define features smaller than the wavelength of light employed, but for a few years now, 70-nanometer features have been routinely made using ultraviolet light with a wavelength of 248 nanometers. To accomplish this magic, lithography had to undergo some dramatic changes. The tools brought to bear have complicated names--optical proximity correction, phase-shifting masks, excimer lasers--but the idea behind them is simple, at least in principle. When the size of the features is smaller than the wavelength of the light, the distortions, which arise through optical diffraction, can be readily calculated and corrected for. That is, one can figure out an arrangement for that mask that, after diffraction takes place, yields the desired pattern on the silicon. For example, suppose a rectangle is needed. If the mask held a plain rectangular shape, diffraction would severely round the four corners projected on the silicon. If, however, the pattern on the mask were designed to look more like a dog bone, the result would better approximate a rectangle with sharp corners.

This general strategy now allows transistors with 50-nanometer features to be produced using light with a wavelength of 193 nanometers. But one can push these diffraction-correction techniques only so far, which is why investigators are trying to develop the means for higher-resolution patterning. The most promising approach employs lithography, but with light of much shorter wavelength--what astronomers would call "soft" x-rays or, to keep with the preferred term in the semiconductor industry, extreme ultraviolet.

Semiconductor manufacturers face daunting challenges as they move to extreme ultraviolet lithography, which reduces the wavelengths (and thus the size of the features that can be printed) by an order of magnitude. The prototype systems built so far are configured for a 13-nanometer wavelength. They are truly marvels of engineering--on both macroscales and nanoscales.

Take, for instance, the equipment needed to project images onto wafers. Because all materials absorb strongly at extreme ultraviolet wavelengths, these cameras cannot employ lenses, which would be essentially opaque. Instead the projectors must use rather sophisticated mirrors. For the same reason, the masks must be quite different from the glass screens used in conventional lithography. Extreme ultraviolet work demands masks that absorb and reflect light. To construct them, dozens of layers of molybdenum and silicon are laid down, each just a few nanometers thick. Doing so produces a highly reflective surface onto which a patterned layer of chromium is applied to absorb light in just the appropriate places.

As with other aspects of chipmaking, these masks must be free from imperfections. But because the wavelengths are so small, probing for defects proves a considerable challenge. Scientists and engineers from industry, academe and government laboratories from across the U.S. and Europe are collaboratively seeking solutions to this and other technical hurdles that must be overcome before extreme ultraviolet lithography becomes practical. But for the time being, chipmakers must accept the limits of conventional lithography and maintain feature sizes of at least 50 nanometers or so.

Using lithography to imprint such features on a film of photoresist is only the first in a series of manipulations used to sculpt the wafer below. Process engineers must also figure out how to remove the exposed parts of the photoresist and to etch the material that is uncovered in ways that do not eat into adjacent areas. And one must be able to wash off the photoresist and the residues left over after etching--a mundane task that becomes rather complicated as the size of the features shrinks.

The problem is that, seen at the nanometer level, the tiny features put on the chip resemble tall, thin skyscrapers, separated by narrow chasms. At this scale, traditional cleaning fluids act as viscous tidal waves and could easily cause things to topple. Even if that catastrophe can be avoided, these liquids have a troubling tendency to get stuck in the nanotechnology canyons.

An ingenious solution to this problem emerged during the 1990s from work done at Los Alamos National Laboratory: supercritical fluids. The basic idea is to use carbon dioxide at elevated pressure and temperature, enough to put it above its so-called critical point. Under these conditions, CO2 looks something like a liquid but retains an important property of a gas--the lack of viscosity. Supercritical carbon dioxide thus flows easily under particles and can mechanically dislodge them more effectively than can any wet chemical. (It is no coincidence that supercritical carbon dioxide has recently become a popular means to dry-clean clothes.) And mixed with the proper co-solvents, supercritical carbon dioxide can be quite effective in dissolving photoresist. What is more, once the cleaning is done, supercritical fluids are easy to remove: lowering the pressure--

say, to atmospheric levels-causes them to evaporate away as a normal gas.

With the wafer cleaned and dried in this way, it is ready for the next step: adding the junctions of the transistors--tubs on either side of the gate that serve as the current "source" and "drain." Such junctions are made by infusing the silicon with trace elements that transform it from a semiconductor to a conductor. The usual tactic is to fire arsenic or boron ions into the surface of the silicon using a device called an ion implanter. Once emplaced, these ions must be "activated," that is, given the energy they need to incorporate themselves into the crystal lattice. Activation requires heating the silicon, which often has the unfortunate consequence of causing the arsenic and boron to diffuse downward.

To limit this unwanted side effect, the temperature must be raised quickly enough that only a thin layer on top heats up. Restricting the heating in this way ensures that the surface will cool rapidly on its own. Today's systems ramp up and down by thousands of degrees a second. Still, the arsenic and boron atoms diffuse too much for comfort, making the junctions thicker than desired for optimum speed. A remedy is, however, on the drawing board--laser thermal processing, which can vary the temperature at a rate of up to five billion degrees a second. This technology, which should soon break out of the lab and onto the factory floor, holds the promise of preventing virtually all diffusion and yielding extremely shallow junctions.

Once the transistors are completed, millions of capacitors are often added to make dynamic random-access memory, or DRAM. The capacitors used for DRAM have lately become so small that manufacturing engineers are experiencing the same kinds of problems they encounter in fashioning transistor gates. Indeed, here the problems are even more urgent, and the answer, again, appears to be atomic-layer deposition, which was adopted for the production of the latest generation of DRAM chips.

New Meets Old

Atomic-layer deposition can also help in the next phase of chip manufacture, hooking everything together. The procedure is to first lay down an insulating layer of glass on which a pattern of lines is printed and etched. The grooves are then filled with metal to form the wires. These steps are repeated to create six to eight layers of crisscrossing interconnections. Although the semiconductor industry has traditionally used aluminum for this bevy of wires, in recent years it has shifted to copper, which allows the chips to operate faster and helps to maintain signal integrity. The problem is that copper contaminates the junctions, so a thin conductive barrier (one that does not slow the chip down) needs to be placed below it. The solution was atomic-layer deposition.

The switch to copper also proved challenging for another reason: laying down copper is inherently tricky. Many high-tech approaches were attempted, but none worked well. Then, out of frustration, engineers at IBM tried an old-fashioned method: electroplating, which leaves an uneven surface and has to be followed with mechanical polishing. At the time, the thought of polishing a wafer--that is, introducing an abrasive grit--was anathema to managers in this industry, which is downright obsessed with cleanliness. Hence, the engineers who originally experimented with this approach at IBM did so without seeking permission from their supervisor. They were delighted to discover that the polishing made the wafer more amenable to lithographic patterning (because the projection equipment has a limited depth of focus), that it removed troublesome defects from the surface and that it made it easier to deposit films for subsequent processing steps.

The lesson to be learned here is that seemingly antiquated methods can be just as valuable as cutting-edge techniques. Indeed, the semiconductor industry has benefited a great deal in recent years from combinations of old and new. That it has advanced as far as it has is a testament to the ingenious ability of countless scientists and engineers to continually refine the basic method of chip manufacture, which is now more than four decades old.

Will the procedures used for fabricating electronic devices four decades down the road look anything like those currently employed? Although some futurists would argue that exotic forms of nanotechnology will revolutionize electronics by midcentury, I'm betting that the semiconductor industry remains pretty much intact, having by then carried out another dazzling series of incremental technical advances, ones that are today beyond anyone's imagination.

G. DAN HUTCHESON is chief executive officer and president of VLSI Research Inc., a market research and economic analysis firm serving the semiconductor industry. Hutcheson, who holds a master's degree in economics from San Jose State University, has constructed various quantitative models that chipmakers can use to forecast costs and to guide them in procuring equipment. As an industry analyst, he follows the emerging technologies of semiconductor manufacture and provides summaries of the latest research advances and manufacturing trends to interested companies.

Tasks. Part 1 (up to ‘provides physical support’).

Task 1. *Find words or expressions meaning:*
(up to ‘straining to accelerate’)

1. Problems, difficulties
2. To declare or make known loudly, praise too much
3. Successes
4. Achievements
5. Hardly enough
6. To push as a filling material
7. Increase
8. To come, bringing or causing to enter
9. To cause difficulty in task

(up to ‘provides physical support’)

10. No more

11. Are kept secret
12. Stick to
13. Difficulty

Task 2. *Say whether the following is true, false or not mentioned:*

1. The people who created nanochips are world famous.
2. The smaller the transistor, the cheaper it is.
3. The speed of the transistor performance is proportional to the gates width.
4. It's much harder to create a nanochip than it was to create the A bomb.
5. Crystal lattice defects deteriorate silicon conductivity in single crystal ingots.
6. Silicon deposition increases the speed of the transistors.
7. An improved version of this method is silicon-on-insulator technology.
8. This method is widely used in most desktops nowadays.
9. IBM was the first to suggest forming an insulating oxide layer directly on top of a silicon layer.
10. The desire to increase the speed of transistor's performance resulted in the method called strained silicon.
11. The lower the capacitance of the gate, the better it is.
12. The capacitance is reverse to the thickness of the oxide layer.

Task 3. Answer the following questions:

1. Why does the author think it's necessary to speak loudly about the latest achievements?
2. Do you agree that the main reason to make things smaller is to pack more transistors into a smaller space? Why?/Why not?
3. How is a silicon crystal traditionally produced?
4. What is the drawback of this method?
5. What is the way out?
6. What is the difference between SIMOX technology and the new faster method? What brought this method about?

7. How does Smart Cut work?
8. Why do strained silicon transistors work faster?
9. Do you agree that capacitance depends on the thickness of the oxide layer: the thicker the layer, the greater the capacitance is?

Tasks. Part 2 (from ‘The key was in developing ‘up to ‘New Meets Old’).

Task 1. *Find words or expression meaning*:

(from “The key was in developing “ up to’ approximate a rectangle with sharp corners’)

1. To be in position in which one must deal with a problem or an unpleasant situation
2. To come to understand
3. To search or examine
4. Disheartening
5. Something new and difficult which may require great effort or determination
6. Temporarily
7. Ordinary and uninteresting
8. Complex
9. Not accidental

(from ‘This general strategy’ up to ‘New Meets Old’)

10. The thing that happens in addition to the main consequences
11. Difficult
12. Disappointment
13. The most advanced
14. Complete, not damaged or spoilt

Task 2: *Find information in support or against the following*:

1. Scientists proved that physical laws do not allow us to use lithography for the features smaller than the wavelength of the light.

2. To get a rectangular pattern on silicon we have to use a rectangular mask. The masks must be perfect but since x-rays or ultraviolet rays are used, to find imperfections is pretty hard.

3. Diffraction-correction methods used to produce transistors with 50 nanometers features have their limitations.

4. The projecting equipment must have high quality extra dispersion lenses letting all the light through.

5. Both the US and EEC are trying to cope with technical problems on their own competing with each other and keeping all the information secret.

6. For the moment chip producing companies have to put up with the fact that ordinary lithography cannot be used beyond a certain point.

7. Under certain conditions CO2 can behave like a liquid in all but one respects.

8. Activating arsenic and boron ions can cause some unwanted effects.

9. This problem hasn't yet been solved.

10. We can draw the conclusion that methods appearing to be outdated can be as good as new

11. The author is of the opinion that in 40 years or so the transistor industry will have another major breakthrough.

6. SCIENTISTS OBSERVE NANOWIRES AS THEY GROW

X-ray experiments reveal exact details of self-catalyzed growth for the first time

Date: February 8, 2018

Summary:

Scientists have followed the growth of tiny wires of gallium arsenide live. Their observations reveal exact details of the growth process responsible for the evolving shape and crystal structure of the crystalline nanowires. The findings also provide new approaches to tailoring nanowires with desired properties for specific applications.

1. At DESY's X-ray source PETRA III, scientists have followed the growth of tiny wires of gallium arsenide live. Their observations reveal exact details of the growth process responsible for the evolving shape and crystal structure of the crystalline nanowires. The findings also provide new approaches to tailoring nanowires with desired properties for specific applications. The scientists, headed by Philipp Schroth of the University of Siegen and the Karlsruhe Institute of Technology (KIT), present their findings in the journal Nano Letters. The semiconductor gallium arsenide (GaAs) is widely used, for instance in infrared remote controls, the high-frequency components of mobile phones and for converting electrical signals into light for fibre optical transmission, as well as in solar panels for deployment in spacecraft.

2. To fabricate the wires, the scientists employed a procedure known as the self-catalysed Vapour-Liquid-Solid (VLS) method, in which tiny droplets of liquid gallium are first deposited on a silicon crystal at a temperature of around 600 degrees Celsius. Beams of gallium atoms and arsenic molecules are then directed at the wafer,

where they are adsorbed and dissolve in the gallium droplets. After some time, the crystalline nanowires begin to form below the droplets, whereby the droplets are gradually pushed upwards. In this process, the gallium droplets act as catalysts for the longitudinal growth of the wires. “Although this process is already quite well established, it has not been possible until now to specifically control the crystal structure of the nanowires produced by it. To achieve this, we first need to understand the details of how the wires grow,” emphasises co-author Ludwig Feigl from KIT.

3. To observe the growth as it takes place, Schroth’s group installed a mobile experimental chamber, specially developed by KIT for X-ray experiments and partially funded by the Federal Ministry of Education and Research (BMBF), in the brilliant X-ray beam of DESY’s synchrotron radiation source PETRA III at experimental station P09. At one-minute intervals the scientists took X-ray pictures, which allowed both the internal structure and the diameter of the growing nanowires to be simultaneously determined. In addition, they measured the fully-grown nanowires using the scanning electron microscope at the DESY NanoLab. “To ensure the success of such complex measurements, an extensive period of growth characterisation and optimisation at the UHV Analysis Lab at KIT was a prerequisite,” explains co-author Seyed Mohammad Mostafavi Kashani from University of Siegen.

4. Over a period of about four hours, the wires grew to a length of some 4000 nanometres. One nanometre (nm) is one millionth of a millimetre. However, not only did the wires become longer during this time, but also thicker: their diameter increased from an initial 20 nm to up to 140 nm at the top of the wire, still making them around 500 times thinner than a human hair.

5. “One rather exciting feature is that the images taken under the electron microscope show the nanowires to have a slightly different shape,” says co-author Thomas Keller from DESY NanoLab. Although the wires were thicker at the top than at the bottom, just as

indicated by the X-ray data, the diameter measured under the electron microscope was larger in the lower region of the wire than what was observed using X-rays.

6. "We found out that the growth of the nanowires is not only due to the VLS mechanism but that a second component also contributes, which we were able to observe and quantify for the first time in this experiment. This additional sidewall growth lets the wires gain width," explains Schroth. Independently of VLS growth, the vapour deposited material also attaches itself directly to the side walls, particularly in the lower region of the nanowire. This additional contribution can be determined by comparing the X-ray measurements taken early on during the growth of the wire, with the electron microscope measurement after growth has ended.

7. Furthermore, the gallium droplets are constantly becoming larger as further gallium is added in the course of the growth process. Using growth models, the scientists were able to deduce the shape of the droplets, which had also been affected by the increasing droplet size. The effect of this is far-reaching: "As the droplet changes in size, the angle of contact between the droplet and the surface of the wires also changes. Under certain circumstances, the wire then suddenly continues growing with a different crystal structure," says Feigl. Whereas the fine nanowires initially crystallise in a hexagonal, so-called wurtzite structure, this behaviour changes after some time and the wires adopt a cubic zinc blende structure as they continue to grow. This change is important when it comes to applications, since the structure and shape of the nanowires have important consequences for the properties of the resulting material.

8. Such detailed findings not only lead to a better understanding of the growth process; they also provide approaches for customising future nanowires to have special properties for specific applications – for example to improve the efficiency of a solar cell or a laser.

Task 1. Find words or expressions meaning the following:

1. to show;
2. correct in every detail; strictly accurate;
3. happening at the same time;
4. a necessary condition, an essential requirement;
5. to result from;
6. conclude;
7. influenced;
8. the way in which a machine works.

Task 2. *Which paragraph(s):*

1. says(say) that the process of producing nanowires has been known for a long time;
2. explains why nanowires grow;
3. mentions an important feature of nanowires;
4. mentions the instruments used in observing the growth of nanowires;
5. explains why the droplet size is so important;
6. mentions the part the gallium droplets play;
7. says that the wires not only change their length but also their diameter;
8. says it is possible to produce nanowires with predetermined properties using new methods.

Task 3. *Answer the following questions:*

1. What are the results of scientists' observations?
2. Why are they so important?
3. What role did x-ray pictures play?
4. Was the wires size the same everywhere? (Prove!)
5. What is the growth caused by?
6. How did growth models contribute to the scientists' work?
7. How does this effect influence the wires growth?
8. What do the structure and shape of nanowires affect?

7. WATER-SOLUBLE WARPED NANOGRAPHENE

Synthesis of a water-soluble warped nanographene and its application for photo-induced cell death

Date: February 9, 2018

Summary:

Graphene and its nano-sized little sibling, nanographene, are well known for their remarkable photoelectronic properties. However, biomedical applications are hampered by the insolubility of the materials, especially in water. A Japanese team of scientists has now introduced substituted ‘warped nanographene,’ which is soluble in a broad range of solvents while maintaining its photophysical properties. In their publication in Angewandte Chemie, the authors also emphasize its photodynamic potential to selectively kill cells upon irradiation.

Full story

Graphene and its nano-sized little sibling, nanographene, are well known for their remarkable photoelectronic properties. However, biomedical applications are hampered by the insolubility of the materials, especially in water. A Japanese team of scientists has now introduced substituted “warped nanographene,” which is soluble in a broad range of solvents while maintaining its photophysical properties. In their publication in Angewandte Chemie, the authors also emphasize its photodynamic potential to selectively kill cells upon irradiation.

Nanographene has the hexagonal carbon lattice of graphene but consists of only a few carbon rings with tunable electronic properties. One of its big issues hampering widespread application in optoelectronic devices or biomedicine is its insolubility. Therefore, to suppress stacking and aggregation, a new type of nanographene with a bended structure has been synthesized, the so-called warped nanographene. Kenichiro Itami at Nagoya University, Japan, and his colleagues have now found a way to furnish the warped nanographene even further to obtain a fully soluble, amphiphilic product. The new structure was biocompatible, but upon irradiation it killed its host cell. This effective photosensitization behavior could inspire future research in photodynamic cancer therapy, the authors believe.

The poor solubility of graphene-like materials has been regarded problematic since the discovery of graphene as an intriguing one-layer carbon modification in 2004. To improve solubility, Itami and his colleagues have developed warped nanographene molecules with chemical substituents at the outer rim of the aromatic structure. The substituents were introduced by the relatively simple and powerful strategy of borylation. Once the molecule is borylated, the boron substituent can be replaced by other substituents, in this case, by an aromatic molecule bearing highly soluble tetra(ethylene glycol) chains (TEG). Applying this substitution-replacement strategy twice, the scientists accomplished the synthesis of a warped, i.e., bended, nanographene molecule that was stable in a broad range of solvents including water. Excited with a laser, it exhibited green fluorescence.

This fluorescence points to applications in biology, for example, as a dye in bioimaging. A further application came rather unexpected, the scientists reported. Upon excitation, the molecule, which was otherwise not harmful to the cells, killed the cell population of the human HeLa cell line to almost 100 percent. The authors proposed: "Although the mechanism is unclear, the relatively high efficiency of the singlet oxygen generation of [the soluble warped nanographene] may contribute to its HeLa cell death." Thus, a mechanism similar to dye sensitization and production of reactive oxygen species can be assumed.

These second-generation nanographenes combine the remarkable optoelectronic properties of graphene with biocompatibility. They may well play a future role in bioimaging, photodynamic therapy, and similar applications.

Task 1. *Find the following words:*

1. each of two or more children;
2. to make it difficult for someone to do smth, to interfere with the operation;
3. to prevent an activity from happening by using force;
4. for that reason;
5. bent or twisted out of shape;
6. achieve or complete successfully;
7. the application of energy to a particle, object, or physical system, in particular.

Task 2. *Say whether the following is true, false or not mentioned*:

1. A great problem preventing graphene from being used In optoelectronics is that it cannot be dissolved in water and other substances;
2. After irradiation the new type of warped nanographene can be used to treat cancer;
3. The inability of graphene-like materials to dissolve has only recently been discovered;
4. 2D materials have existed for a long time;
5. After being zapped with laser pulses nanographene started to emit the red light;
6. Being zapped with a laser the graphene molecule became dangerous for a certain type of human cells;
7. What causes this effect still remains a mystery but may be akin to the effect of dye sensitization;
8. In graphene layers move past each other;
9. Nanographene has the octagonal carbon lattice of ghraphene but consists of a dozen of nanorings with unpredictable electronic properties.

8. BEYOND GRAPHENE

The ultrathin form of carbon has inspired other atoms-thick materials that promise even bigger technological payoffs

By Robert F. Service, in San Antonio, Texas

Sticky tape isn't normally thought of as the stuff of scientific breakthroughs. But when physicists Andre Geim and Konstantin Novoselov of the University of Manchester in the United Kingdom and colleagues reported in Science in 2004 that they had used clear tape to peel off single atomically thin sheets of carbon atoms from a chunk of graphite, it set off a revolution in materials science that is still unfolding.

Last year, researchers around the globe published more than 15,000 papers on single-layer graphite, called graphene, a number that has grown exponentially since the Manchester team's sticky innovation 11 years ago. And for good reason. Graphene is the thinnest material ever made. It's 100 times stronger than steel, a better electrical and heat conductor than copper, flexible, and largely transparent. Investigators envision a future for it in everything from the next generation of computer chips and flexible displays to batteries and fuel cells.

Yet graphene may have its biggest impact not as a wonder material in its own right, but through its offspring. For all its dazzling promise, graphene has drawbacks, especially its inability to act as a semiconductor, the keystone of microelectronics. Now, chemists and materials scientists are striving to move beyond graphene. They're synthesizing other two-dimensional sheetlike materials that promise to combine flexibility and transparency with electronic properties graphene can't match. And they are already turning some of them into thin, flexible, speedy electronic and optical devices that they hope will form the backbone of industries of the Graphene (top) has spurred scientists to explore flat semiconductors such as phosphorene (middle) and molybdenum disulfide (above). future. “The field is wide open,” says David Tomanek, a condensed matter physicist at Michigan State University in East Lansing. Keji Lai, a physicist at the University of Texas (UT), Austin, agrees, calling 2D materials “one of the hottest topics in physics.”

IN ONE SENSE, 2D materials aren’t new at all. Researchers have been growing atomically thin sheets of materials since the 1960s using tools called molecular beam epitaxy (MBE) machines. But MBE machines are typically used to deposit thin layers of materials like silicon and gallium arsenide: crystalline materials whose component atoms normally prefer to bond in three dimensions.

In that respect, the layers made by MBE are like a slice of cheese, a 2D version of a 3D substance.

Graphene is different. It’s more like the pages in a book, says Yi-Hsien Lee, a materials scientist at the National Tsing Hua University in Hsinchu, Taiwan. Its carbon atoms form strong, covalent links with other carbons in a single 2D plane, creating a hexagonal lattice that looks like miniature chicken wire. But separate planes of atoms are only loosely paired with weak bonds known as van der Waals interactions. As a result, the layers can slip past one another, which is why graphite is used to make the gray flaky “lead” in pencils.

The big surprise was that when researchers began to study graphene closely, they discovered it had electronic and optical properties not found in bulk graphite. “The biggest lesson is that less is different,” says Yuanbo Zhang, a condensed matter physicist at Fudan University in Shanghai, China. And with that lesson, Tomanek says, “graphene brought 2D materials into the limelight.”

Yet when it comes to making high-tech devices, graphene’s promise dims a bit. While the most prized materials of the electronics age are semiconductors, whose conductivity can be switched on and off to generate the digital currency of Is and Os, graphene is more like a conducting metal. “Graphene is an absolutely wonderful material,” Tomanek says. “But it’s irrelevant for electronics.”

Researchers have spent years trying to convert graphene into a semiconductor by bonding oxygen to the graphene sheets or by cutting the sheets into ribbons just a few nanometers wide. Both changes do alter graphene's electronic structure, turning it into a semiconductor. But these "solutions" brought other problems. Graphene oxide's electronic properties are strongly affected by molecules that interact with it, a foible that undermines its reliability. And the nanoribbons' electronic properties depend so critically on a ribbon's precise structure that they are hard to control.

Yet graphene opened researchers' eyes to a new world of flatland electronics. They saw that similar materials might have novel optical and electrical properties. And because 2D sheets are so thin and mostly transparent, they offered the prospect of creating flexible and transparent electronics that could produce see-through displays of the sort dreamed up years ago by Hollywood. Since then, researchers have been surveying that landscape for richer treasures.

By looking for materials that naturally form 2D sheets and finding ways of stabilizing sheets of atoms that normally want to form a 3D architecture, materials scientists have already come up with dozens of new 2D materials, and many more are likely to follow. They've engineered single-layer silicon (known as silicene), single-layer germanium (germanene), and single-layer tin (stanene). They've created an insulator made from boron nitride, which has the same chicken- wire lattice structure as graphene. They've made single-layer metal oxides that may serve as highly active catalysts for controlling particular chemical reactions. And they've even trapped water molecules in thin sheets, although what this will be useful for isn't yet clear.

But for now, most of the buzz among flatlanders surrounds just two materials: a compound called molybdenum disulfide (MoS2) and a double layer of phosphorus atoms called phosphorene. Both have tantalizing electronic properties, and the competition between their acolytes is fierce.

Of the two materials, MoS2 had the head start. Originally synthesized in 2008, MoS2 is a member of a broader family of materials called transition metal dichalcogen- ides (TMDs). The name is just a fancy term for their makeup: one transition metal atom (in this case molybdenum) and a pair of atoms from column 16 of the periodic table (a family known as the chalcogens), which contains sulfur and selenium, among others. Much to the delight of electronics makers, all TMDs are semiconductors. They aren’t quite as thin as graphene (in MoS2, twin sheets of sulfur atoms sandwich a middle layer of molybdenum atoms), but they offer other advantages. In the case of MoS2, one is the speed at which electrons travel through the flat sheets – a property called electron mobility. MoS’s mobility is a decent 100 or so centimeters squared per volt second (cm2/vs). That’s well below the 1400 cm2/vs mobility of crystalline silicon, but it’s better than the number for amorphous silicon and many other ultrathin semiconductors being tested for use in futuristic applications such as roll-up displays and other flexible, stretchable electronics.

MoS2 also turns out to be fairly easy to make, even in large sheets. And that has helped engineers move quickly to testing it in devices. In 2011, for example, researchers led by Andras Kis of the Swiss Federal Institute of Technology in Lausanne reported in Nature Nanotechnology that they had made the first transistors using a single layer of MoS2 just 0.65 nanometers thick. Those devices and their successors turned out to have other exceptional properties that rival those of far more developed silicon-based technology. They can switch on and off billions of times per second. They also boast a large on/off ratio, which makes it easy to differentiate between digital Is and Os – a property prized by circuit designers. Since 2011, Kis’s group and others have engineered a host of MoS2-based electronic devices including logic circuits and always-on flash memory devices, both of which are widely used in today’s computers.

Beyond that, MoS2 has another desirable property known as a direct bandgap, which enables the material to convert electrons into photons of light – and vice versa. That makes MoS2 a good candidate for use in optical devices, such as light emitters, lasers, photodetectors, and even solar cells. Lee, an expert in growing large-area MoS2 films, notes the material is also abundant, cheap, and nontoxic. “It has a bright future,” he says.

Tomanek, however, is among MoS2’s detractors, saying “it has been oversold.” In particular, Tomanek says he isn’t convinced that MoS2’s electron mobility will ever be high enough to compete in the crowded electronics marketplace. The reason, he says, lies in the material’s very makeup. Electrons traveling through it ricochet off large metal atoms in its structure and slow down.

That stumbling block will prove temporary, Lee says. Researchers are already learning to navigate around it by growing slightly thicker multilayers of MoS2 that offer zipping electrons alternative routes to bypass roadblocks. “The mobility issue of MoS2 will be solved,” Lee says.

Its rival, phosphorene, has sparked even more excitement. Also known as black phosphorus, phosphorene is one of three different crystal structures – or allotropes – that pure phosphorus can adopt. The others are white phosphorus, which is used in making fireworks, and red phosphorus, used to make the heads of matches. Phosphorene, which consists of a corrugated pattern of phosphorus atoms that lie in two different planes, was first synthesized only last year. But its properties have already made it a materials-science darling. It has an electron mobility of 600, which some researchers hope to increase even further, and its bandgap – the voltage needed to drive a current through it – is tunable. Electrical engineers can adjust the bandgap simply by varying the number of phosphorene layers they stack one atop another, making it easier to engineer devices with the exact behavior desired. “All this makes black phosphorus a superior material,” Tomanek says.

Researchers have made rapid progress toward incorporating it into devices. On 2 March 2014, Zhang and his colleagues at Fudan University reported online in Nature Nanotechnology that they had made phosphorene-based field effect transistors, devices that serve as the heart of computer logic circuitry. Two weeks later, Tomanek and colleagues at Michigan State, together with researchers led by Peter Ye, an electrical engineer at Purdue University in West Lafayette, Indiana, reported online in ACS Nano that they, too, had made phosphorene-based transistors, along with simple circuits.

Unfortunately, phosphorene is unstable in air. “We see bubbles cover the surface after 24 hours and total device failure in days,” says Joon-Seok Kim, a phosphorene device maker at UT Austin. The culprit, Lee says, is water vapor, which reacts with the phosphorus, eroding it by converting it to phosphoric acid. Even so, Kim’s group at Texas and others are making progress in protecting it. Kim reported at the March meeting of the American Physical Society (APS) in San Antonio, Texas, for example, that he and his colleagues were able to stabilize phosphorene-based transistors for 3 months and counting by encapsulating them in a protective layer of aluminum oxide and Teflon. At the same meeting, researchers from Northwestern University in Evanston, Illinois, reported that a similar strategy gave them stable devices out to 5 months and counting.

But Lee, for one, is not convinced the fixes will lead to long-term stability. ‘You can put a capping layer on top, but it just reduces the degradation rate,” Lee says. Phosphorene, he argues, is gaining attention because it’s easy for researchers to get their hands on: It can simply be peeled off a chunk of black phosphorus with sticky tape, like graphene. “It’s a kind of fashion,” Lee says. “But that doesn’t mean it will have a future.”

IN THE END, there may be plenty of room for both materials. ‘We’re still just at the beginning,” says Luis Balicas, a physicist at Florida State University and the National High Magnetic Field Laboratory in Tallahassee. He suggests that over time engineers may wind up favoring MoS2’s strong interactions with light to make solar cells, light emitters, and other optical devices, while harnessing phosphorene’s higher electron mobility for making electronic devices.

Two-dimensional materials also offer another tantalizing option: They can be stacked like cards in a deck to create the different electronic layers needed in functional electronic devices.

In devices made using conventional 3D materials, neighboring crystalline layers usually bind tightly to one another. But if the atomic lattice of adjacent layers differs by more than 15% or so, the strain at the interface causes one or both layers to crack, a potential device killer. That means electrical engineers must either severely limit their selection of neighboring materials so that the layers can join without strain, or resort to complex workarounds, such as adding “buffer” layers at each interface. With stacked 2D materials, “we don’t need to worry about this,” Lee says, because they don’t form tight bonds with the layers above and below.

That advantage has prompted scientists to build such devices, called van der Waals heterostructures after the weak bonds be-tween adjacent layers. The first ones are already emerging. Last year, Ye’s group at Purdue reported that they had used both MoS2 and phosphorene to make ultrathin photovoltaics (PVs). At the APS meeting, Balicas’s group reported similar PVs made by combining layers of TMDs, boron nitride, and graphene. And in February, Geim and colleagues reported online in Nature Materials that they had assembled multiple 2D materials to make efficient, thin light-emitting diodes.

Such progress has the community of device makers salivating over what may soon be possible. “In principal, we can build an electronic system fully based on 2D materials,” says Xiaomu Wang, an electrical engineer at Yale University. Such devices would M be flexible, transparent, temperature stable, 8 and cheap to manufacture, Wang says. Con- 2 templating prospects like that, Tomanek J thinks the latest revolution in electronics and optics is just getting started: “2D materials are here to stay.”

Task 1. *Find the paragraph(s) which:*

1. Says that materials like graphene have existed for a long time;
2. Explains why there is such a fuss about the new substance;
3. Speaks about a very exciting property of 2D materials;
4. Says that MoS2 has been overhyped;
5. Says that the interest in graphene is only temporary;
6. Mentions the advantages of molybdenum bisulphide electronics;
7. Says that is not graphene as such that is important;
8. Says that both molybdenum bisulphide and phosphorene can find their uses;
9. Explains what makes graphene unsuitable for electronics;
10. Explains what makes phosphorene so good.

Task 2. *Answer the following questions.*

1. What makes graphene so good?
2. Why are scientists not so enthusiastic about it now? What proves it?
3. 2d materials have existed for a long time. Why was there so much fuss when graphene was discovered?
4. What are the most popular 2d materials now?
5. Which is better?
6. What is MoS2 disadvantage?
7. Is there hope the problem will be coped with?
8. Which material is thought to be more prospective now?
9. Was the problem of phosphorene stability solved?
10. Does everybody agree it is the final solution?
11. How can 2d materials be used?

Task 3. *Find words or expressions meaning the following:*

1. a great success;
2. to cause an event to start happening;
3. influence;

4. on that issue;
5. to put at the center of attention;
6. to think of a plan or idea and suggest it;
7. a person or thing that follows;
8. a problem which stops you from achieving something;
9. together with;
10. tormenting or teasing (someone) with the sight or promise of something that is unobtainable;
11. to do something bad, extreme or difficult because you cannot think of any other way to deal with a problem;
12. next to or adjoining something else.

9. MAGNETIC FIELD NANOSENSORS

By Stuart A. Satin

It often happens in science that research focused on one phenomenon results in the unexpected discovery of a new effect that is much more exciting and important. In 1995 a case of this serendipity occurred with my research group, then at the NEC Research Institute in Princeton, N.J.

We were studying the properties of a microelectronics structure called a semiconductor superlattice, which consisted of layers of gallium arsenide and gallium aluminum arsenide stacked like a club sandwich. We knew that this superlattice had very interesting electrical properties. In particular, we were investigating how the thickness of the layers determined whether the superlattice behaved as a metal, with low electrical resistance, or as an insulator, with high resistance. We immersed the system in a magnetic field, a procedure that enabled us to study dynamical processes involving the electrons in the superlattice.

To our great surprise, we saw that the resistance of the superlattice increased dramatically when we strengthened the magnetic field. Such behavior would be expected in a magnetic material but not in something like our superlattice, which was made entirely of nonmagnetic constituents. The percentage increase in resistance, called the magnetoresistance (MR), was so big and so unusual that my team immediately redirected its efforts to explain the fundamental physics of this new effect.

By 1997 we had developed a sound basic understanding of this new kind of large MR. Moreover, we predicted that considerably greater MR might be obtained from a much simpler structure fabricated from a nonmagnetic metal such as gold (Au) and a single layer of the semiconductor indium antimonide (InSb). In 1998, working with Jean Here-mans of Ohio University, we built an InSb-

Au structure that fulfilled our prediction [see box on page 49]. In a magnetic field of five teslas, the MR was about 1 million percent at room temperature, thousands of times as great as any MR previously observed at that temperature. We dubbed this phenomenon "extraordinary magnetoresistance," or EMR, and we knew that it could be useful for a wide variety of technologies that require sophisticated magnetic field sensors, such as ultrahigh-density data recording, automotive control systems, industrial applications, medical devices and consumer electronics.

What's So Special about EMR

EMR was far from being the first large MR effect discovered. In recent decades, a series of such phenomena have been observed, in part as a response to the demand for small yet highly sensitive magnetic field sensors [see box on opposite page]. EMR is unique among large MRs, however, in that it does not require a magnetic material as part of the structure – a property that is scientifically intriguing and also advantageous for certain applications, as I will explain later.

The other big MR effects occur when the magnetic field of a material's atoms interacts with the intrinsic magnetism of the electrons flowing through the material. You can picture the innate magnetism of the electrons by imagining that each one contains a tiny bar magnet with a north and a south pole. Normally these magnets point in random directions and have no effect on the flow of current. But in a magnetic material, the electrons tend to become polarized, with their magnets aligned with the material's magnetic field. Once an electric current is polarized, it flows more easily through a material whose magnetic field is parallel with its polarization than through one that is antiparallel.

Thus, MR structures typically have one layer of magnetic material that polarizes the current and a second layer that has a controllable magnetization; the second layer impedes or lets through the current depending on how its field is oriented with respect to the first layer. Devices that utilize the electron's magnetism in this way are called either magneto-electronics or spintronics, the latter because the magnetism is closely related to a quantity called spin [see "Spintronics," by David D. Awschalom, Michael E. Flatte and Nitin Samarth; SCIENTIFIC AMERICAN, June 2002].

Magnetoresistance is the phenomenon in which the electrical resistance of a metal or a semiconductor increases or decreases in response to a magnetic field. A variant of this effect thousands of times as great as any previously observed was discovered in 1998 and dubbed extraordinary magnetoresistance (EMR). EMR depends on the detailed geometry of a device made out of conductive metal and semiconductor.

EMR could be used to make computer disk-drive read heads that are faster and capable of handling higher densities of data than present-day read heads (which depend on giant magnetoresistance, or GMR). Because EMR read heads contain no magnetic materials, they would have lower noise than GMR read heads, thereby improving performance.

Many other applications could benefit from EMR, including position-sensing robots, other speed and position sensors in industry, antilock brakes, "smart" shock absorbers, ignition timing and control systems, flip-phone switches, and nonvolatile memory in low-cost appliances.

How, then, does EMR work in the absence of a magnetic material? The answer lies in a second way that magnetic fields interact with moving electrons. When a charged particle, such as an electron, travels through a magnetic field, the field exerts a transverse force on the particle, curving its trajectory [see box on page 48]. This effect is what causes ordinary MR. The field curves the electrons' trajectories, even turning them into helices if it is strong enough. Because the electrons travel along longer, winding paths, their net motion from one end of the material to the other is slowed down. In this way, the current is reduced; the resistance is enhanced. To be more precise, the electrons actually travel along random zigzag paths because of collisions with impurities or other defects in the material. Nevertheless, the magnetic field turns each straight zig or zag into a curve, increasing the total path length traveled as the electrons make their erratic way through the material.

The very much larger effect of EMR also depends on the magnetic field curving the electrons' paths. EMR's great magnitude, however, is caused by the interplay of the curved paths and the detailed geometry of the EMR device at the nanometer scale (billionths of a meter).

The shape, location and electrical properties of the elements of the device – such as electrical contacts and regions of different materials – can all contribute to this geometrically based MR.

For magnetic MR devices and ordinary MR in nonmagnetic semiconductors, the geometric contribution to the MR is insignificant compared with the physical contribution (the part that depends on the intrinsic physical properties of the material, such as the number of electrons per unit volume available to carry a current). By designing novel hybrid structures of nonmagnetic semiconductors and metals, my group was able to construct devices in which the geometric contribution to the MR far exceeded the physical contribution.

Understanding EMR

TO UNDERSTAND EMR, consider the device shown at the bottom of the illustration on page 48. The key part is a disk of gold that is embedded in a thin slab of narrow-gap semiconductor, such as InSb. (The "gap" of a semiconductor is a band of quantum states forbidden to its electrons, the size of which influences many of the material's electronic properties.) The conductivity of the metal is about 2,000 times greater than that of the semiconductor.

When we apply a voltage across electrical contacts at each end of the slab, current flows through the device. The current flows along electric field lines that the voltage establishes in the material. A property of electric field lines is that they tend to align themselves at right angles to the outside surface of a good conductor. This effect causes them to curve inward and concentrate on the metal disk. The current is thus funneled through the highly conductive metal, which causes the device as a whole to have a low resistance. The exact value of the resistance will depend on the geometry – that is, on the relative dimensions and shape of the metal and semiconductor.

Now consider what happens if we apply a magnetic field perpendicular to the slab. As in ordinary MR, the field produces an additional force on the charges, deflecting them like a plane in a cross wind, so that they travel at an angle to the electric field lines. Given a strong enough magnetic field, they can be deflected a full 90 degrees at the boundary of the metal In other words, the currentaround the perimeter of the metal disk instead of entering it. (There is a little more to the story than that, as is explained in the illustration, but the current's avoiding of the metal disk is the key end result.)

The current behaves exactly as if the metal disk was replaced by a big cavity in the semiconductor that had to be circumnavigated. Such a structure – a semiconductor with a disk cut out of it, which squeezes the current through the two narrow channels of semiconductor – has a much higher resistance than an uninterrupted slab of semiconductor (which itself has higher resistance than a semiconductor with a disk of metal embedded in it). Thus, at zero magnetic field the metal disk acts as a short circuit (very low resistance), and in a strong enough field it is equivalent to an empty space – an open circuit (very high resistance). This change in state produces the EMR effect.

Achieving this understanding of EMR was greatly stimulated by the pioneering work of Charles Wolf and Lester Stillman of the University of Illinois, who in the 1970s studied structures made of semiconductor and metal (called hybrid structures). In particular, they looked at the hybrid structures' carrier mobility, which is a measure of the ease with which the carriers of electric current move in an electric field. Carriers can be electrons or holes. A hole is the absence of an electron from a sea of electrons that behaves in many like a positively charged particle.

Building on Wolf and Stillman's c, my colleagues and I realized that the EMR in weak magnetic fields ought to be much bigger for semiconductors with higher carrier mobility. Narrow-gap materials such as InSb have the requisite high mobility. This prediction prompted efforts to develop semiconductor materials with increased mobility. Lesley Cohen and the late Tony Stradling of Imperial College London made significant progress preparing high-mobility, ultrathin films of InSb. Michael Santos of the University of Oklahoma has successfully focused on heterostructures (structures combining two types of semiconductor) made of InSb and indium aluminum antimonide (InAlSb) layers. Dirk Grundler and his colleagues at Hamburg University in Germany have carried out extensive studies of EMR in indium arsenide-metal hybrid structures.

Myriad Applications

Two factors have driven the discovery and study of MR phenomena during the past 16 years: pure intellectual curiosity and the promise of technological applications for magnetic sensors. That promise has certainly been realized in the case of giant MR, or GMR, which was discovered in 1988. Most, if not all, of the magnetic disk drives used in today's computers employ GMR read-head sensors to detect the magnetic bits of stored information.

MR sensors in general and EMR sensors in particular have myriad potential applications. Industrial ones include process monitors, position-sensing robots for factory production lines, magnetic-field testing for machinery and engines, speed sensing for gears, and position sensors for ferromagnetic parts. Some automotive applications are antilock brakes, "smart" shock absorbers, vehicle counting systems, and ignition timing and control systems. Consumers benefit from the sensors in flip-phone switches, solid-state compasses, nonvolatile memory in low-cost appliances, elevator control switches, and noiseless motor controls in disk drives. They might see the gadgets used in banks to do currency sorting and counting based on magnetic inks. Sensors of both low and high fields could also find uses in medical devices.

Of these applications, computer disk drive read heads are probably the most technologically challenging. Disk drives have three key components: the magnetic disk medium, which stores the information, the write-head element, which writes information onto the disk, and the read-head element, which reads the information. All three components will have to be improved significantly to satiate the ongoing demand for low-cost, high-speed storage at ever greater densities.A bit of information on a magnetic disk consists of a small magnetized region that produces a minute magnetic field just above that spot on the disk. For simplicity, you can think of a field pointing up out of the disk as a “one” and a field pointing down into the disk as a “zero.” Every square inch of a modern disk drive has about 20 billion of these bits, for a density of 20 gigabits per square inch (Gb/in2). As the size of the bit is reduced to increase storage density, the read head must be shrunk and its sensitivity must increase to detect the weaker magnetic field of the smaller bit. The head must also respond to the field faster, because a smaller bit on the rotating disk spends less time under it.

In evaluating a read head, what really matters is not the raw magnitude of the MR effect but the head’s signal-to-noise ratio, which depends on a number of other factors in addition to the amount of MR. A major source of noise for all MR sensors that use magnetized materials – that is, all but EMR – is magnetic noise. This effect occurs because the magnetism in the material is generated by innumerable magnetic atoms, like a host of tiny bar magnets, all roughly aligned but randomly fluctuating like compass needles being jiggled about. For large volumes of material, the fluctuations average out to be negligible relative to the total magnetism. As the sensor volume decreases, however, the proportion of noise increases. Magnetic noise might fundamentally limit read heads based on magnetic materials to data densities of a few hundred Gb/in2, yet the five-year target for the magnetic recording industry is 1,000 Gb/in2, or one terabit per square inch (Tb/in2). Because read heads based on EMR use nonmagnetic materials, they would not suffer from magnetic noise limitations. They thus represent a possible option for the design of a 1-Tb/in2 read head.

But a density of 1 Tb/in2 corresponds to each bit occupying a square 25 nanometers on a side. The read head needs to be of similar size. Fabricating a viable, nanoscopic EMR device is a significant scientific and technological challenge. The scientific problem is to design a nanoscopic device with sufficient EMR to be of practical use. When one crosses into the nanoscopic regime, the physics of the electrical conduction process changes in a way that significantly reduces EMR. Technologically, one must design a workable EMR nanostructure that can be fabricated using convenient techniques. Unfortunately, the disk structures used in the first demonstration of EMR are not easily scalable to nanoscopic dimensions. To meet these challenges, the NEC Princeton team was expanded to include physicists J. Shen Tsai and Yu. A. Pashkin of NEC Japan, who are, respectively, experts in the electrical conduction of nanostructures and in the methods of electron-beam lithography used to fabricate them.

The basic EMR device that I described earlier is said to be internally shunted – the metal disk (the shunt) lies inside a ring of semiconductor, like an island surrounded by a circular moat. My expanded NEC team realized that this geometry could be rearranged by a mathematical process called conformal mapping to form an externally shunted device [see illustration at left]. The end result is that the semiconductor and metal form two strips side by side, with all the electrical contacts – two for sensing a voltage, two for passing a current in and out – along the free edge of the semiconductor. The shunt (a strip of conductive metal) is now on the outside, across from all the electrical contacts. It is not as easy to describe in words what shape the electric field lines take or how the flowing carriers get deflected from those lines by a magnetic field (and hence avoid the conducting metal). But the magic of a conformal mapping is that the device is guaranteed to operate in identical fashion to the circular version, just with the geometry of all the critical elements (semiconductor, metal, field lines and current flows) transformed by the mapping. The linear, external-shunt version has the added advantage that it can be readily constructed and operated at nanoscopic sizes.

To make our devices, we used state-of-the-art electron-beam lithography – and airplanes: our samples traveled back and forth between Princeton to Tsukuba four times during their fabrication. The final result was worth all the miles that were clocked. We ended up with EMR devices – made from the Santos type of heterostructures – that had a raw data density of about 700 Gb/in2. The practicalities of incorporating this proof-of-principle device into a working read head will probably roughly halve that density .date, our group’s design has achieved MR values in excess of 35 percent at a field of 0.05 tesla – good enough, I believe, for practical technology.

A Puzzle

While striving to grasp the fundamental physics of the EMR effect in the nanoscopic-size regime, we realized that the device that we had fabricated should not work. It “should” have an EMR of less than 1 percent. The reason has to do with how the electrons (or holes) travel in random zigzag paths that drift in the direction of the current flow (called diffusive transport). The average length of each straight section (the distance traveled between collisions with defects) is called the mean free path. Some of the elements of our nanoscopic structure are smaller than the mean free path. Consequently, a charge carrier is much more likely to strike the sidewall of the structure before it has a chance to ricochet from a defect. Therefore, a carrier's motion through the device is ballistic – it traverses the device in a straight line, not by zigzags. It works out that a magnetic field deflects ballistic carriers that are confined in nanoscopic structures much less than it does diffusive carriers traversing macroscopic structures. Thus, the smaller deflection at the metal-semiconductor interface in a nanoscopic device significantly reduces the EMR.

Fortunately, and not by design, our fabrication process produced rippled sidewalls with an approximate periodicity that enhanced the scattering of carriers striking them [see micrograph in box on opposite page}. This scattering transformed the carrier motion from ballistic to diffusive, and the large EMR associated with diffusive transport resulted. Serendipity, which led to the original discovery of the EMR phenomenon, was repeated in the process of fabricating a viable nanoscopic prototype! Happily, we now know why these ripples form, and we believe that we can control their size.

EMR read heads would have many good features in addition to the high data densities and low magnetic noise [see table above}. Their intrinsic response speed could be more than 100 times as fast as that of other read heads. They can be integrated onto semiconductor substrates easily and should have low fabrication costs. A disadvantage is the need to operate at relatively low temperatures – not much warmer than room temperature. One feature is both an advantage and a disadvantage: the response of the EMR read heads increases with the square of the magnetic field strength. That behavior is "nonlinear" (which is bad) but makes for high sensitivity (which is good).

The biggest challenge at present is that EMR sensors are still a new and unproved technology. Significant technological and economic barriers must be overcome if EMR is to be commercially successful for magnetic recording. Such obstacles are not atypical in the development of potentially disruptive technologies. Indeed, other disruptive technologies could render an EMR read head obsolete before it is even developed. Heat-assisted magnetic recording (HAMR), which is being worked on at Seagate Corporation, and Millipede nonmagnetic recording, an IBM project, are examples of competing technologies [see “Avoiding a Data Crunch,” by Jon William Toigo; SCIEN¬TIFIC AMERICAN, May 2000; and “The Nanodrive Project,” by Peter Vettiger and Gerd Binnig; SCIENTIFIC AMERICAN, January 2003]. Yet even if that happens, EMR’s discoverers hope to see EMR employed for a number of the other applications I have cited. What lies ahead is the hard work necessary to bring serendipity’s two generous gifts to fruition.

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Tasks. Part 1 (from the beginning up to ‘Now consider what happens’).

Task 1. *Find words/expressions which mean the following*:

1. the natural ability to make interesting or valuable discoveries by accident;
2. to put deep into a body of liquid;
3. thorough, complete;
4. to name humorously or descriptively;
5. being part of the nature of something or someone;
6. (of a quality) someone was born with;
7. to slow down the movement and development;
8. related to;
9. to apply a force or pressure
10. something with the form of a spiral;
11. turning or twisting repeatedly;

12. not regular in movement or behavior;
13. to be greater than;
14. to pass through a narrow space;
15. to turn from a fixed course or straight direction;.
16. a small space or hole in something solid;
17. to go completely around;
18. to be only able to pass through a narrow space;
19. necessary;
20. to cause;
21. to satisfy fully.

Task 2. *Which paragraph(s):*

1. explain the factors EMR depends on;
2. prove that scientists did not expect the new phenomenon;
3. explain what helped to understand EMR;
4. show that EMR and ordinary MR have something in common;
5. deal with direction of electric field lines;
6. deal with the nature of MR effects;
7. explain the origin of the name of the effect;
8. explain what caused the discovery of similar phenomena;
9. deal with possible uses of all MR phenomena;
10. mention the factor that contributed to understanding EMR;
11. show the relation between the form of the metal and semiconductor and the magnitude of the resistance;
12. deal with the time it takes electrons and holes to travel in semiconductor –metal slabs;

Task 3. *Say whether the following is true, false or isn't mentioned.*

1. EMR was discovered as a side effect of semiconductor superlattice experiments;
2. Such an effect had long ago been predicted but it came as a surprise to the researchers;

3. The fundamental physics of the effect still remains unclear;
4. The researchers immediately understood EMR could be used to create a supercomputer or in state-of-the-art communication systems;
5. There is nothing special about EMR .It is only one of many MR effects recently discovered;
6. The effect holds for a gold disc surrounded by a narrow gap semiconductor ,only;
7. The greater is the magnetic field , the higher the metal disc resistance.
8. By carrier mobility we understand the value describing the time electrons and holes travel with in an electric field;
9. In contrast to other MR structures EMR does not need a magnetic material.
10. This effect will give rise to new logic gates.
11. EMR depends on the length, width, height and form of a metal semiconductor hybrid and also on magnetic field curvature to the same degree as other MR phenomena.
12. The value of the EMR depends on the value of time it takes electrons and holes to reach the NP junction in a semiconductor provided the magnetic field applied is weak.

Task 4. *Answer the following questions*:

1. How was the phenomenon of EMR discovered?
2. Why did researchers have to focus on EMR?
3. What was the necessary condition for MR to increase greatly?
4. What brings about MR phenomena ?
5. What makes EMR different from the other MR phenomena?
6. Is it correct to say that ordinary MR phenomena are immune to geometry?
7. How does an electric field affect a narrow gap semiconductor with a gold disc in it?
8. Why does an electric field change resistance so much?

9. What is understood by carrier mobility?
10. Why is it so important for EMR?
11. What are EMR possible applications?

Tasks. Part 2 (from’ Now consider what happens’ up to the end).

Task 1. *Find words/expressions meaning the following*:

1. very small;
2. to move up and down or from side to side more than once;
3. so small or unimportant that it is not worth considering;
4. capable to do what is intended to do;
5. to cope with the problems;
6. a long deep hole dug for defense round a castle;
7. the part or place that is farthest from the centre or where something ends;
8. in the same way;
9. the most recently developed (ideas, technology);
10. to make a great effort to gain something;
11. to understand;
12. the average of a set of numbers;
13. to form a wavelike mark or covered with wavelike marks;
14. a number of things spread over a large area;
15. preventing an activity or a system from working normally;
16. no longer needed because a better thing already exists;
17. to produce to help;
18. fulfillment of plans, aims.

Task 2. *Find the paragraph/paragraphs which*:

1. prove that EMR has a great future (a lot of various uses);
2. say that the sensor size can be limited by fundamental laws of physics;
3. explain why the author‘s device was not supposed to work;

4. say that an EMR device could be out of date before it was created;
5. explain how we can go round fundamental laws of physics in creating an EMR read head;
6. mention a drawback of EMR read heads;
7. show that the authors were lucky;
8. explain the need to reduce the read head size;
9. explain the difficulties on the way of creating a workable EMR device.

Task 3. *Say whether the following is true, false or isn't mentioned:*

1. The head size depends on the size of the bit.
2. In large volumes of material changes in the atoms' magnetic fields cancel each other and can be ignored.
3. One way of coping with magnetic noise is to cool the sensor to a very low temperature.
4. The author means that the metal disk inside a semiconductor is separated from it by empty space.
5. The author says that the difference in the way an internally shunted device and an externally shunted one overlap is negligible.
6. The linear design is preferable to the circular one.
7. The author makes the point that the result they obtained justified the distance covered and the efforts taken.
8. He was surprised that the device they had created did work contrary to all laws of physics.
9. The author is still puzzled why his device works though it is not supposed to.
10. There are still a lot of obstacles on the way to a wide use of EMR.

Task 4. *Answer the following questions*:

1. How is information stored on a hard drive?

2. What prevents us from decreasing the size of a read head?
3. How can this effect be eliminated?
4. What problems arose on the way of creating a workable nanoscopic EMR device?
5. Why is an externally shunted device preferable to an internally shunted one?
6. Explain the sentence ‘The final result was worth all the miles that were clocked. (para5, line6)
7. Why were the results obtained with the device they produced unexpected?
8. Why did the device work while it couldn‘t?
9. What can the advantages of EMR read heads be?
10. What is both a benefit and a drawback of EMR read heads?

10. THE PROMISE OF PLASMONICS

A technology that squeezes electromagnetic waves into minuscule structures may yield a new generation of superfast computer chips and ultrasensitive molecular detectors

By Harry A. Atwater

Light is a wonderful medium for carrying information.

1. Optical fibers now span the globe, guiding light signals that convey voluminous streams of voice communications and vast amounts of data. This gargantuan capacity has led some researchers to prophesy that photonic devices – which channel and manipulate visible light and other electromagnetic waves – could someday replace electronic circuits in microprocessors and other computer chips. Unfortunately, the size and performance of photonic devices are constrained by the diffraction limit; because of interference between closely spaced light waves, the width of an optical fiber carrying them must be at least half the light's wavelength inside the material. For chip-based optical signals, which will most likely employ near-infrared wavelengths of about 1,500 nanometers (billionths of a meter), the minimum width is much larger than the smallest electronic devices currently in use; some transistors in silicon integrated circuits, for instance, have features smaller than 100 nanometers.

2. Recently, however, scientists have been working on a new technique for transmitting optical signals through minuscule nanoscale structures. In the 1980s researchers experimentally confirmed that directing light waves at the interface between a metal and a dielectric (a nonconductive material such as air or glass) can, under the right circumstances, induce a resonant interaction between the waves and the mobile electrons at the surface of the metal. (In a conductive metal, the electrons are not strongly attached to individual atoms or molecules.) In other words,

the oscillations of electrons at the surface match those of the electromagnetic field outside the metal. The result is the generation of surface plasmons – density waves of electrons that propagate along the interface like the ripples that spread across the surface of a pond after you throw a stone into the water.

3. Over the past decade investigators have found that by creatively designing the metal-dielectric interface they can generate surface plasmons with the same frequency as the outside electromagnetic waves but with a much shorter wavelength. This phenomenon could allow the plasmons to travel along nanoscale wires called interconnects, carrying information from one part of a microprocessor to another. Plasmonic interconnects would be a great boon for chip designers, who have been able to develop ever smaller and faster transistors but have had a harder time building minute electronic circuits that can move data quickly across the chip.

4. In 2000 my group at the California Institute of Technology gave the name "plasmonics" to this emerging discipline, sensing that research in this area could lead to an entirely new class of devices. Ultimately it may be possible to employ plasmonic components in a wide variety of instruments, using them to improve the resolution of microscopes, the efficiency of light-emitting diodes (LEDs) and the sensitivity of chemical and biological detectors. Scientists are also considering medical applications, designing tiny particles that could use plasmon resonance absorption to kill cancerous tissues, for example. And some researchers have even theorized that certain plasmonic materials could alter the electromagnetic field around an object to such an extent that it would become invisible. Although not all these potential applications may prove feasible, investigators are eagerly studying plasmonics because the new field promises to literally shine a light on the mysteries of the nanoworld.

5. For millennia, alchemists and glassmakers have unwittingly taken advantage of plasmonic effects when they created stained-

glass windows and colorful goblets that incorporated small metallic particles in the glass. The most notable example is the Lycurgus cup, a Roman goblet dating from the fourth century A.D. and now held in the British Museum. Because of plasmonic excitation of electrons in the metallic particles suspended within the glass matrix, the cup absorbs and scatters blue and green light – the relatively short wavelengths of the visible spectrum. When viewed in reflected light, the plasmonic scattering gives the cup a greenish hue, but if a white light source is placed within the goblet, the glass appears red because it transmits only the longer wavelengths and absorbs the shorter ones.

6. Research into surface plasmons began in earnest in the 1980s, as chemists studied the phenomenon using Raman spectroscopy, which involves observing the scattering of laser light off a sample to determine its structure from molecular vibrations. In 1989 Thomas Ebbesen, then at the NEC Re-search Institute in Japan, found that when he illuminated a thin gold film imprinted with millions of microscopic holes, the foil somehow transmitted more light than was expected from the number and size of the holes. Nine years later Ebbesen and his colleagues concluded that surface plasmons on the film were intensifying the transmission of electromagnetic energy.

7. The field of plasmonics received another boost with the discovery of novel “metamaterials” – materials in which electron oscillations can result in astounding optical properties [see “The Quest for the Superlens,” by John B. Pendry and David R. Smith; Scientific American, July 2006]. Two new classes of tools have also accelerated progress in plasmonics: recent increases in computational power have enabled investigators to accurately simulate the complex electromagnetic fields generated by plasmonic effects, and novel methods for constructing nanoscale structures have made it possible to build and test ultrasmall plasmonic devices and circuits.

8. At first glance, the use of metallic structures to transmit light signals seems impractical, because metals are known for high optical losses. The electrons oscillating in the electromagnetic field collide with the surrounding lattice of atoms, rapidly dissipating the field's energy. But the plasmon losses are lower at the interface between a thin metal film and a dielectric than inside the bulk of a metal because the field spreads into the nonconductive material, where there are no free electrons to oscillate and hence no energy-dissipating collisions. This property naturally confines plasmons to the metallic surface abutting the dielectric; in a sandwich with dielectric and metal layers, for example, the surface plasmons propagate only in the thin plane at the interface.

9. Because these planar plasmonic structures act as waveguides, shepherding the electromagnetic waves along the metal-dielectric boundary, they could be useful in routing signals on a chip. Although an optical signal suffers more loss in a metal than in a dielectric such as glass, a plasmon can travel in a thin-film metal waveguide for several centimeters before dying out. The propagation length can be maximized if the waveguide employs an asymmetric mode, which pushes a greater portion of the electromagnetic energy away from the guiding metal film and into the surrounding dielectric, thereby lowering loss. Because the electromagnetic fields at the top and bottom surfaces of the metal film interact with each other, the frequencies and wavelengths of the plasmons can be adjusted by changing the thickness of the film. In the 1990s research groups led by Sergey Bozhevolnyi of Aalborg University in Denmark and Pierre Berini of the University of Ottawa developed planar plasmonic components that could perform many of the same functions – such as splitting guided waves – usually done by all-dielectric devices. These structures could prove useful in transmitting data from one part of a chip to another, but the electromagnetic fields accompanying the plasmons are too large to convey signals through the nanoscale innards of a processor.

10. Plasmons propagate like the ripples that spread across the surface of a pond after you throw a stone in the water.

11. To generate plasmons that can propagate through nanoscale wires, researchers have explored more complex waveguide geometries that can shrink the wavelength of the signal by squeezing it into a narrow space. In the late 1990s my lab group and a team led by Joachim Krenn of the University of Graz in Austria launched parallel efforts to produce these “subwavelength” surface-plasmon waveguides. Working with me at Caltech, Stefan Maier built a structure consisting of linear chains of gold dots, each less than 100 nanometers across. A visible beam with a wavelength of 570 nanometers triggered resonant oscillations in the dots, generating surface plasmons that moved along the chains, confined to a flattened path only 75 nanometers high. The Graz group achieved similar results and imaged the patterns of the plasmons carried along the chains. The absorption losses of these nanowires were relatively high, however, causing the signal to die out after it traveled a few hundred nanometers to a few microns (millionths of a meter). Thus, these waveguides would be suitable only for very short-range interconnections.

12. Fortunately, the absorption losses can be minimized by turning the plasmonic waveguides inside out, putting the dielectric at the core and surrounding it with metal. In this device, called a plasmon slot waveguide, adjusting the thickness of the dielectric core changes the wavelength of the plasmons. My lab at Caltech and Mark Brongersma’s Stanford University group have shown that plasmon slot waveguides are capable of transmitting a signal as far as tens of microns. Hideki Miyazaki of the National Institute for Materials Science in Japan obtained a striking result by squeezing red light (with a wavelength of 651 nanometers in free space) into a plasmon slot waveguide that was only three nanometers thick and 55 nanometers wide. The researchers found that the wavelength of

the surface plasmon propagating through the device was 51 nanometers, or about 8 percent of the free-space wavelength.

13. Plasmonics can thus generate signals in the soft x-ray range of wavelengths (between 10 and 100 nanometers) by exciting materials with visible light. The wavelength can be reduced by more than a factor of 10 relative to its free-space value, and yet the frequency of the signal remains the same. (The fundamental relation between the two – frequency times wavelength equals the speed of light – is preserved because the electromagnetic waves slow as they travel along the metal-dielectric interface.) This striking ability to shrink the wavelength opens the path to nanoscale plasmonic structures that could replace purely electronic circuits containing wires and transistors.

14. Just as lithography is now used to imprint circuit patterns on silicon chips, a similar process could mass-produce minuscule plasmonic devices with arrays of narrow dielectric stripes and gaps. These arrays would guide the waves of positive and negative charge on the metal surface; the alternating charge densities would be very much akin to the alternating current traveling along an ordinary wire. But because the frequency of an optical signal is so much higher than that of an electrical one – more than 400,000 gigahertz versus 60 hertz – the plasmonic circuit would be able to carry much more data. Moreover, because electrical charge does not travel from one end of a plasmonic circuit to another – the electrons bunch together and spread apart rather than streaming in a single direction – the device is not subject to resistance and capacitance effects that limit the data-carrying capacity of integrated circuits with electrical interconnects.

15. Plasmonic circuits would be even faster and more useful if researchers could devise a “plasmonster” switch – a three-terminal plasmonic device with transistorlike properties. My lab at Caltech and other research groups have recently developed low-power versions of such a switch. If scientists can produce plasmonsters

with better performance, the devices could serve as the core of an ultrafast signal-processing system, an advance that could revolutionize computing 10 to 20 years from now.

16. The potential uses of plasmonic devices go far beyond computing, however. Naomi Halas and Peter Nordlander of Rice University have developed structures called nanoshells that consist of a thin layer of gold – typically about 10 nanometers thick – deposited around the entire surface of a silica particle about 100 nanometers across. Exposure to electromagnetic waves generates electron oscillations in the gold shell; because of the coupling interaction between the fields on the shell’s inner and outer surfaces, varying the size of the particle and the thickness of the gold layer changes the wavelength at which the particle resonantly absorbs energy. In this way, investigators can design the nanoshells to selectively absorb wavelengths as short as a few hundred nanometers (the blue end of the visible spectrum) or as long as nearly 10 microns (the near infrared).

17. This phenomenon has turned nanoshells into a promising tool for cancer treatment. In 2004 Halas, working with her Rice colleague Jennifer West, injected plasmonic nanoshells into the bloodstream of mice with cancerous tumors and found that the particles were nontoxic. What is more, the nanoshells tended to embed themselves in the rodents’ cancerous tissues rather than the healthy ones because more blood was circulated to the fast-growing tumors. (The nanoshells can also be attached to antibodies to ensure that they target cancers.)

18. Fortunately, human and animal tissues are transparent to radiation at certain infrared wavelengths. When the researchers directed near-infrared laser light through the mice’s skin and at the tumors, the resonant absorption of energy in the embedded nanoshells raised the temperature of the cancerous tissues from about 37 degrees Celsius to about 45 degrees C.

19. The photothermal heating killed the cancer cells while leaving the surrounding healthy tissue unharmed. In the mice treated with nanoshells, all signs of cancer disappeared within 10 days; in the control groups, the tumors continued to grow rapidly. Houston-based Nanospectra Biosciences is currently seeking permission from the Food and Drug Administration to conduct clinical trials of nanoshell therapy in patients with head and neck cancer.

20. Plasmonic materials may also revolutionize the lighting industry by making LEDs bright enough to compete with incandescent bulbs. Beginning in the 1980s, researchers recognized that the plasmonic enhancement of the electric field at the metal-dielectric boundary could increase the emission rate of luminescent dyes placed near the metal's surface. More recently, it has become evident that this type of field enhancement can also dramatically raise the emission rates of quantum dots and quantum wells – tiny semiconductor structures that absorb and emit light – thus increasing the efficiency and brightness of solid-state LEDs. In 2004 my Caltech colleague Axel Scherer, together with co-workers at Japan's Nichia Corporation, demonstrated that coating the surface of a gallium nitride LED with dense arrays of plasmonic nanoparticles (made of silver, gold or aluminum) could increase the intensity of the emitted light 14-fold.

21. Furthermore, plasmonic nanoparticles may enable researchers to develop LEDs made of silicon. Such devices, which would be much cheaper than conventional LEDs composed of gallium nitride or gallium arsenide, are currently held back by their low rates of light emission. My group at Caltech, working with a team led by Albert Polman of the FOM Institute for Atomic and Molecular Physics in the Netherlands, has shown that coupling silver or gold plasmonic nanostructures to silicon quantum-dot arrays could boost their light emission by about 10 times. Moreover, it is possible to tune the frequency of the enhanced

emissions by adjusting the dimensions of the nanoparticles. Our calculations indicate that careful tuning of the plasmonic resonance frequency and precise control of the separation between the metallic particles and the semiconductor materials may enable us to increase radiative rates more than 100-fold, allowing silicon LEDs to shine just as brightly as traditional devices.

22. Scientists are even working on a plasmonic analog to a laser. Mark Stockman of Georgia State University and David Bergman of Tel Aviv University have described the physics of such a device, which they called a SPASER (for surface plasmon amplification of stimulated emission of radiation). Although the SPASER exists only in theory so far, the researchers have suggested routes to fabricating it using semiconductor quantum dots and metal particles. Radiative energy from the quantum dots would be transformed into plasmons, which would then be amplified in a plasmonic resonator. Because the plasmons generated by a SPASER would be much more tightly localized than a conventional laser beam, the device could operate at very low power and selectively excite very small objects. As a result, SPASERs could make spectroscopy more sensitive and pave the way for hazardous-materials detectors that could identify minute amounts of chemicals or viruses.

23. Perhaps the most fascinating potential application of plasmonics would be the invention of an invisibility cloak. In 1897 H. G. Wells published The Invisible Man, a tale of a young scientist who discovers how to make his own body’s refractive index equal to that of air, rendering him invisible. (A material’s refractive index is the ratio of the speed of light in a vacuum to the speed of light in the material.) Exciting a plasmonic structure with radiation that is close to the structure’s resonant frequency can make its refractive index equal to air’s, meaning that it would neither bend nor reflect light. The structure would absorb light, but if it were laminated with a material that produces optical gain –

amplifying the transmitted signal just as the resonator in a SPASER would – the increase in intensity would offset the absorption losses. The structure would become invisible, at least to radiation in a selected range of frequencies.

24. A true invisibility cloak, however, must be able to hide anything within the structure and work for all frequencies of visible light. The creation of such a device would be more difficult, but some physicists say it is possible. In 2006 John B. Pendry of Imperial College London and his colleagues showed that a shell of metamaterials could, in theory, reroute the electromagnetic waves traveling through it, diverting them around a spherical region within.

25. Although Wells's invisible man may never become a reality, such ideas illustrate the rich array of optical properties that inspire researchers in the plasmonics field. By studying the elaborate interplay between electromagnetic waves and free electrons, investigators have identified new possibilities for transmitting data in our integrated circuits, illuminating our homes and fighting cancer. Further exploration of these intriguing plasmonic phenomena may yield even more exciting discoveries and inventions.

Tasks. Part 1 (up to " Just as lithography").

Task 1. *Find the paragraph(s) th*at:

1. Explains why metal makes a bad light conductor;
2. Compares plasmons with waves in a waterpool;
3. Deals with a serious limitation of plasmonic devices;
4. Explains why plasmonic structures can be applied in computer devices;
5. Mention an interesting effect connected with waveguides;
6. Mentions possible uses of plasmonics;
7. Mentions two factors contributing to the recent development of plasmonics;
8. Mentions the effect of the early plasmonics use;

9. Explains how absorption losses can be reduced;
10. Says that under certain conditions an object can disappear from view.

Task 2. *Answer the following questions.*

1. Why haven't photonic devices replaced traditional electronics?
2. How are plasmons produced?
3. When and why did an extensive study of plasmonics begin?
4. Why are metals bad light conductors?
5. How can the distance plasmons travel in a waveguide be increased?
6. Why is this this distance so small?
7. Why is the basic formula for the speed of light true for plasmonic devices though the wave length is reduced while the frequency remains the same?

Task 3. *Find words or expressions meaning the following*:

1. to limit;
2. advantage, benefit;
3. movement back and forth in a regular rhythm;
4. possible;
5. to throw in various random directions;
6. guiding;
7. to result in, cause
8. surprising.

Tasks. Part 2 (from "Just as lithography"up to the end).

Task 1. *Find the paragraph(s) that*:

1. mentions the possibility of creating a plasmonic analog of a very popular elecgtronic device;
2. explains the scientific background behind the use of plasmonics for medical purposes;

3. explains the difference between light and electricity;
4. how science fiction can become a reality;
5. mentions creating new light sources and explains the scientific ideas they are based on;
6. speaks about a possible breakthrough in computer industry;
7. mentions a serios drawback of existing LEDs;
8. explains what makes plasmonics so good for coping with a terrible disease;
9. says what future has in store for us;
10. compares two similar electronic devices and explains the advantages of a plasmonic one;
11. says that silicon light sources can be as good as the existing light devices.

11. NANOPLASMONIC SENSING AND DETECTION

Enhanced optical fields in nanoplasmonic systems provide efficient sensing and detection

By Mark I. Stockman

Measuring minute amounts of chemical and biological objects in the environment and in living organisms is one of the most common and important tasks in chemistry, biology, medicine, environmental monitoring, transportation, homeland security, and defense. Although the existing methods of sensing and detection are numerous and powerful, they are not without shortcomings: insufficient sensitivity; long detection times; necessity for enzymatic, fluorescent, or radioactive labeling; high costs, and so on. Optical spectroscopic methods have the advantage of being fast, noncontact, and relatively inexpensive, but they are not necessarily sensitive enough.

Nanoplasmonics deals with optical phenomena localized at surfaces and interfaces of metals that are due to light-induced electronic excitations called surface plasmons (SPs). For a metal nanoparticle embedded in a dielectric, the SPs are oscillations of electric field and polarization localized in space. These are localized surface plasmons (LSPs), whose excitation frequencies depend mainly on the dielectric properties of the constituents and weakly depend on the system size. For extended systems, the SPs are electromagnetic waves, the so-called surface plasmon polaritons (SPPs), bound to the surfaces and interfaces and propagating along them (1, 2).

The SPs are oscillations of dielectric polarization, which create opposite surface charges at the nanoscale, whose attraction supplies the restoring force necessary for any oscillations. Objects to be detected (for example, analyte) bind to the surface carrying SPs. This binding can be made chemically and immunologically specific by using corresponding antibodies linked to the surface. The result is a change of the permittivity of the dielectric adjacent to this surface and, thus, an increase in the dielectric screening that then reduces the restoring force for plasmonic oscillations and, hence, reduction of the LSP resonant frequency and the SPP propagation velocity. High sensitivity of the SP sensing is due to the fact that SPs are tightly localized at the surface and thus highly sensitive to its dielectric environment. The proximity of the object to be detected to the surface carrying SPs results in a shift in surface plasmon resonance peak – detectable with both high selectivity and high signal-to-noise ratio.

In biomedical research and applications, SPPs have been used for more than two decades (3, 4). However, a problem is that the SPPs on flat surfaces propagate too slowly to be directly excited by laser light. To resolve this problem, most SPP sensors are based on the so-called Kretschmann geometry (5), which requires precise adjustment of the incidence angle of the probing radiation.

The observation of extraordinary transmission through a periodic array of nanoholes (6) is a foundation of a novel plasmonic detection method (7) (see the figure, panel A). External radiation is incident normally on a periodic array of nanoholes in a plasmonic metal (gold) nanofilm and excites SPPs when the period is a multiple of the SPP wavelength; these SPPs carry optical energy through the holes with a high efficiency. The surface of the holey array is functionalized by antibodies selectively binding to components (antigens) of the Ebola virus. The model virus in biologically relevant concentrations is delivered by microfluidics to the surface and binds to it, decreasing the SPP velocity. The measured resonant frequency shift is very pronounced, thus demonstrating detection of this highly contagious pathogen. Due to the absence of the moving parts, stability, and low weight, the corresponding device can be made handheld for field use.

In another example, detection of the Dengue fever antibodies (8) uses a SPP interferometer (see the figure, panel B). Although interferometric SPP sensing is already known (4), this approach represented a first study on real patients suffering from this highly contagious and potentially deadly disease. The detection of the marker of the infection (antibodies to the virus in the blood) is so reliable that the detection efficiency is an order of magnitude better than for a “gold-standard” enzyme-linked immunosorbent assay (ELISA) method that is widely used in research and clinic.

One of the serious limitations of ultrasensitive detection comes not from plasmonics but from kinetics of the binding to the surfaces: The concentration of analyte should be on the order of or greater than ~5 to 20 fmol/l (3, 9) for immunological reactions, which tends to make femtomolar to attomolar sensing and detection impossible. A novel approach overcomes this kinetic barrier and allows precise nanofocusing of the analyte at the active sensing center (10). This is achieved by using superhydrophobic coating of the shown micropillars. Surface-enhanced Raman scattering (SERS) detection is performed using the effect of adiabatic concentration of SPPs (11): Light is converted to SPPs by the grating in the metal nanocone shown in the center of this panel. The SPPs propagate to the tip, concentrating and creating a hot spot of optical near-field at the tip, exciting SERS in the analyte delivered to the tip due to super-hydrophobicity. The analyte, enzyme lysozyme, was delivered in a concentration of 1 fmol/l in a 160-nl drop, containing ~100 molecules overall. The subsequently detected Raman signature spectrum of lysozyme demonstrates a highly promising approach for ultrasensitive detection with chemical identification.

One of the most important issues in clean energy is hydrogen technology, where a critical and yet unsolved problem is rapid and sensitive enough detection of hydrogen leaks. A single nanoparticle sensing for such detection (12) (see the figure, panel D) uses a gold nanorod covered with palladium nanospheres. Palladium is known to absorb hydrogen from air, which changes its dielectric properties and shifts the frequency of the LSP resonance of the nanorod. Such measurable shifts allow one to reliably and reversibly detect hydrogen in the air in concentrations relevant for hydrogen energy applications.

Plasmonic sensing of single proteins has been done with a hybrid photonic-plasmonic sensor consisting of a silica microsphere covered by a gold nanoshell (13). Here, the attachment of a single protein molecule to the nanoshell affects its plasmonic response and shifts the frequency of a whispering-gallery mode of the micro-sphere. More sensitive than the previous examples, such a shift affords the detection of single protein molecules.

A fundamentally novel principle, active plasmonic nanosensing, has recently been developed (14) based on spaser (plasmonic nanolaser) (15) as a metal nanoparticle surrounded by gain medium to generate coherent and intense local optical fields. The detection device consists of a nanoslab of semiconductor (CdS) separated by MgF2 nanofilm from a silver surface. Optical pumping induces spasing on a mode localized mostly between the CdS and the silver surface. Exposure of such a spaser to 2 to 8 parts per billion concentration of vapor of explosive precursor dinitrotoluene causes an appreciable and reversible increase of the generated intensity – corresponding to one of the highest sensitivities of explosives sensors yet demonstrated. The examples discussed here demonstrate that plasmonics provides the fundamental basis and practical device designs that allow for the rapid sensing and detection of a wide range of important chemical and biological objects, such as hydrogen molecules, explosives vapors, protein molecules, and pathogenic viruses, and it can do so with unprecedented sensitivity and robustness.

Task 1. *Say whether the following is true, false or not mentioned:*

1. Nanoplasmonics studies optical phenomena caused by electrons movement along metal surfaces due to light pulses.

2. Excitation frequencies of localized plasmons are principally conditioned by the system size.

3. The oscillations of electrons at the surface match those of the electromagnetic field outside the metal.

4. The nearer the object to be detected to the surface carrying surface plasmons, the greater surface plasmon resonance.

5. This phenomenon can be used to detect dangerous diseases.
6. A surface plasmon can travel in a thin film like metal waveguide for several centimeters before dying out.
7. Shooting a metal particle with coherent laser light generates intense optical fields and increases the sensitivity of a plasmonic device.
8. Such a device is capable of finding a very small amount of a substance necessary to produce explosives.

Task 2. *Answer the following question*:

1. What are the main advantages of the existing methods of sensing and detecting?
2. What makes optical spectroscopic methods different?
3. What are surface plasmons?
4. Why are they highly sensitive to the dielectric surface environment?
5. How can we speed up the propagation of surface plasmons on flat surfaces?
6. How does active plasmonic nanosensing work?
7. What is new about it?

Task 3. *Find words or expressions meaning the following.*

1. In spite of,
2. Benefit;
3. To result from;
4. Analogous or equivalent in character, form, or function; comparable;
5. Having something to do with;
6. Because of;
7. Large or important enough to be noticed;
8. To consider the possible facts, problems etc. when making a plan, calculation or judgement;
9. Not able to be undone or altered.

12. NANOMATERIALS IN TRANSISTORS

From high-performance to thin-film applications

Aaron D. Franklin

For more than 50 years, silicon transistors have been continuously shrunk to meet the projections of Moore’s law but are now reaching fundamental limits on speed and power use. With these limits at hand, nanomaterials offer great promise for improving transistor performance and adding new applications through the coming decades. With different transistors needed in everything from high-performance servers to thin-film display backplanes, it is important to understand the targeted application needs when considering new material options. Here the distinction between high-performance and thin-film transistors is reviewed, along with the benefits and challenges to using nanomaterials in such transistors. In particular, progress on carbon nanotubes, as well as graphene and related materials (including transition metal dichalcogenides and X-enes), outlines the advances and further research needed to enable their use in transistors for high-performance computing, thin films, or completely new technologies such as flexible and transparent devices.

Fifty years ago, Gordon Moore published his seminal paper that included a projection that the semiconductor industry would double the number of components on a chip (integrated circuit) roughly every couple of years (1). Although slightly modified over time, this projection from one of Intel’s founders has served as the marching orders for what is now a >$330 billion global industry (2) and has been given the moniker “Moore’s law.” Notable innovations have allowed the silicon metal oxide semiconductor field-effect transistor (MOSFET) to be made smaller, the latest being from strained-silicon channel materials to three-dimensional (3D) fin gate structures, as depicted in Fig. 1C. Despite these advances, fundamental physical limits for the minimum size of silicon MOSFETs are now being approached, and the question of "what's next" for transistors has become inescapable.

The microprocessor, now driven by billions of MOSFETs on a single chip, is the most prominent transistor application, as it is the computational "brain" to every electronic system. Yet there are other needs for the transistor that do not necessarily require the high performance (and high cost) of MOSFETs – for example, chemical and biological sensors, optical detectors, and the pixel-driving circuits for displays. Aside from the microprocessor, the most prominent use of transistors is in the backplane electronics of flat-panel displays. Departure from the cathode ray tube was made possible, in part, by the use of low-cost amorphous silicon (a-Si) thin-film transistors (TFTs) in liquid-crystal displays.

That a-Si TFTs were made from silicon is one of very few attributes TFTs have in common with silicon MOSFETs. MOSFETs are generally high- performance and high-cost transistors used for computational devices (e.g., smartphones, computers, servers), whereas TFTs are less cost intensive and are used in applications with much lower performance requirements. Consider the different perspectives on Moore's law shown in Fig. 1 for these two types of transistors. The traditional Moore's law in Fig. 1A is obeyed by high- performance transistors, wherein the density of devices doubles approximately every 2 years (3). For TFTs, the integration density has changed relatively little, with the focus being more on improving stability and driving down cost. The Moore's law perspective in Fig. 1B focuses on the component substrate size (4); here, the trend for TFTs is based on the display market, where the ability to fabricate large areas of transistors is crucial (5). Meanwhile, the die size of the MOSFET – the area of a single chip on a much larger production wafer – has been capped at ~300 mm2 to minimize production costs by yielding more chips per wafer. Overall, these two perspective plots highlight the importance of recognizing the differences in applications and deliverables between high-performance transistors and TFTs.

Nanomaterials are of great interest for use in transistors of all types, as they offer many electrical and mechanical advantages. Unlike silicon- based transistors, the general structure of a nanomaterial transistor changes very little between the high-performance and thin-film varieties, except in size (see Fig. 1C). This similarity has led to much confusion in the research community as to whether certain reported nanomaterial transistor advancements are useful for high-performance or thin-film applications. Such confusion occurs only for nanomaterials, as the silicon community developed different materials expressly for TFTs. Consider the substantial difference in target performance metrics – often orders of magnitude – between high-performance transistors and TFTs (from any material), as shown in Table 1. In this Review, in addition to considering the great progress and promise in the field of nanomaterial transistors, clarification of this important distinction between the intended application spaces will be provided. Guided by an understanding of the relevant dimensional and performance targets (see Table 1), it is hoped that future research on nanomaterial transistors can more accurately address the scientific challenges limiting their ultimate realization.

Nanomaterials

The term "nanomaterial" can refer to any material with dimensions at the nanoscale (< 100 nm), but for transistor applications, the materials that naturally exhibit quantum confinement and occur without the need for thinning or patterning are of greatest interest. Hence, the focus of this Review will be on such naturally quantum- confined nanomaterials, including single-walled carbon nanotubes (CNTs), graphene, transition metal dichalcogenides (TMDs), and X-enes (the newest and least naturally occurring variant of 2D crystals, typically consisting of a buckled hexagonal structure to mimic graphene – hence the name “X-ene”; examples include phosphor- ene for phosphorous and silicene for silicon). There certainly are benefits in transistors from other types of nanomaterials, such as nanowires (6, 7), which are nanoscale versions of bulk materials. However, it is typically best to avoid quantum confinement in such materials rather than embrace it as a key aspect of their electronic structure because it would introduce considerable variation in the resulting device performance and degrade carrier transport properties. Most of the nanomaterials discussed herein are often classified as van der Waals materials, as they do not covalently or ionically bond to other materials but exist as 1D or 2D constituents that are either isolated or assembled in some fashion via van der Waals weak attraction forces.

Extensive articles reviewing the distinctive properties of each of these nanomaterials have been published (8−15); as the focus of this Review is on the use of the nanomaterials in transistors, only a brief summary of their key attributes is given. Of note is that single-walled CNTs and graphene share the sp2-bonded, hexagonal carbon lattice and thus exhibit similar carrier transport properties, including high Fermi velocity (vF), which can lead to higher switching speeds. Low effective mass and correspondingly high carrier velocity make CNTs and graphene the most ideal electron transport systems available. Consequently, CNTs are favorable options for very small transistors that can operate at low voltages, thus conserving power, because silicon-based transistors suffer degradation in performance (e.g., leakage currents) when operated below ~1 V. The nanotubes, which can be conceptualized as rolled up sheets of graphene, are circumferentially quantum-confined, which makes them true 1D electronic systems with reasonable energy band gaps that allow them to turn off with little leakage current. The lack of an energy band gap in graphene is the nanomaterial’s greatest pitfall for transistors, rendering the devices unable to block current flow and be switched to the off state (digital “0”). Great efforts have been made to induce a band gap in graphene (16, 17), but to date, they lack practicality. Even thinning graphene to create quasi-1D nanoribbons (18, 19) to create a band gap still has disadvantages, such as edge states, compared with the naturally 1D nanotubes. The most likely use of graphene in digital transistors arises from its ability to enable distinct 2D heterostructures, which will be discussed below. A summary of some of the most relevant intrinsic properties of these nanomaterials for electronics applications is given in Fig. 2. Note that the focus in Fig. 2 is not given to mobility or extrinsic device metrics, such as contact resistance, as these are only relevant in certain devices or are highly variable, depending on specific interfacial materials. Further discussion of such other metrics is given below.

The interest in studying graphene for transistors spurred reconsideration of a very well-known class of van der Waals nanomaterials that had not been studied for electronics in many years: TMDs. Many combinations of transition metals (e.g., Mo, W, Hf) and chalcogens (e.g., S, Se, Te) can yield the three-atom-thick arrangement of a monolayer TMD (9). For transistors, the greatest interest has been in the Mo and W families, especially MoS2. Electron transport in TMDs is slower by a factor of 20 compared with carbon nanomaterials, but TMDs offer sizable energy band gaps for switching and maintain the attractive 2D confinement of graphene. If more than one monolayer is stacked to form a many-layer TMD, the band gap changes markedly, typically saturating to approximately the bulk value at ~15 layers with a gap that is barely two-thirds that of the monolayer.

Most recent to join the options of nanomaterials for transistors is the so-called X-ene family (20-26). Exploration began a few years ago, motivated by the electronic structure of graphene, including a linear dispersion relation of Dirac cones, for other group IV and V nonmetals arranged in a similar fashion to the graphene hexagonal lattice. Thus far, demonstrations of silicene (silicon) (21), germanene (germanium) (24), phosphorene (black phosphorus) (23,25,26), stanene (tin) (20), and arsenene (arsenic) (22) have been made. Their lattice structures are not as perfectly planar hexagonal as that of graphene but tend to be some variation in a buckled hexagonal form (20). Phosphorene exhibits van der Waals stacking, but the other X-enes are synthesized as adlayer structures on certain substrates. Limited experimental work has been performed on X-enes, but theoretical projections indicate potentially attractive electronic properties, including the presence of a reasonable band gap and transport behavior about half as favorable as that of graphene (Fig. 2). One of the biggest challenges for X-enes compared with other nanomaterials is that X-enes tend to be highly reactive in air, making even simple device structures extremely difficult to realize (21).

To consider the progress that has been made in demonstrated nanomaterial transistors, a summary of a few key device metrics is given in Fig. 3A For high-performance transistors, there is a need to scale the channel length Lch and contact length Lc while operating at low voltage VDD. Note that the approximate progress shown for each metric in Fig. 3A is from diverse reports; in other words, there has yet to be a solution that shows the scaling of all relevant dimensions along with low-voltage operation. As will be discussed below, the focus for TFTs is on mobility m and on-state current Ion, where nanomaterials have already shown substantial improvements over silicon- based options. Based on the Fig. 3A comparisons, CNTs show the most consistent promise thus far, which is partly an artifact of their being studied the longest but also undoubtedly related to their superior carrier transport properties compared with the TMDs or X-enes. These metrics are certainly not comprehensive, but when considering any of these nanomaterials for the indicated applications, such target deliverables must be kept in mind.

Benefits of nanomaterials

Despite the substantial differences in intrinsic properties among the nanomaterial options, they have common advantages for transistors, as summarized in Fig. 3B. Foremost, nanomaterials are all atomically thin. For high-performance transistors, there is a need to scale the channel length to sub-10-nm dimensions because this will be required for technologies targeted for the early 2020s, and silicon is unable to operate at such length scales. Such scaling requires the transistor gate to maintain electrostatic control over the channel – a difficult feat when the channel thickness (dbody) is greater than Lch. The atomic thinness of nanomaterials, especially in their monolayer form for 2D nanomaterials, offers ideal electrostatic control. Often the ultimate scalability of a transistor with an undoped (intrinsic) channel – such as all nanomaterials shown in Fig. 2 – is determined by the screening or natural length 1 being proportional to dbody. The rule-of-thumb is that a Lch > 31 will ensure that the gate maintains electrostatic control and that deleterious short-channel effects are avoided (27).

Another benefit shared by most nanomaterials is their substrate independence. CNTs can be synthesized in a reactor chamber, dispersed in solution to isolate a certain diameter or energy band gap (28-38), and then deposited onto any substrate of choice, all while keeping their crystal structure and transport properties intact. The same is true for graphene and TMDs, with the exception of X-enes, as they are generally substrate-bound (except for phosphorene). Although synthesis conditions are extreme in most cases, the ability to transfer nanomaterials to virtually any substrate and fabricate transistors from them is one of their greatest strengths.

Heterostructures of the nanomaterials in Fig. 2 are becoming an attractive possibility for transistors, including the use of all 2D nanomaterials for fabricating transistors (e.g., graphene contacts, TMD channel, and hexagonal boron nitride gate dielectric) (39−41), as well as the stacking of dverse TMDs in a fashion similar to epitaxial III-V materials (42−49). Work continues on understanding what governs transport at these nanomaterial heterostructure junctions. Several devices that make explicit use of such heterostructures in their operation have been demonstrated, and it will be exciting to see the types of new transistors this approach will enable.

Other strengths that nanomaterials offer for transistors typically depend on device structure or type. For instance, the presence of a small quantum capacitance (dependent on the density of states), especially in CNTs, has been shown to enable more extensive modulation of the surface potential in the on state of a transistor (50). Operation in this quantum capacitance limit is of great value for tunneling transistors, for which the thinning of tunnel barriers to achieve higher current is crucial. Other nanomaterial properties that are useful for specific devices include spin transport, Coulomb blockade, charge density, waves, and plasmons, but the focus of this Review will be on more conventional digital transistors.

Just as the nanomaterials in Fig. 2 share many advantages for transistors, they also have challenges in common, as summarized in Fig. 3C. Without question, the biggest challenges relate to the controlled synthesis and placement of the nanomaterials. Although there has been widely varied progress on addressing the synthesis and placement challenges among the different nanomaterials, they all require substantial improvement to be viable for a transistor technology. Synthesis of nanomaterials takes place at high temperatures (typically >800°C). In most cases, the nanomaterials are synthesized on a sacrificial substrate and then transferred in some fashion to the substrate for fabricating transistors. Whether or not they are kept on their synthesis substrate, the distribution in dbody (diameters for CNTs and number of layers for 2D nanomaterials) must also be controlled. Tremendous progress has been made in separating CNTs of certain electronic type (band gap in CNTs is dependent on dbody) (28-38), which indicates promise for reaching technology targets so long as scientific investment continues (current highest verified purity is 99.99% with a target of 99.9999%) (51). Progress has also been made in synthesizing TMDs (52-60), although there has yet to emerge a process capable of growing a TMD with complete coverage, high quality (low defect and grain boundary density), and a uniform number of layers. Being the newest explored nanomaterial and not exhibiting van der Waals stacking behavior, X-enes have the farthest to go for improved synthesis.

Challenges for nanomaterials

Just as the nanomaterials in Fig. 2 share many advantages for transistors, they also have challenges in common, as summarized in Fig. 3C. Without question, the biggest challenges relate to the controlled synthesis and placement of the nanomaterials. Although there has been widely varied progress on addressing the synthesis and placement challenges among the different nanomaterials, they all require substantial improvement to be viable for a transistor technology. Synthesis of nanomaterials takes place at high temperatures (typically > 800°C). In most cases, the nanomaterials are synthesized on a sacrificial substrate and then transferred in some fashion to the substrate for fabricating transistors. Whether or not they are kept on their synthesis substrate

If the nanomaterial is synthesized on one substrate and then transferred to another for transistor fabrication, then precision placement is important. For CNTs, this problem is especially pronounced, as they require accurate positioning into arrays. The target pitch for CNTs in high-performance transistors is 5 to 8 nm (125 to 200 CNTs per micrometer) (13), and promising advancements continue to be made to this end (61-68), including the use of selective deposition to predefined regions of a substrate (50-nm pitch achieved). It is less favorable to have tightly packed (~0-nm pitch) arrays of CNTs for high- performance transistors (62), as they will result in deleterious charge screening effects and challenges for establishing good electrical contacts. Requirements for TFTs are much more relaxed, where even tangled films of CNTs with no alignment can be used (69-71). The 2D nanomaterials do offer planar coverage, but it is difficult to transfer the films without inducing defects that are detrimental to transistor performance. An additional complication for X-enes is their pronounced dependence of carrier transport on crystallographic direction (23); orientation of the X-ene film will change the effective mass of the carriers by up to one order of magnitude.

Interfaces to nanomaterials are another challenge. Without having available surface states in the way that bulk materials do, the formation of covalent bonds to nanomaterials can be difficult. For instance, nucleating the growth of high-quality dielectrics (insulating barriers) with atomic layer deposition (ALD) is problematic for nanomaterials, as they do not offer typical end groups for reacting with the ALD precursors. Creative solutions have been presented for potentially addressing the creation of high-quality dielectric interfaces (72-75), but there has been much less progress on improving the contact metal interfaces. Regardless of whether a nanomaterial transistor is for high-performance or thin-film applications, the device will depend heavily on the quality of transport at the source and drain metal contact interfaces. Studies have been performed on the impact of different metals on the contact resistance for CNTs (76-78), TMDs (79-81), and even X-enes (82), most of which consider the metal-nanomaterial interface as a traditional Schottky barrier structure. However, with no covalent bonding between the metal and nanomaterial, the reality of what determines transport at the interface remains elusive, and the Schottky barrier picture has been shown to break down under certain conditions (78).

In all cases, the metal-nanomaterial contact interface requires further scientific study and engineering improvement to yield the necessary performance and consistency for a transistor technology. Many have interpreted this to simply mean the achievement of low contact resistance (Rc), but depending on the transistor application, realizing a low Rc may not address all of the relevant contact issues, including scalability and reproducibility. For example, for high-performance transistors with contact lengths <15 nm (see Fig. 3A), the target Rc must be <150 ohm-pm (measured contact resistance multiplied by device width) per contact (78) – a substantial challenge even at very long (>200-nm) contact lengths.

A final point regarding challenges for nanomaterials in transistors is the need for further discovery and innovation of the transistor structures. Thus far, nanomaterials are integrated into transistors that essentially mimic the silicon MOSFET, especially for high-performance applications (Fig. 1). Considering their substrate independence, there are undoubtedly much more favorable transistor structures that have yet to be discovered for nanomaterials. Such structures would take more specific advantage of the electrical and mechanical properties of nanomaterials for boosting performance, lending new functionality, or both for certain applications. Additionally, regardless of the transistor structure into which nanomaterials are integrated, a need remains for studying the reliability of resultant devices and circuits to ensure their utility under certain application requirements, such as high clock speeds.

High-performance transistors

High-performance transistors are those that enable the primary computing electronics that we rely on daily. Servers that fill warehouses (server farms) are the lifeblood of the Internet and rely on the highest-performing scaled transistors. Semiconductor companies such as Intel and Taiwan Semiconductor Manufacturing Company will develop the transistor technology – for example, "14 nm" (83) – for the highest-performance applications and then use mostly the same transistor for other less-demanding applications. An example is the low-power chips that are used for mobile electronics (e.g., smartphones, tablets, laptops), where the chip will still make use of transistors with the latest technology (14 nm) but will be integrated less densely and run at lower voltages. In this case, the term “high-performance transistor” refers to the transistor technology itself that is applied to all such peripheral applications – from servers to smartphones.

A closer look at Moore’s law for high- performance transistors, given in Fig. 4, helps to highlight why nanomaterials are so advantageous. In the early 2000s, the performance (as measured by chip clock frequency) was necessarily capped to address the runaway power density problem (84): Smaller transistors could leak power even in the off state, leading to power-consumption and heat-generation issues. Anything beyond ~100 W/cm2 is detrimental to the chip and surrounding components; heating a semiconductor causes performance fluctuations, and the ability for cooling technologies to dissipate the heat is limited to ~100 W/cm2. Active power (PA) depends on clock frequency f), operating voltage (VDD), and the number of transistors per square centimeter (N) as PA a N*f*(VDL)2. With Moore’s law demanding that N continue to increase, the most logical solution would be to reduce VDD because of the squared dependence. However, the cost in terms of performance was too great, and VDD has remained pegged for more than a decade at ~1 V for high-performance transistors. Reducing f would also seriously compromise performance, leading to the need for multicore architectures. The advantage of multicore chips in terms of the power problem is that the architecture ensures that, at any given time, a much smaller fraction of the transistors will be turned to the on state than for a single core chip – a phenomenon known as dark silicon (85). However, the multiplication of the number of cores will hit a level of maximized benefit at ~16 cores, leaving reduction of VDD the only hope for further progress.

Nanomaterials offer several ways of reducing the operating voltage in high-performance transistors. First, their atomic thinness enables highly effective gate control over the channel potential through the reduced screening length discussed above. Improved gate control means that even at aggressively scaled channel lengths (needed for driving an increase in N), nanomaterial transistors can switch to the on state at the lowest possible voltages (i.e., small subthreshold swing, which is an indicator of how many volts are required to switch the current in a transistor by one order of magnitude). The subthreshold swing is referred to as the performance metric in the off state, indicating the ability of a transistor to switch at low voltages. Beyond improved gate control, nanomaterials also enable advanced transistor structures that may offer solutions for scaling VDD. One such option is the tunneling transistor, where the small effective mass (me) in CNTs (as well as some 2D options) would offer dramatic improvement (increase) in the tunneling current to boost the on state, which limits the realization of these transistors (86, 87).

Exceptional electron transport in most nanomaterials is another attractive feature for high- performance transistors. In the case of CNTs, nearly ballistic (zero resistance) transport has been observed at room temperature at lengths up to 40 nm (88, 89). Such favorable transport has experimentally been shown to enable sub- 10-nm CNT transistors that outperform any similarly scaled silicon-based transistor at low voltages (VDD < 0.5 V) (90). Transport in TMDs is actually worse than in most bulk semiconductors, including silicon; yet at sufficiently scaled channel lengths, TMDs could still offer advantages, as performance in the transistor will become dominated by contacts rather than transport through the channel. For the required dimensions of a high-performance transistor, the performance of every device will be determined more by the contacts than by the channel, regardless of whether it is a nanomaterial or silicon or any other semiconductor. For this reason, the use of the prevalent transport metric, mobility, must be reevaluated.

Mobility

One of the most widely used metrics for describing the quality of carrier transport through a semiconductor is mobility (m). Initially defined as the constant of proportionality between carrier velocity and the electric field across a material, m has often been considered an intrinsic indicator of semiconductor quality and even quoted in textbook tables. Though it is understood that m depends on other factors such as doping density and temperature, it has nevertheless been taken as the most important parameter for semiconductor consideration. In fact, consideration of channel materials other than silicon (which suffers from a relatively low m compared with other bulk semiconductors) for high-performance transistors has largely focused on semiconductors with higher mobility, eventually leading to the classification “high-mobility semiconductors” (usually germanium or III-V compound semiconductors, such as GaAs, which despite higher mobility have other issues in achieving high levels of integration).

For the first 50 years of Moore’s law, using mobility as a key parameter to indicate the quality of a semiconductor for transistors made sense. Channel lengths were long enough to yield an average transport length between scattering events (mean free path) or time between scattering events (mean free time t) and, thus, a certain mobility: m = qt/me (here, q is elementary charge of an electron). What happens if the channel length falls below the average length between scattering events, or, in the most extreme case, what happens if the channel is ballistic? As shown in Fig. 5, the use of mobility in such a short-channel transistor is misleading, as it no longer accurately indicates the quality of carrier transport through the semiconducting channel.

Long-channel transistor

With performance in short-channel transistors being determined almost exclusively by the injection of carriers at the source-drain contacts, extraction of mobility from device data defies the actual meaning of the parameter. The example in Fig. 5 illustrates how the band structure and relevant resistances change between long- and short-channel transistors. Extraction of mobility from two such transistors could yield m that is an order of magnitude smaller for the short-channel devices, even though the performance is much better. This is a fallout of the widely used field- effect mobility expression, wherein m = gmLch/ (WCVds) (here, W is the device width, C is the capacitance, and Vds is the drain-source voltage), where the transconductance (gm) goes up but not nearly as much as Lch goes down when scaling from long to short channels (all other terms remain the same). The contacts, including Rc, are identical in the two devices, as is the applied voltage, but the extraction of mobility from the device data relies on the assumption that transport is limited by the scattering in the channel, as in the long-channel case.

In reality, mobility is no longer meaningful for high-performance transistors (all of which are of the short-channel variety), regardless of whether they have silicon, III-V materials, or nanomaterial channels. The saturation velocity of carriers will matter, as will the effective mass, for determining how well carriers move through the channel. Consider the difference in common expressions for current in a long-channel (traditional) MOSFET (91)

In addition to voltage dependencies [gate-source voltage (Vgs), threshold voltage (Vt), and Vds], current in the long-channel transistor depends on mobility, gate capacitance (Cox), and spatial parameters (W and Lch). In contrast, the short- channel nanomaterial transistor shares none of these dependencies. Rather, the current for the 1D nanomaterial transistor relies on the Fermi function f (indicates electron distribution)]; carrier velocity (v); transmission probability (Tp), including the probability that carriers will make it through the metal-nanomaterial contact without scattering; and density of energy states (D), with respect to energy (E) and temperature (T). The only material consideration in the long- channel expression is m, whereas the short-channel transistor accounts for D, v, and f, as these are the material-related parameters that become relevant when scattering in the channel is minimal. Hence, at this point of development, relying on mobility as a metric when discussing options for high-performance transistors causes confusion and distraction from the parameters that matter most. This is especially true for nanomaterials, for which reports of mediocre mobilities extracted from short-channel transistors undercut the actual potential of the material. Mobility remains a useful parameter for comparing TFTs, as they are long-channel devices.

Thin-film transistors

There are many applications for which a digital transistor switch is needed without the extreme performance requirements of computational devices. This became especially clear in the 1980s, when a revolution was beginning to stir in display technology with the need for a more compact, mobile display for laptops. Liquid crystal displays were favored but needed transistors for the backplane to drive the pixels. In 1981, researchers showed that a-Si provided the answer – it could be deposited onto glass substrates, was mostly stable, and had sufficient mobility (0.1 to 1 cm2 V1 s-1) to yield the necessary level of drive current (Ion). The size of the a-Si TFTs did not have to be small, as the typical pixel is on the order of 100 mm by 100 mm, and the TFTs needed to be large to provide the required Ion. Perhaps most importantly, the a-Si TFTs could be fabricated on large substrates at relatively low cost.

With a-Si TFTs, the display revolution began. Shortcomings, including bias-stress instability (change in the voltage needed to turn the TFT on after prolonged operation) and low mobility, led to development of other TFT options, including polysilicon (m ~ 100 cm2 V-1 s-1) (4). Although too costly for replacing a-Si in the backplane, polysilicon has become important for display driver circuits in mobile applications, as it is still considerably cheaper than using high-performance MOSFETs. Much effort was devoted to using polysilicon to drive organic light-emitting diode (OLED) displays, which require much higher drive currents than a-Si TFTs could ever deliver, but the nonuniformity in threshold voltage in the polysilicon TFTs gave concern for causing nonuniformity in display brightness (5). The latest advancement has been the use of metal oxide materials – in particular, InGaZnO (IGZO), which offers manufacturing costs on par with a-Si, mobility near that of polysilicon, and better stability. IGZO TFTs now drive the latest OLED displays on the market, yet they have their own limits based on processing temperature and mobility pegged at ~100 cm2 V-1 s-1 for reasonable synthesis temperatures.

Nanomaterials hold much promise for TFTs. Even though being formed into an inhomogeneous thin film seems to belie the advantages of the nanomaterials, they still are shown to deliver superb performance and processing benefits. For example, CNTs that are simply drop cast from solution onto a substrate to form a thin film (the cheapest fabrication approach possible, as it is amenable for printing processes) consistently deliver mobilities of 10 to 100 cm2 V-1 s-1 (69−71,93−95). Further efforts to induce alignment in the CNT thin films could boost mobility much higher than 100 cm2 V1 s-1 (68), which would be revolutionary performance improvement for TFTs processed in solution phase. TMDs have also shown encouraging performance in thin films, with mobilities of 1 to 40 cm2 V-1 s-1 (96−100), but they remain limited by insufficient synthesis to fabricate large numbers of transistors on a single substrate and the required use of high- temperature synthesis (not processed in solution). With cost being one of the most important driving factors for TFT applications, the most promising nanomaterial options are those that help break the cost barrier of current technologies. The most attractive way for this to happen is for a TFT to be printed rather processed in a vacuum or at a high temperature. This strength is beginning to receive attention for nanomate¬rial TFTs (101-106).

There are many other applications that benefit from current and future TFT technologies. Displays are presently the largest, and thus the most emphasized, but gas and biological sensors, optical detectors, radio-frequency identification tags, and Internet-of-Things applications also abound.

Advancements in TFTs that allow for performance improvement and cost reduction are needed to open the way for a myriad of such exciting applications. Nanomaterials are poised to provide such solutions, requiring further improvement in synthesis and thin-film formation; discovery of better contact interfaces; and realization of stable, consistent TFT operation.

New generation of transistors

Thus far, the focus of this Review has been how nanomaterial transistors have the potential to provide transformative solutions in high-performance and thin-film applications. Yet there are other, completely new and distinct application spaces for which nanomaterial transistors are particularly suited. Just as TFT research is focused more on cost than performance, studies of these new generations of transistors focus on other opportunities, such as optical transparency or biocompatibility. A subset of new-generation transistor applications – including printed electronics (103), flexible electronics (93), transparent electronics (40), and biomedical electronics (107) – is depicted in Fig. 6. In addition to these areas (though not specifically highlighted here), nanomaterial transistors are beneficial in harsh environments [high temperature or radiation (108,109)] such as space or medical imaging applications, where the thinness and small cross-sectional area are among several nanomaterial advantages enabling greater protection from device damage.

The field of printed electronics has grown dramatically over the past 20 years. Relying almost exclusively on organic polymer materials, applications of printed electronics have been quite limited. Nanomaterials have the potential to offer conducting, semiconducting, and insulating printable inks that are compatible, stable, and able to be modulated for specific application needs. Such a toolkit of inks would be groundbreaking for this field that has potential to revolutionize on-the-fly electronics in an analogous fashion to how 3D printing of mechanical structures has transformed prototyping.

Nanomaterials offer some of the most promising possibilities for electronics that are flexible, transparent, or both. In addition to their substrate independence (discussed above), the atomic thinness of the nanomaterials also renders them nearly 100% transparent to visible light and has been exploited in some demonstrated all-2D transistors (40, 43), motivated by the ability to create completely transparent circuits. Furthermore, the electronic properties of nanomaterials have proven to be robust to mechanical deformation for flexible substrate applications.

Finally, biomedical applications that have requirements of biocompatibility could also benefit from nanomaterials (107). For in vivo applications, small quantities of nanomaterials could be sufficiently safe to enable diagnostic circuits. Electronics applied directly to the skin are another possibility, where nanomaterials would mostly provide the types of benefits outlined in the flexible electronics discussion above.

Outlook

Transistors have completely transformed our daily lives, in areas ranging from communication to computation to comfort. As the limits of silicon transistors are unavoidably upon us, an intensified consideration of other transistor options is imperative. It is also important to keep clear the relevant deliverables for certain transistor applications spaces: namely, high performance and thin film. High-performance transistors are used in all computational devices, from servers to smart-phones, whereas TFTs primarily provide the backplane circuitry for displays. The meaningfulness of parameters such as mobility must be kept in context for the different transistor applications so that scientific advances can be kept in proper perspective.

Nanomaterials, including carbon nanotubes and TMDs, show great promise for both high- performance transistors and TFTs. Not every scientific discovery or advancement benefits both nanomaterial high-performance transistors and TFTs, yet many reports confuse this fact. What is clear from the thousands of demonstrated nanomaterial transistors is that they offer considerable advantages, promoting transformative advancement in high-performance, thin-film, and completely new application spaces. Comparison of the distinctive aspects of the different nanomaterial options, or the transistors assembled from them, suggests greater suitability of certain nanomaterials for particular applications (e.g., the instability of most X-enes in air largely precludes their use in low-cost, thin- film processing).

Going forward, much work remains in terms of improving the synthesis and resultant uniformity of nanomaterials, positioning them onto target device substrates, understanding and optimizing key interfaces (contacts and gate), and exploring re-invented transistor structures that make more direct use of the nanomaterial benefits. Varied levels of progress have been achieved in addressing these challenges for each nanomaterial, but each requires further attention to be suitable for a transistor technology. The most accessible area in the near term is the use of nanomaterials for printed (low-cost) TFTs, where they are already beginning to show consistent advantages over existing technologies.

Perhaps the greatest challenge to this unprecedentedly large research field of nanomaterial transistors is to make appropriate use of the deluge of scientific and engineering advancements. Hopefully, in the years to come, more collaborative and comprehensive advancements will be published that not only demonstrate a singular breakthrough on one of the challenges for nanomaterials but also give thorough evidence of the impacts of their solution on other key deliverables for a certain nanomaterial transistor application. With sufficient continued research investment into exploring nanomaterial transistors, there is little doubt that 50 years from now the next generation of scientists will be reflecting on a full century of Moore's law, in one form or another.

Tasks. Part 1 (up to “challenges for nanoparticles”).

Task 1. *Find the paragraph(s) which:*

1. explains why graphene is not exactly suitable for transistors;
2. says why we were able to give up traditional displays;
3. speaks about the property of nanomaterials to be ignored;
4. says that transistors cannot be scaled endlessly;
5. mentions long forgotten materials;
6. mentions the necessary conditions for transistors size to be further reduced;
7. says scientists are not sure of usefulness of some nanomaterials properties;
8. shows that nanomaterials advantages vary from device to device;
9. implies that some nanomaterials may have the quality to become transistors which graphene lacks;
10. mentions the principle the electronic industry has been guided by for many years;
11. speaks about a most important advantage of nanomaterials.

Task 2. *Find words meaning the following*:

1. having a great influence in particular field;
2. a deviation from an accepted, prescribed, or usual course of action;
3. bent and giving way under pressure or strain;
4. manifest(show) clearly (a quality or a type of behaviour);
5. occur as a result of;
6. to encourage someone or make them want to do something;
7. produce or generate (a result, gain, or financial return);
8. remember and take into account;
9. harmful;
10. a final or fundamental fact or principle;

11. expressed or shown clearly and openly, without any attempt to hide anything.

Tasks. Part 2 (from ‘challenge’ up to the end).

Task 1. *Which paragraph(s):*

1. says that our knowledge of transistors is limited;
2. mentions the difference between the production of transistors and the nanomaterials mentioned;
3. says that little is known abot the boundary between a metal and a nanomaterial;
4. says that the same term can mean slightly different things;
5. explains why a popular fabrication method does not work with nanomaterials;
6. mentions a great drawback of very small transistors;
7. speaks about a great fault of TFTs;
8. says what factors are important for high performance transistors;
9. explains what makes nanomaterials so good for printed electronics;
10. mentions great expectations about the future fate of nanomaterials.

Task 2. *Answer the following questions*:

1. What problems do transistors and nanomaterials share?
2. What are the difficulties in the way of using nanomaterials;
3. Why are multicore chips so power saving?
4. Why isn’t mobility an important criterion now?
5. Why wasn’t the polysilicon TFT good for LEDs?
6. What makes nanomaterials suitable for TFTs?
7. Where can new generations of transistors be used?

Task 3. *Find words or expressions meaning the following:*

1. problem;
2. relating to or constituting a sacrifice;
3. very noticeable;
4. causing harm or damage;
5. without taking into account, in spite of;
6. talk about subject or person or mention them;
7. to throw or drop things so that they spread all over the area;
8. result, outcome;
9. with reference;
10. drawback;
11. achievement, progress;
12. innovative; pioneering;
13. to think carefully and deeply about something.

13. NANOPHOTONICS: SHRINKING LIGHT-BASED TECHNOLOGY

A. Femius Koenderink,1 Andrea Alu,1’2 Albert Polman[1]

The study of light at the nanoscale has become a vibrant field of research, as researchers now master the flow of light at length scales far below the optical wavelength, largely surpassing the classical limits imposed by diffraction. Using metallic and dielectric nanostructures precisely sculpted into two-dimensional (2D) and 3D nanoarchitectures, light can be scattered, refracted, confined, filtered, and processed in fascinating new ways that are impossible to achieve with natural materials and in conventional geometries. This control over light at the nanoscale has not only unveiled a plethora of new phenomena but has also led to a variety of relevant applications, including new venues for integrated circuitry, optical computing, solar, and medical technologies, setting high expectations for many novel discoveries in the years to come.

Optics and the science of light is a lively field of research that continues to surprise decade after decade, with fundamental breakthroughs and disruptive applications. Communications technology has been revolutionized by the invention of the laser and the optical fiber, incandescent light bulbs are being replaced by efficient solid-state lighting, and solar energy technologies are on their way to price parity with fossil fuel-based power generation. A large number of these developments have resulted from increased control over the flow of light at length scales smaller than the wavelength. Squeezing light to nanoscale dimensions also opens the prospect of dense optical integrated circuits, which may overcome fundamental challenges related to bandwidth and energy dissipation in today’s electronic integrated circuit technology. More broadly, the field of nanophotonics aims at overcoming Abbe’s diffraction limit, developing technology able to manipulate light on a deep subwavelength scale. As photons are shrunk to the nanometer scale, ultimately approaching the scale of the wave function of electrons, fundamental new science is expected, and important technological advances appear. In this article, we review recent highlights in the science and applications of nanophotonics, focusing on the ultraviolet (UV)/visible/near-infrared spectral range, and provide an outlook for the bright future of this research field.

Photonic crystals

The initial concept for on-chip miniaturization of light dates back to the late 1990s, when photonic crystals – periodic structures fabricated from high-refractive-index materials such as Si or GaAs – were proposed and realized (Fig. 1A).

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As the periodicity in these structures approaches the wavelength of light, a photonic bandgap can appear, analogous to the energy bandgap in a semiconductor. The propagation of light with a frequency in the band gap is then forbidden, except in localized regions created by a well-designed break in periodicity, such as line defects that can guide light, or point defects that confine light. Band structure engineering provides exquisite control over light dispersion – that is, over the relation between its frequency co and its effective propagation constant к = 2n Д – and thereby also over how fast signals of different wavelengths propagate, as given by the group velocity dm/dk. Slowing down light in waveguides, and confining it in optical nanocavities, can be used to create optical memories and enhance light switching and manipulation schemes based on ultrafast modulation of the local refractive index. Impressively, data transmission with just one femtoJoule of energy expenditure per bit was recently demonstrated by using this photonic crystal platform, and as many as 100 individually addressable and switchable optical cavities have been multiplexed to reach a low-power optical memory with nanosecond storage time (7).

Plasmonics

Confining light waves is much more difficult than confining electron waves because there is no optical equivalent to the Coulomb force, based on which deep electron traps can be created. Instead, the only parameter to shape light is the material dielectric constant (e = те2, where те is the refractive index), which is limited to the range n = 1.3 to 4.0 for nearly all dielectrics in the visible

In a recent series of breakthroughs for nanophotonics, it was demonstrated that light can be hybridized with electrons in layers that are just one atomic layer thick, such as in graphene. Plasmons have been excited on graphene at mid- infrared frequencies (4,5), with wavelengths that are shrunk relative to free space by a factor of ~50. Graphene can be electrostatically gated to locally control its carrier concentration, and thereby its dielectric constant, promising a versatile platform for dynamically controlling plasmon propagation and reaching the ultimate confinement limit for optical integrated circuits.

Antennas for light

The unprecedented level of light concentration offered by plasmonic nanostructures suggests interesting new perspectives to interface light and matter, possibly even down to the level of illuminating a single molecule with a single photon. This level of control becomes possible as light is shrunk in all three dimensions. Optical antennas are nanophotonic elements designed to achieve this functionality, transducing free-space, far-field radiation to localized electromagnetic energy. The simplest nanoantenna is a single metal nanoparticle whose free electrons can support localized plasmon resonances at visible wavelengths, implying that its far-field excitation can result in a strongly localized near-field response. Reciprocally, an optically excited nanoparticle can efficiently radiate light in a controlled way.

A small isolated nanoparticle scatters as an electric point dipole, with a well-defined but broad angular distribution of radiation. Yet, tools borrowed from radio-frequency antenna design have allowed far-reaching control over the directivity of light radiation and scattering from proper arrangements of nanoantennas, and conversely over how far-field radiation drives near-field focusing in properly designed nanoclusters. Following these principles, antennas coupled to a single quantum emitter can result in highly directional beaming of spontaneous emission (6), and phased-array antennas coupled to efficient single-photon sources can serve as light-steering elements. Over 1000-fold brightness enhancement per fluorophore has been recorded in single-molecule experiments aimed at improving fluorescence microscopy in biological systems (7). Besides engineering emission directivity, antennas open a completely new regime for light-matter interaction strengths, especially in the case of dimer antennas with narrow gaps, through which plasmon modes can efficiently interact (Fig. 1C). A quantitative measure of the light-matter interaction enhancement around a nanoantenna is the Purcell factor: the spontaneous emission rate increase due to enhanced photon mode density in the antenna’s optical near field. Recently, a Purcell factor as high as 1000 was reported in metallic nanoantennas with gaps in the order of just a few nanometers (8). The capability of plasmon antennas to transduce between light and molecules has large relevance for microscopy, such as in the case of observation of single molecules, and infrared vibrational spectroscopy by use of field enhancement at sharp metal tips (9).

Shrinking light and quantum photonics

As light is shrunk to smaller and smaller scales, its interaction with matter occurs over volumes that eventually become comparable with a single atomic unit cell. In these situations, classical models for describing optical interactions fail. In the dimer nanoantenna of Fig. 1C, for instance, classical electromagnetic theory would predict a diverging light intensity in the gap as the distance between particles approaches zero. For gaps below a few nanometers, however, quantum tunneling effects start dominating, and the nonlocality of the electron wave function, which extends across the gap, fundamentally limits the overall light intensity enhancement (10). As nanofabrication tools allow finer and finer control, such nano¬scale quantum effects become increasingly relevant in experiments.

At these scales, our understanding of quantum optical effects also faces new challenges to properly describe the interaction of single emitters with single plasmons. For example, the Purcell factor has needed rewriting in plasmonics because the conventional definition of a resonant mode, and its associated cavity volume, must be revised as light shrinks to deep-subwavelength volumes at which optical absorption losses and quantum effects become dominant (11). Further-more, in the case of very high Purcell factors, the characteristic spontaneous emission decay time can become comparable with a single cycle of the electromagnetic field, in which case Fermi's Golden Rule breaks down (12).

In this context, it is currently being debated whether the quantum mechanical regime of strong coupling can be reached with plasmons and single emitters. When a single emitter releases its energy as a quantum of light near a nanoresonator, the decay is not irreversible. Instead, the coupling may be made sufficiently strong to enable Rabi oscillations, coherently exchanging the excitation (13). This regime may enable ultrafast integrated quantum circuits based on single photons, with plasmons and emitters taking the role of information carriers and processors (14). The current state of the art in integrated quantum photonics has been reached in photonic crystals, in which single photon sources with near-unity efficiency have been reported (IS), setting the stage for single-photon transistors and quantum-logic gates based on single-photon nonlinearities (16). These remarkable advances are opening a new paradigm for scalable, integrated quantum photonics.

Shrinking vector fields to boost magnetism and chirality

Antennas not only localize the photon energy density but also provide a way to control the vector nature of light at the nanoscale. The relevance of magnetic effects in optics is conventionally neglected for small objects because material magnetization rapidly vanishes as the frequency grows. This also implies that chiral effects such as circular dichroism and optical rotary power are inherently weak in ordinary matter because they require that distinct optical responses – such as an electric dipole plus a magnetic dipole response, or an electric dipole plus a quadrupole response – occur simultaneously in the same object with a controlled phase lag. Such magnetic and magnetoelectric effects can be boosted to become as strong as conventional electric responses by setting up scattering resonances in loop-shaped and helical antennas that carry circulating optical currents, or by pairing achiral resonances in strongly asymmetric geometries (17,18). These nanostructures may allow enhancement in the local chirality of the optical field so that enantiomers – molecular stereoisomers that are mirror images of each other – may be optically screened at the single molecule level by placing them near a chiral antenna (19). Furthermore, helicity-dependent near-field enhancements may be used to control spin-polarized optical transitions.

Metamaterials and metasurfaces

The unprecedented opportunity to localize light at deep-subwavelength scales has not only been applied to isolated optical nanoresonators but has also led to the synthesis of optical metamaterials, artificial materials with an unusual optical response, formed by ordered or disordered collections of resonant nanoscale plasmonic scattering elements. Many unusual bulk optical responses have been theoretically predicted and experimentally verified on the basis of complex three-dimensional (3D) metallodielectric architectures by using nanoantennas as their basic elements.

Remarkable nanofabrication advances have allowed the realization of nanostructured materials with unusual optical responses such as, for example, a metamaterial slab composed of 3D chiral helix antennas (Fig. ID) (20), offering large selectivity to circular polarization with a broadband response in an optical frequency band in which optical components filtering circular polarization do not exist. The fact that constituent antennas can carry both a strong electric and a strong magnetic response gives the opportunity to reach optical properties far outside the scope of naturally available refractive indices, permittivities, and permeabilities. Such materials can, for example, refract light in unexpected directions, as demonstrated in various geometries, most recently in the UV spectral range (21). Negative refraction has been a precursor to the broad paradigm of transformation optics (22), which is most popular for enabling invisibility cloaks that can make objects undetectable in a certain frequency band by wrapping them in a metamaterial shell with suitably graded electric and magnetic response. Strong frequency dispersion, as well as absorption that takes place in the constituent antennas, are fundamental constraints of passive metamaterials that have so far limited their practical applicability.

The need to overcome loss, combined with the continuous drive toward integration and large- area fabrication, has inspired a recent shift from 3D metamaterials toward 2D optical metasurfaces (Fig. IE). Metasurfaces are planarized, ultra- thin, patterned artificial surfaces that are designed to mimic the functionalities of conventional optics and metamaterials in two dimensions, avoiding absorption losses by light propagation in the third dimension. Strongly localized optical resonances induced by plasmonic nanoantennas enable abrupt phase and amplitude discontinuities, which can be tailored at will across the surface to provide a controllable transverse gradient, inducing anomalous refraction, reflection, and control over subwavelength structure of the impinging wavefront (23, 24). This enables the realization of ultrathin lenses, beam steering devices, and generation of orbital angular momentum of light, to name just a few examples. A promising trend in metasurface design is the use of arrays of dielectric nanoscatterers that show geometric Mie-type resonances, avoiding absorption losses (25,26).

Recent work has shown that flat and ultrathin metamaterials may be used to engineer to a large extent both the spatial and spectral response of the impinging wavefront. In this sense, metasurfaces and metamaterials can operate as all- optical circuitry, processing the impinging signals at the nanoscale with nanocircuit elements that may form thin metasurfaces acting as complex operators (27). These concepts may lead to all-analog filtering, signal processing, and even computing functionalities performed as light interacts with these devices (28).

Probing nanoscale optical fields

Measuring light confinement is inherently difficult because the diffraction limit of conventional microscopy places a lower limit to imaging resolution. Yet, advances in nanophotonics research require new techniques to excite materials and probe them at the nanoscale. Although super-resolution microscopy tools such as photo- activated localization microscopy (PALM), stochastic optical reconstruction microscopy (STORM), and stimulated emission depletion (STED) have made it possible to circumvent Abbe's limit, they work best for specimens that are almost transparent and that can be functionalized with proper fluorescent markers. Nanophotonics research instead often requires a point detector, or a point source of vector fields that can be brought into the optical near field. Near-field scanning microscopy uses a sharp raster scanning probe to approach a nanostructure of interest to within 10 nm from its surface. The probe either acts as a scatterer that converts near fields into far-field light (4, 5) or as a fiber-coupled source or detector. This technique has become so advanced in recent years that electric and magnetic field components of light can be separately imaged at a length scale far below the

Nanophotonic characterization techniques. (A) Near-field scanning optical microscopy – either in transmission, collection, or scattering mode – can measure the magnetic and electric field components of light at a 10- to 100-nm spatial resolution in the femtosecond time domain. (B) Resonant modes and light dispersion of plasmonic and dielectric nanostructures can be probed by means of electron irradiation, either by collecting the induced radiation (cathodoluminescence) or by measuring the EELS. The spatial resolution of these techniques is determined by the electron beam width: -10 nm. wavelength, and at femtosecond time scales. Scanning emitter lifetime imaging microscopy can probe the optical density of states in two dimensions by use of a single fluorescent source attached to the end of a sharp fiber probe. Electron beam-induced excitation in a scanning/ transmission electron microscope is another highly controllable way to study optical modes and resonances in polarizable metallic and dielectric nanostructures with deep subwave length spatial resolution. Cathodoluminescence spectroscopy enables spatial mapping of the radiative density of states in two dimensions by using the light emitted when a beam of fast electrons impinges on a sample. Conversely, electron energy loss spectroscopy (EELS) maps the kinetic energy lost by electrons during their interaction with photonic structures. EELS and CL have recently been demonstrated in tomography mode, imaging the localized surface plasmon modal field distribution of Au nanoparticles in three dimenions. Electron beam-induced optical images routinely provide a spatial resolution of ~5 nm, which is on par with the best optical superresolution microscopy.

Practical applications of nanophotonics

Nanophotonics has already delivered many of the original promises dating back to when this research field started to develop around 10 years ago. One of the earliest nanophotonics discoveries to transcend the laboratory were chemically synthesized silica-core/Au-shell nanoparticles for applications in medical diagnostics and therapy. When introduced into the blood stream, these “nanoshells” are preferentially trapped in malicious tissues. When irradiated with a laser tuned to their plasmon resonance, the particles are locally heated, destroying the cells. This concept is presently being tested in clinical trials on humans for cancer treatment.

Molecular sensing and spectroscopy have motivated the drive to controllably shrink light to the size of a single molecule. It was found that optical hotspots in rough metal surfaces arising from localized surface plasmons result in a strong enhancement of the molecular Raman scattering signal, forming the basis for surface-enhanced Raman scattering (SERS), a well-established spectroscopy tool in chemistry. In a similar area, new sensors have been proposed based on the plasmon resonance wavelength shift caused by different molecular species placed in the plasmonic near field. Antibody-specific chemistry may also be used to bind or cluster plasmon particles by using the fact that gold is easily functionalized through thiol chemistry; commercial pregnancy tests today use this concept. An intriguing application of plasmonic light focusing is in DNA sequencing, in which a DNA molecule is transported through a small hole in a metal film, with the aim to read out the base-pair sequence through the subsequent detection of fluorescent markers that are selectively bound to different base pairs.

Lasers, solid-state lighting, and photovoltaics are also important fields in which nanophotonic structures have enabled new designs for improved functionality. Photonic crystal lasers have now become so advanced that they can deliver power in the watt range. The emission of light-emitting diodes (LEDs) is strongly enhanced if a suitably designed periodic array of Ag nanoparticles is embedded in the light- emitting phosphor . These nanostructures help to efficiently couple and scatter light from the UV pump TED into the phosphor material and, at the same time, aid the directional outcoupling of the phosphor emission, which enhances LED efficiency and brightness. Conversely, periodic and aperiodic metasurfaces composed of resonant plasmonic or dielectric nanoparticles can lead to improved light coupling and trapping into solar cells, supporting increased photovoltaic energy conversion efficiency, as well as thinner cell designs that can be made at lower cost. Recently, efficient solar cells were realized by using InP nanowires. Here, the small radius of the wire enables efficient collection of electrical carriers. At the same time, optical resonances in the nanowire can lead to light concentration, increasing the photovoltage.

Metal nanowire networks have been developed as transparent electrically conducting coatings. Even though these nanowires suffer from ohmic losses owing to plasmon excitation, they show a beneficial tradeoff between optical transmission and electrical conduction and can be made at relatively low cost. These nanowire networks are already finding applications in solar cells, computer display, and tablet technology, replacing the commonly used, expensive, and brittle indium-tin-oxide as a transparent top-contact.

The near-field focusing provided by plasmonic nanostructures has also found applications in heat-assisted magnetic recording (HAMR) for data storage, a technique in which the magnetic phase change in a recording medium is facilitated by a transient temperature increase. This increase is induced by an optical hotspot resulting from nanofocusing of plasmons onto a magnetic film. Plasmonic hole arrays have been demonstrated as color multiplexers in charge-coupled display (CCD) imaging systems. Here, light within specific wavelength bands is guided to the matching light collection pixels on a CCD array and then converted to electrical signals. This represents an important advantage over the use of conventional color filters, in which a substantial portion of the impinging light is lost by absorption.

Future developments and perspectives

Nanophotonics provides a diverse set of tools to build on: Photonic crystals offer ultimate dispersion control and low-loss storage, whereas plasmonics is the platform of choice to control light on ultrafast time scales and ultrasmall length scales, matching optical interactions with single molecules. Metamaterials and metasurfaces provide the ultimate control over all properties of light. With the great control over light at the nanoscale example, when optical fields and acoustic vibrations are colocalized at the nanoscale, light can be used to control mechanical motion and vice versa, with optomechanical coupling strengths that are not achievable with other geometries. These interactions have, for example, been used for laser cooling of a nanomechanical resonator to its quantum ground state

It has even been suggested that plasmon-enhanced SERS can be described by the dynamic backaction of the plasmon on a molecule’s vibration, paving the way to a new form of molecular quantum optomechanics. Future hybrid nanophotonic systems hold the promise to couple electron spins with light, enabling integrated networks for quantum nanophotonics – for example, by using singlephoton emission by color centers in diamond or defect centers in materials such as SiC.

Nanophotonics is also at the brink of making key contributions to the development of novel energy-conversion mechanisms. The recently discovered plasmoelectric effect in metal nanoparticles and hole arrays, in which optical illumination directly creates an electric potential by off-resonant excitation of a plasmonic structure, is being further explored to investigate how electrical power can be best generated. Another intriguing challenge is to harvest the excess energy of hot electrons excited in optically excited plasmonic nanostructures. This may find applications in energy harvesting and also plasmon-assisted surface catalysis for the generation of fuel (such as ethanol and hydrogen) from sunlight. More generally, plasmon-assisted photochemistry and catalysis is a research field with many opportunities to be explored.

An initial motivating factor for nanophotonics research was its direct impact on optoelectronic integration, aiming to bring together electronic and photonic length scales. The development of novel nanostructures that enable a nonreciprocal flow of light paves the way to on-chip all-optical isolation, in which light can only propagate in one direction, which is one of the missing components toward a fully integrated light-based communication system. Recent proposals and experimental demonstrations have shown that nonreciprocity can be indeed achieved by using a suitably designed spatiotemporal modulation of the local permittivity in waveguides and microring resonators. Another interesting direction in this context lies in the exploration of the photonic equivalent of topological insulators. In such structures, unidirectional flow of light and reflectionless propagation robust to disorder may be achieved by designing periodic metasurfaces that support topologically nontrivial band diagrams.

Two further important ingredients for optoelectronic integration are access to strong non-linearities within a very compact footprint and dynamic tunability and adaptability. The nonlinear optical response of materials is typically weak, and therefore large volumes are required to realize a measurable response. The recent observation of a giant nonlinear response from plasmonic metasurfaces coupled to intersubband transitions in semiconductors may open exciting venues for nonlinear nanophotonics. Similarly, one may ask how metasurfaces can enable new schemes for dynamically tunable integrated photonics. For example, can electrically tunable metasurfaces be used to steer and multiplex light on a chip, integrating an optical fiber communication system within an electronic integrated circuit? Also, how can “metatronic” optical signal processing and computing circuits be built and reconfigured by using building blocks with discrete optical functions? Novel 2D materials and heterostructures based on graphene, MoS2, and WSe2 will play an important role in bringing light to the nanoscale, enabling 2D electrically tunable integrated optical nanocircuits. It will be interesting to see to what degree of integration complexity optical and electronic functionality can ultimately be achieved on a chip by using these materials. A decisive factor will be to find the right tradeoff between light confinement and optical absorption losses.

The control over light at the nanoscale that scientists have achieved in recent years leads to a continuous stream of new fundamental insights in the interaction of light with matter at a deep-subwavelength scale. There is no doubt that this intense research activity promises a bright future for nanophotonics in the years to come.

Tasks. Part 1 (from the beginning up to ‘This technique has become so advanced’).

Task 1. *Find the paragraph that:*

1. speaks about the relation between material magnetization and frequency;
2. explains how local optical resonances can be used;
3. speaks about the latest advances in optics;
4. says that light can go far beyond the value limiting the optics resolution;
5. compares photonic structures behavior with that of semiconductors;
6. explains what makes nanophotonics better than other microscopy methods;
7. mentions devices normally used in radioelectronics;
8. says that light can be combined with electrons;
9. says it is possible to create tiny and extremely fast integrated circuits;

10. mentions a popular material which can be used as a simple device to let plasmons through or to stop them;
11. explains what optical antennas are intended for.

Task 2. *Find words or expressions meaning the following*:

1. finally;
2. to limit;
3. to increase;
4. caused to continue without interruption, supported;
5. depending on;
6. to adapt or be adapted to many different functions or activities;
7. because of;
8. to happen;
9. not able to be changed back to the way they were beforel;
10. using the most modern and recently developed methods, materials, or knowledge;
11. to pay too little attention to something;
12. happening at the same time;
13. sudden and unexpected;
14. to avoid a problem or rule that restricts you.

Part 2 (from this technique has become so advanced' up to the end).

Task 1. *Say whether the following is true, false or is not mentioned*:

1. Nanophotonics dates back to a decade ago.
2. Nanophotonics can be used to cure brain cancer.
3. Plasmonic light may help us to combine DNA sequences.
4. Since resonant plasmon nanoparticles can capture light solar cells become more efficient.
5. Despite the fact that plasmonic excitation in the nanowires increases resistance they are cheaper and their optical transmission /electrical conduction ratio is good enough.

6. Hybrid nanophotonic systems are used to find impurities in diamond and in defecoscopy.

7. Nanophotonics can be used to create portable and powerful batteries due to the recently discovered plasma…… effect in nanoparticles.

8. Nanophotonic research was stimulated by a possibility to combine electronics and photonics.

9. By shrinking light to nanoscale it will be possible to create new and powerful computing devices.

10. The important thing here is to balance light confinement and optical absorption losses.

11. Recent advances in light control leads to a better understanding of how matter affects light at the nanoscale.

12. Nanophotonics is likely to have a bright future.

Task 2. *Find words/expressions meaning the following:*

1. having an uneven or irregular surface; not smooth or level;
2. deflect or diffuse;
3. to provide;
4. because of, thanks to;
5. in a contrary or opposite way; on the other hand;
6. something that helps you to be more successful than others;
7. to be likely to succeed;
8. almost ready to do or experience something, on the verge of;
9. to gather, to collect;
10. problem, difficulty;
11. for that reason; consequently;
12. able to be adjusted;
13. a balance achieved between two desirable but incompatible features; a compromise.

14. PEROVSKITE SOLAR CELLS

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Henry J. Snaithisa professor of physics at the University of Oxford and is chief scientific officer at Oxford Photovoltaics, which he co-founded.

Sitting in a dimly lit bar then graduate student Michael Lee was scribbling on a beer coaster as night fell, jotting down a list of chemical ingredients before he forgot them. Earlier that day scientists at Toin University of Yokohama had generously shared their groundbreaking recipe for making solar cells from a new material called perovskite rather than the usual silicon. The cells were only 3.8 percent efficient in converting sunlight to electricity, so the world had not taken notice. But Lee was inspired. After the 2011 fact-finding mission, he returned to Clarendon Laboratory at the University of Oxford, where all three of us worked at the time, and made a series of tweaks to the recipe. The changes yielded the first perovskite cell to surpass 10 percent efficiency. His invention sparked the clean-energy equivalent of an oil rush, as researchers worldwide raced to push perovskite cells even higher.

The latest record, set at 20.1 percent by the Korea Research Institute of Chemical Technology in November 2014, marked a fivefold increase in efficiency in just three years. For comparison, after decades of development state-of-the-art silicon solar cells have plateaued at about 25 percent, a target that perovskite researchers like us have squarely in our sights. We are also anticipating a commercial debut, perhaps through a spin-off company such as Oxford Photovoltaics, which one of us (Snaith) co-founded.

Perovskites are tantalizing for several reasons. The ingredients are abundant, and researchers can combine them easily and inexpensively, at low temperature, into thin films that have a highly crystalline structure similar to that achieved in silicon wafers after costly, high-temperature processing. Rolls of perovskite film that are thin and flexible, instead of thick and rigid like silicon wafers, could one day be rapidly spooled from a special printer to make lightweight, bendable, and even colorful solar sheets and coatings.

Still, to challenge silicon's dominance, perovskite cells will have to overcome some significant hurdles. The prototypes today are only as large as a fingernail; researchers have to find ways to make them much bigger if the technology is to compete with silicon panels. They also have to greatly improve the safety and long-term stability of the cells – an uphill battle.

Winning the efficiency race

Today the best silicon cells are 25.6 percent efficient. Why can't solar cells convert 100 percent of the sun's light energy? And why should perovskites be able to surpass the silicon record?

The answers to these questions are found in the excitable and errant electron. When a solar cell is in the dark, electrons in the material stay bound to their respective atoms. No electricity flows. But when sunlight strikes a cell, it can liberate some of the electrons. Infused with energy, the "excited" electrons careen drunkenly through the crystal lattice of the cell until they either exit one end of the cell – whisked away by an electrode as useful current – or run into an obstacle or a trap, losing their energy in the form of waste heat.

Crystalline silicon has dominated the solar cell market for decades, but prototype cells made from a different crystalline material, perovskite, are rapidly approaching the same efficiency levels.

Perovskite could become cheaper than silicon because it can be made at much lower temperatures. The perovskite cells can be rolled out as flexible, colorful films, leading to a wider variety of products than silicon cells, which are rigid. Big challenges remain, however.

Techniques to reliably seal water out of perovskite are needed to prevent the cells from degrading in a matter of hours.

Lead, used in small quantities in each cell, must be permanently sealed in for safety. Cells must get much larger, too; right now the high-efficiency versions are only as big as a fingernail.

The higher the crystal quality, the fewer defects there are to derail the electron's journey. Silicon cells are typically heated to as much as 900 degrees Celsius to remove defects. Perovskites are largely free of such defects even though they are processed at much lower temperatures, around 100 degrees C. As a result, electrons excited by light are just as successful in exiting perovskite cells, and they are unlikely to lose as much energy along the way when colliding with obstacles. Because the electrical power of a cell is the product of the flow of electrons exiting that cell (the current) and the energy that those electrons carry (the voltage), the efficiency of perovskites can rival silicon, with much less processing effort.

But there is a ceiling to how much of the sunlight's energy a solar cell made of semiconductors such as silicon and perovskites can convert into electrical power. That is primarily because of a property of semiconductors called the bandgap – a minimum level of energy needed to liberate electrons. Sunlight includes all wavelengths of light, but only certain wavelengths exceed the energy bandgap. Other wavelengths will simply pass through the material, doing nothing.

The bandgap is different for different semiconductors, and it sets up a fundamental trade-off: the lower the bandgap, the more of the sun's spectrum a cell can absorb to excite electrons, but the lower the energy each electron will have. Because electrical power depends on both the number and energy of electrons, even a cell with the ideal bandgap can convert only around 33 percent of the sun's energy.

Silicon has a fixed bandgap that is not ideal, but it commands the solar industry because effective ways to manufacture the technology are well understood. When making perovskites, however, researchers can adjust the bandgap at will by tweaking the mix of ingredients, which raises the prospect of exceeding silicon efficiencies. Researchers can also layer different perovskites with different bandgaps on top of one another. Double-decker perovskites should be able to break through the nominal 33 percent ceiling; some projections indicate they could put 46 percent of the sun's energy to work.

Teaching an old material new tricks

Mineralogists have known about the natural forms of perovskite in the earth's crust since the 19th century. The crystals graced a 1988 cover of this magazine when scientists thought they could form high-temperature superconductors (some work continues today). During the past two decades engineers also made experimental electronics with man-made perovskites, but they overlooked the material's potential use in solar cells.

Finally, in 2009, a group at Toin University turned a manmade version – a lead halide perovskite first synthesized in 1978 – into a solar cell. The researchers dissolved selected chemicals in solution, then spun and dried that solution on a glass slide. The drying left behind a film of nanometer-scale perovskite crystals on top of the slide, much the way salt crystals emerge from evaporating tidal pools. This film generated electrons when it absorbed sunlight but not very well. The researchers added thin layers of material on either side of the perovskite nanocrystals to help them transfer the electrons to an external electrical circuit, supplying useful power.

The first tiny cells were only 3.8 percent efficient, and they were highly unstable, deteriorating within hours. Lee altered the perovskite's composition and replaced a problematic layer in the cell, pushing the efficiency beyond 10 percent. Another set of investigators, led jointly by Michael Gratzel of the Swiss Federal Institute of Technology in Lausanne and Nam-Gyu Park of Sungkyunkwan University in Korea, made a similar advance.

The recent march to 20 percent has been driven by some clever innovations. Creating a defect-free crystalline film requires tricky deposition methods, so a group headed by Sang Il Seok of the Korea Research Institute of Chemical Technology devised a multistep process that forced a more orderly crystal film to drop out of the spinning solution. By optimizing processing, Seok marched through three consecutive record efficiencies in 2014, from 16.2 to 20.1 percent.

Other scientists simplified the layering of added materials; the newest perovskite cells look more like a silicon cell – a simple stack of flat layers. In silicon's case, this design has made low-cost mass production possible. Recently perovskite researchers have also heated up the solution and the glass slide on which it is deposited, resulting in crystals that are several orders of magnitude bigger than those in the initial cells, an encouraging sign that the crystallinity is still improving.

Scientists are devising some novel traits, too. Varying the chemical ratio can create cells that have a gentle shade of yellow or a blush of crimson. Depositing perovskite on glass in islands instead of one thin layer can create films that are opaque or transparent or degrees in between. Together these options – refreshing choices over rigid, opaque, blue-black silicon cells – could help architects design skylights, windows and building facades that incorporate colorful perovskite solar films. Imagine a skyscraper with perovskite-tinted windows that shade the interior from hot sunlight by converting it into electricity, reducing the cooling bill while also providing power.

Long road to commercialization

Perovskites have a long way to go before they fulfill such visions. Although Korean and Australian researchers recently demonstrated printable cells that are 10 by 10 centimeters – large enough for commercially competitive products – the most efficient cells are still small prototypes. As labs and start-up companies scale up the devices, they must accomplish three prerequisites for commercialization: ensure that the cells are stable enough to produce electricity for decades, design a product that customers feel is safe to put in their homes and buildings, and satisfy critics who caution that the claims for perovskite efficiency levels are inflated.

The stability of the perovskite solar cell is arguably its Achilles' heel. Perovskites can degrade rapidly because they are sensitive to moisture, so they must be encased in a watertight seal. Cells fabricated by us in an inert atmosphere and encapsulated in epoxy have performed stably for more than 1,000 hours when exposed continuously to light. Researchers at the Huazhong University of Science and Technology in China, in collaboration with Gratzel, have also reached 1,000 hours even without encapsulation, and in recently published work they have deployed test panels outdoors in Saudi Arabia to show that their design will function in real-world conditions. At a recent Materials Research Society meeting in San Francisco, we disclosed results from Oxford Photovoltaics that demonstrate that perovskite cells can generate stable power output for more than 2,000 hours under full sunlight.

The industry convention for solar panels is a 25-year warranty, however. That equates to about 54,000 hours under constant, bright sunlight. Finding an effective moisture barrier that works for that long, over a wide temperature range, is crucial. Silicon manufacturers solved the problem by laminating the cells between glass sheets. This is perfect for large, ground-based installations. But because perovskite cells can be made as films that are much lighter and more flexible than cells on glass, alternative encapsulation strategies may open up broader applications, such as veneers for walls or windows that can generate electricity.

Fortunately, some progress has been made by companies trying to commercialize other flexible solar materials, such as the-semiconductor made of copper indium gallium selenide. The encapsulation technologies work well, yet businesses have struggled to gain market share from silicon because the cells are less efficient and cost more. Perovskites, which should have higher efficiencies and lower processing costs, may be able to exploit the encapsulation advances.

Just as important as sealing out moisture is sealing in the cells' contents because of the tiny amount of lead added to the perovskite recipe. Lead is toxic, so the market will demand a high burden of proof that perovskite power is safe. For inspiration, researchers can again look to an alternative solar material, the only one besides silicon that has achieved significant commercial success: cadmium telluride.

Manufactured by First Solar, cadmium telluride panels have been deployed around the world and have exceeded safety standards despite the presence of an element far more toxic than lead: cadmium. First Solar has convinced communities that its panels are so well sealed that no cadmium could escape, even in a desert wildfire at 1,000 degrees C. The panels use a glass substrate, however, which precludes the flexibility and lower weight that perovskites promise. Yet perovskite companies can learn from First Solar's success in sealing and rigorously testing products.

An encouraging development related to lead recently emerged from the Massachusetts Institute of Technology as well: Angela Belcher and her colleagues demonstrated that lead-acid car batteries can be recycled safely, with the lead content recovered to make perovskite cells. This result could be an environmental plus. Belcher estimates that the lead in a single car battery could enable production of around 700 square meters of perovskite cells, which at 20 percent efficiency would be enough to power 30 houses in a warm but sunny climate such as that in Las Vegas.

A different route would be to eliminate the lead altogether. Both our group and another one at Northwestern University have published preliminary reports on cells that use tin instead of lead. The efficiency and stability are worse, however, because tin tends to cause the perovskite to lose its crystalline structure over time, hampering an electron's ability to get out of the cells. A major advance would be needed for tin to match lead's longterm performance.

In addition to the issues listed here, researchers have to solve a smaller, quirkier problem. Critics have claimed that the efficiency numbers for perovskite cells might be inflated because of hysteresis – a jitter in the measurement that is likely caused by charged molecules migrating from one side of a cell to the other, which could create the appearance of greater current. This ion migration is very brief, however. Scientists are looking for ways to halt it, but in the near term, there is a simple remedy: wait out the migration and measure efficiency over a longer period. In most cases, this process renders efficiency readings that are similar to quick, initial measurements, but researchers may be tempted to report the higher of the readings. We are working with investigators worldwide to standardize the measurement process so that our results meet a high standard of scrutiny.

Finally, to succeed commercially, perovskite innovators need to provide a compelling economic narrative to attract the investment dollars required for scaling up production. Although materials for perovskites are abundant and cells can be processed at low temperatures into films that roll off inexpensive equipment, perovskite solar companies should not fall into the trap of competing on silicon's terms. There is little room to undercut silicon panels because most of the cost of an installation is not related to the panels but to what is called the "balance of system," which includes installation materials and labor, permits and inspections, and other expenses related to system installation. An average U.S. residential solar installation in 2014 was priced at $3.48 per watt of electricity-generating capacity, yet the cost of the actual solar panel was only 72 cents per watt. Even if perovskite panels achieve the dirt-cheap 10 to

20 cents per watt that researchers think is possible, the improvement would reduce the final installed price by only a small percentage.

Perovskite companies can build on those small savings, though, by devising products that beat silicon's efficiencies. A highly efficient perovskite solar panel reduces the total installed cost per watt by requiring less land or roof space and therefore less labor and equipment. An even more imaginative example of changing the rules would be to sell perovskite products for applications that silicon cannot compete in, such as films that could be integrated right into building materials for walls, roofs and windows.

The hybrid solution

For now Perovskites might have the best chance to reach the market as an ally rather than a competitor of silicon. Perovskites could literally piggyback off silicon's success, gaining entry to a $50-billion market.

An alliance could happen by adding a perovskite layer right on top of a silicon layer, creating a "tandem" solar cell. Perovskites are good at harnessing the higher-energy colors of sunlight, such as blue and ultraviolet, which silicon fails to capture, generating a much higher voltage in electrons. Researchers at Stanford University and M.I.T. recently stacked a perovskite cell on top of a sealed silicon cell, raising efficiency from the silicon's original 11 to 17 percent. They also assembled a tandem cell by layering perovskite on top of unsealed silicon, creating a single structure. The combination achieved just 14 percent efficiency, but that figure could surely go up with manufacturing refinements. Based on the two experiments, the researchers sketched out a scenario by which a tandem cell made with a state-of-the- art silicon component and a state-of-the-art perovskite device, combined using clever engineering, could surpass 30 percent efficiency without any radical change in either technology.

If a tandem solar panel could reach 30 percent efficiency, the impact on the balance-of-system cost could be enormous: only two thirds of the number of panels would be needed to produce the same amount of power as panels that are 20 percent efficient, greatly reducing the amount of roof space or land, installation materials, labor and equipment. Oxford Photovoltaics, Snaith's spin-off company, is partnering with traditional silicon manufacturers to boost silicon's efficiency with a perovskite coating over the silicon cell; the company is targeting prototypes of the tandem cells this year. Down the line, cheap solar coatings integrated into roofing or glazing materials could transform the entire cost structure of a solar-powered building.

Running in reverse

The quick rise of perovskite solar cells has inspired scientists and engineers to fabricate other types of prototype products that also might one day make it to market. Working with our colleagues at the University of Cambridge, we recently created light-emitting diodes (LEDs) and lasers using metal halide perovskites, which efficiently emit light (instead of absorbing it) through a process called luminescence.

This turnabout is not really surprising; when run in reverse, the world's most efficient solar cell, gallium arsenide, acts as an LED. Cheap, printable LEDs and lasers could lead to intriguing applications, from large-scale lighting to medical imaging.

Research into these novel products is very early, of course, but we think the work will become more popular. Perovskites make scientists feel like children in a candy shop; we have found a material whose properties fill almost every checkoff box on our wish list, including high efficiency, low cost, light weight, flexibility and aesthetic appeal. It will take a concerted, global effort by academia, industry and government to fully realize the potential perovskites have to move beyond the silicon era. But given the prize – cheap, clean energy and the next generation of electronics – we think perovskites are a good bet.

Tasks. Part 1 (up to ‘The stability of the perovskite solar cell is arguably its Achilles’ heel’).

Task 1. *Find words/expressions meaning the following:*

1. pioneering;
2. to give someone confidence or enthusiasm to do something well;
3. to give;
4. the most recent stage in the development of a product;
5. regard as probable; expect or predict;
6. the creation of an independent company through the sale or distribution of new shares of an existing business or division of a parent company;
7. that can be shaped or forced into a curve or angle;
8. obstacle;
9. to rush forward in an uncontrollable way;
10. a balance achieved between two desirable but incompatible features; a compromise;
11. to appear;
12. become progressively worse;
13. to make bigger.

Task 2. *Answer the following questions.*

1. Why were people unimpressed with the idea of making solar cells from a new material called perovskite?
2. Why is the invention compared to an oil-rush?
3. What makes perovskites so interesting?
4. What are the obstacles in the way to their wide-spread use?
5. What are perovskites advantages over solar cells?
6. How does the forbidden zone affect the efficiency of solar cells and perovskites?
7. Why is perovskite more promising than silicon?
8. How can it be used in rooms and buildings? Due to what property?
9. What are the stages of perovskite cells development?

Tasks. Part 2 (from ‘The stability of the perovskite solar cell is arguably its Achilles’ heel’up to the end).

Task 1. *Find words/expressions meaning the following:*

1. a written promise by a company that, if you find a fault in something they have sold you within a certain time, they will repair it or replace it free of charge;
2. to make it difficult to do what one is trying to do;
3. a successful way of dealing with a problem;
4. connected;
5. to use something to one’s advantage;
6. to increase
7. sudden and complete change or reversal of policy, opinion, or of a situation;
8. coordinated;

Task 2. *Answer the following questions:*

1. What causes perovskite solar cell degradation?
2. How were they made to last longer?
3. How did slicon solar cells cope with the problem?
4. Why cannot this method be applied to perovskite cells?
5. What is cadmium telluride panels great drawback?
6. Why did people feel apprehensive about them?
7. Why might the efficiency numbers for perovskite cells seem bigger than they really are?
8. What is the way out?
9. How can companies profit by perovskite cells, considering small economy due to installation costs?
10. How are tandem solar cells created?
11. What makes them so good?
12. What are the other uses of perovskites?
13. Does the phrase ‘Perovskites make scientists feel like children in a candy shop’ mean that scientists are very fond of candy? Why? Why not?

15. 2D OR NOT 2D

A wave of innovative flat materials is following in the wake of graphene – but the most exciting applications could come from stacking them into 3D devices.

By Elizabeth Gibney

Physicists have used almost every superlative they can think of to describe graphene. This gossamer, one-atom-thick sheet of carbon is flexible, transparent, stronger than steel, more conductive than ш copper and so thin that it is effectively two-dimensional (2D). No sooner was it isolated in 2004 than it became an obsession for researchers around the world.

But not for Andras Kis. As miraculous as graphene was, says Kis, "I felt there had to be more than carbon." So in 2008, when he got the chance to start his own research group in nanoscale electronics at the Swiss Federal Institute of Technology in Lausanne (EPFL), Kis focused his efforts on a class of super-flat materials that had been languishing in graphene's shadow.

These materials had an ungainly name – transition-metal dichalcogenides (TMDCs) – but a 2D form that was quite simple. A single sheet of transition-metal atoms such as molybdenum or tungsten was sandwiched between equally thin layers of chalcogens: elements, such as sulfur and selenium, that lie below oxygen in the periodic table. TMDCs were almost as thin, transparent and flexible as graphene, says Kis, but "somehow they got a reputation as not that interesting. I thought they deserved a second chance."

He was right. Work by his team and a handful of others soon showed that different combinations of the basic ingredients could produce TMDCs with a wide range of electronic and optical properties. Unlike graphene, for example, many TMDCs are semiconductors, meaning that they have the potential to be made into molecular-scale digital processors that are much more energy efficient than anything possible with silicon.

Within a few years, laboratories around the world had joined the 2D quest. “At first it was one, then two or three, and suddenly it became whole zoo of 2D materials,” says Kis. From a scattering ofpublications in 2008, 2D TMDCs alone now generate six publications each day. Physicists think that there may be around 500 2D materials, including not just graphene and TMDCs, but also single layers of metal oxides, and single-element materials such as silicene and phosphorene. “If you want a 2D material with a given set of properties,” says Jonathan Coleman, a physicist at Trinity College Dublin, “you will find one.”

Ironically, one of the most exciting frontiers in 2D materials is stacking them into structures that are still very thin, but definitely 3D. properties of each. By taking advantage of the vastly different properties ofvarious super-flat materials, it should be possible to build entire digital circuits out of atomically thick components, creating previously unimagined devices. Applications are already being touted in fields from energy harvesting to quantum communications – even though physicists are just beginning to learn the materials’ potential.

“Each one is like a Lego brick,” says Kis. “If you put them together, maybe you can build something completely new.”

Adventures in flatland

A material that is just a few atoms thick can have very different fundamental properties from a material made of the same molecules in solid form. “Even if the bulk material is an old one, if you can get it into 2D form it opens up new opportunities,” says Yuanbo Zhang, an experimental condensed-matter physicist at Fudan University in Shanghai, China.

Carbon is the classic example, as physicists Andre Geim and Konstantin Novoselov found in 2004 when they first reported isolating graphene1 in their laboratory at the University of Manchester, UK. Their technique was almost absurdly simple. The basic step is to press a strip of sticky tape onto a flake of graphite, then peel it off, bringing with it a few of the atom-thick layers that make up the bulk material. By repeating this process until they had single layers – which many theorists had said could not exist in isolation – Geim and Novoselov were able to start investigating graphene's remarkable properties. Their work won them the 2010 Nobel Prize in Physics.

Physicists were soon hurrying to exploit those properties for applications ranging from flexible screens to energy storage (see page 268). Unfortunately, graphene proved to be a poor fit for digital electronics. The ideal material for that application is a semiconductor – a material that does not conduct electricity unless its electrons are boosted with a certain amount of energy from heat, light or an external voltage. The amount of energy needed varies with the material, and is known as the band gap. Turning the material's conductivity on and off creates the 1s and 0s of the digital world. But graphene in its pure form does not have a band gap – it conducts all the time.

Still, Geim and Novoselov's success in making graphene spurred them, Kis and many others to start investigating alternative 2D materials that could have a band gaps2. They began with TMDCs, which had been studied in bulk form since the 1960s. By 2010, Kis's team had built its first single-layer transistor3 from the TMDC molybdenum disulfide (MoS2; see 'Flat-pack assembly'), speculating that such devices could one day offer flexible electronics whose small component size and low voltage requirements would mean that they consumed much less power than conventional silicon transistors. Being semiconducting was not their only advantage. Studies in 2010 showed that MoS2 could both absorb and emit light 4,5 efficiently, making it – and probably other TMDCs – attractive for use in solar cells and photodetectors.

A single layer of TMDCs can capture more than 10% of incoming photons, an incredible figure for a material three atoms thick, says Bernhard Urbaszek, a physicist at the Physics and Chemistry of NanoObjects Laboratory in Toulouse, France. This also helps them in another task: converting light into electricity. When an incoming photon hits the three-layer crystal, it boosts an electron past the band gap, allowing it to move through an external circuit. Each freed electron leaves behind a kind of empty space in the crystal – a positively charged 'hole' where an electron ought to be. Apply a voltage, and these holes and electrons circulate in opposite directions to produce a net flow of electric current.

This process can also be reversed to turn electricity into light. If electrons and holes are injected into the TMDC from an outside circuit; when they meet, they recombine and give up their energy as photons.

This ability to convert light to electricity and vice versa makes TMDCs promising candidates for applications that involve transmitting information using light, as well as for use in tiny, low-power light sources and even lasers. This year, four different teams demonstrated the ultimate control over light emission, showing that the TMDC tungsten diselenide (WSe2) could absorb and release individual photons6-9. Quantum cryptography and communications, which encode information in one photon at a time, need emitters like this, where you "press a button and get a photon now", says Urbaszek. Existing single-photon emitters are often made of bulk semiconductors, but 2D materials could prove smaller and easier to integrate with other devices. Their emitters are necessarily on the surface, which could also make them more efficient and easier to control.

Even as researchers were getting to grips with TMDCs, theorists were seeking other materials that could be engineered in two dimensions. One obvious candidate was silicon, which sits right below carbon in the periodic table, forms chemical bonds in a similar way, has a natural band gap and is already widely used in the electronics industry. Calculations suggested that, unlike graphene, a sheet of atomically thick silicon would have a ridged structure that could be squashed and stretched to create a tunable band gap. But like graphene, this ‘silicene’ would be a much faster conductor of electrons than most TMDCs.

Unfortunately, theory also suggested that a 2D sheet of silicene would be highly reactive and completely unstable in air. Nor could it be ripped from a crystal like other 2D materials: natural silicon exists only in a 3D form analogous to a diamond crystal, with nothing resembling the layered sheets of carbon found in graphite.

“People said it was insane and would never work,” says Guy Le Lay, a physicist at Aix-Marseille University in France. But Le Lay, who had been growing metals on silicon surfaces for years, saw a way to make silicene by doing the reverse – growing atomically thin sheets of silicon on metal. And in 2012 he reported success10: he had grown layers of silicene on silver, which has an atomic structure that matches the 2D material perfectly (see Nature 495, 152-153; 2013).

Buoyed by that effort, Le Lay and others have since moved down the carbon column of the periodic table. Last year, he demonstrated a similar technique to grow a 2D mesh of germanium atoms – germanene – on a substrate of gold11. His next target is stanene: a 2D lattice of tin atoms. Stanene should have a band gap larger than either silicene and germanene, which would allow its devices to work at higher temperatures and voltages. And it is predicted to carry charges only on its outside edges, so it should conduct with super efficiency. But Le Lay has competition. Although no one has yet reported growing stanene successfully, research groups in China are rumoured to be close.

Elemental shift

Others are exploring different parts of the periodic table. Zhang’s team and another led by Peide Ye at Purdue University in West Lafayette, Indiana, last year described12,13 stripping 2D layers of phosphorene from black phosphorus, a bulk form of the element that has been studied for a century. Like graphene, phosphorene conducts electrons swiftly. But unlike graphene, it has a natural band gap – and it is more stable than silicene.

Phosphorene has enjoyed a meteoric rise. At the 2013 meeting of the American Physical Society, it was the subject of a single talk by members of Zhang's group; by 2015, the meeting had three entire sessions devoted to it. But like its fellow pure-element 2D materials, phosphorene reacts very strongly with oxygen and water. If it is to last longer than a few hours, it needs to be sandwiched between layers of other materials. This natural instability makes fabricating devices with the 'enes' difficult; Le Lay estimates that around 80% of the papers about them are still theoretical.

Nonetheless, both Zhang and Ye succeeded in making phosphorene transistors. This year, the first transistor from silicene emerged14,

Flat-pack assembly

Transition-metal dichalcogenide (TMDC) crystals contain one transition-metal atom (green) for every two chalcogen atoms (orange). Some 40 such TMDCs – mostly those made with the metals highlighted in dark green in the periodic table – can be split into 2D layers that are flexible, transparent and excellent conductors of electricity. Some are also semiconductors.

Chemical bonds link metal atoms and chalcogens into a strong, flat sheet just although it survived for only a few minutes. Still, Le Lay is optimistic that these issues are not insurmountable. Just two years ago, he points out, Geim and other physicists were saying that a silicene transistor could not be made with current technology. "So it's always dangerous to predict the future" laughs Le Lay.

The next dimension

Even as some physicists search for new 2D materials and try to understand their properties, others are already sandwiching them together. “Instead of trying to pick one and say this is the best, maybe the best thing to do is to combine them in such a way that all their different advantages are properly utilized" says Kis.

This could mean stacking components made of different 2D materials to make tiny, dense 3D circuits. Materials could also be layered inside components – something that chip designers already do when they grow layers of different semiconductors on top of one another to make devices such as the lasers inside DVD players. In standard devices, this is tricky: each layer has to chemically bond with the next, and only certain combinations can be matched. Otherwise, the strain between the different crystal lattices in each layer makes bonding impossible. With 2D materials, that problem goes away: the atoms in each layer bond only very weakly to the neighbouring sheets, so the strain is minimal. Many layers of semiconductors, insulators and conductors can be stacked to form complex devices known generically as van der Waals heterostructures, after the weak bonds that bind the layers.

Already, for example, graphene has been used alongside MoS2 and WSe2 to create the junctions at the heart of solar cells* 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 and photodetectors16, exploiting the semiconductor’s abilities to absorb photons and graphene’s swift ability to carry the freed electrons away. In February this year, N ovoselov and his team reversed the solar-cell concept to make a light-emitting diode17 from MoS2 and other TMDCs between graphene electrodes. By selecting different TMDCs, the team could choose the wavelength of the photons released.

Better still, sandwiching together different 2D layers can allow physicists to fine-tune their devices. Although the bonds between layers are weak, the close proximity of their atoms means that they can affect each other’s properties in subtle ways, says Wang Yao, a physicist at the University of Hong Kong. Stacking order, spacing and orientation all control device behaviour. “Modelling this gives theorists like me a headache, but the new physical properties are definitely there" says Yao.

Even graphene can get a leg up from other 2D materials, says Marco Polini, a physicist at the National Enterprise for Nanoscience and Nanotechnology (NEST) in Pisa, Italy. His team has been working on devices in which graphene is sandwiched between 2D layers of the insulator boron nitride18. When laser light is focused on the device, it gets compressed and channelled through the graphene layer, much more than in devices that sandwich graphene between bulk materials. In principle, this could provide a way for information to be carried between chips using photons rather than electricity. That, says Polini, could mean faster and more efficient communications within the chips.

Practical predictions

The current buzz around 2D materials is reminiscent of the excitement about graphene in 2005, says physicist Jari Kinaret of Chalmers University of Technology in Gothenburg, Sweden, who heads the European Unions Graphene Flagship – a programme that also studies other 2D materials. But Kinaret cautions that it could take two decades to really assess the potential ofthese materials. “The initial studies on 2D materials are focusing a lot on their electronic properties, because these are close to physicists’ hearts" says Kinaret. “But I think that the applications, if and when they come, are likely to be in a completely unpredicted area"

Materials that look good in the lab are not always those that make it out into the real world. One major issue facing all 2D materials is how to produce uniform, defect-free layers cheaply. The sticky-tape method works well for TMDCs and phosphorene, but is too time-consuming to scale up. It is also expensive to make bulk black phosphorus, because it involves subjecting naturally occurring white phosphorus to extreme pressure. No one has yet perfected the process of growing single sheets of 2D materials from scratch, let alone the layered structures that physicists find so promising. “It took a long time to make our heterostructures" says Xiaodong Xu, a physicist at the University of Washington in Seattle. “How can we speed that up or make it automatic? There is a lot of work to do.”

Such practical considerations could prevent 2D materials from living up to their early promise. “There have been many rushes like this, and some have turned out to be fads," says Kis. “But I think the sheer number of materials and different properties should make sure something comes out of this" Meanwhile, the zoo is expanding, says Coleman. Arsenene, a heavier cousin to phosphorene, is already on researcher’s minds.

“As people start to branch out, they are discovering new materials that have these wonderful properties," says Coleman. “The most exciting 2D material is probably that hasn’t been made yet

Tasks. Part 1 (up to ‘Buoyed by that effort’).

Task 1. *Find words/expressions meaning the following:*

1. very surprising and unexpected;
2. losing or diminishing in strength energy;
3. awkward or clumsy;
4. to try to sell something or convince people that it is good;
5. worthy of attention; striking;
6. capable of bending easily without breaking;
7. to take into one's possession or control by force;
8. to include;
9. to allow or enable to escape from confinement; set free;
10. to deal with (a problem or subject);
11. crush or squeeze (something) with force so that it becomes flat, soft, or out of shape;
12. to look like;
13. firmly press (something soft or yielding.

Task 2. *Say whether the following is true, false or not mentioned:*

1. A Swiss physicist concentrated on a class of 2D materials as they were very popular.
2. They had the same properties as graphene so he decided they are worth paying more attention to.
3. TMDCs-based electronic devices may be far more economical than their silicon counterparts.
4. TMDCs form two dimensional networks that are only one atomic layer thick.
5. Whether the basic 3D material is old or not, its 2D analogue properties differ greatly.
6. Graphene is especially suitable for digital electronics.
7. Since the ideal material for digital electronics is semiconductors, silicon nanosheets are particularly interesting because today's information technology builds on silicon.
8. TMDC MoS2 devices could have tiny elements and be very economical.
9. TMDCs can convert light to electricity, this being a one way process.
10. A silicon nanosheet can be given almlost any shape to make a changeable forbidden zone.
11. As silicene 2D sheets are highly unstable a French physicist invented a way to grow silion nanosheets on metal.

Task 3. *Answer the following questions:*

1. Why wasn’t Kis impressed with graphene?
2. What did TMDCs have in common with graphene?
3. What’s the difference between TMDCs and graphene ?
4. Are graphene and TMDCs the only classes of 2D materials? (Prove!)
5. Why is it so important to be able to make 3D structures out of 2D materials?
6. What prevents graphene from being used in digital electronics?

7. What is a forbidden zone?
8. How is light converted into electricity?
9. Is the opposite process possible? Why? Why not?
10. Why cannot silicene be used in electronics?
11. What was the way out?
12. What does phosphorene differ from graphene in?
13. How are 2D materials used?
14. What can this usage lead to?
15. What is an important problem all 2D materials face?

Tasks. Part 2 (from 'Buoyed by that effort' up to the end).

Task 1. *Find words/expressions meaning the following*:

1. to pass around or circulate as unverified information;
2. to continue for a specified period of time;
3. too great to be overcome;
4. not immediately obvious or noticeable;
5. to get support;
6. an atmosphere of excitement and activity;
7. to find inroads into;
8. to expand or extend one's interests.

Task 2. *Say whether the following is true, false or not mentioned*:

1. Stanene is as good as silicone and germanene.
2. Le Lay is the only one to try to grow stanene.
3. Combining silicon nanosheets and a polymer scientists get a composite material that is both UV-resistant and easy to process.
4. As phosphorene and the likes are naturally unstable, they are hard to produce.
5. Le Lay has no doubt these problems can be addressed.
6. Combining parts made of 2D materials can result in minute 3D circuits.

7. Scientists managed to make the solar cell concept work the other way and created an LED from MoS2 and other TMDCs between graphene electrodes.
8. In the LED the wavelength of the photons released depends on the material selected.
9. Sandwiching graphene between bulk material may lead to a new kind of devices where information is carried by light
10. Kinaret implies that 2D materials may have properties we do not suspect of.
11. Materials which are promising under laboratory conditions usually exhibit good properties in real life.
12. For practical reasons 2D materials may not live up to scientists' expectations.

Task 3. *Answer the following questions*:

1. What technique was used to grow on a substrate of gold?
2. Why is stanene supposed to be better than germanene or silicene?
3. What is a common drawback of all 2D materials?
4. How does Le Lay feel about the problems facing TMDCs?
5. What arguments does he give to support his opinion?
6. What's the point of combining several 2D materials?
7. What does devices behavior depend on?
8. How can graphene gain from being combined with other 2D materials?
9. What is a great obstacle in the way of 2D materials?
10. How do you understand the phrase "Meanwhile, the zoo is expanding"?

CONTENTS

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АКАДЕМИЧЕСКАЯ И ПРОФЕССИОНАЛЬНАЯ КОММУНИКАЦИЯ НА ИНОСТРАННОМ ЯЗЫКЕ
English Reader for Students of Nanophysics

Учебное пособие

Издается в авторской редакции
Техническая подготовка материалов: *Л. Н. Голубцова*

Подписано к использованию 03.12.2018
Объем данных – 5 Мб

Размещено в открытом доступе
на сайте www.psu.ru
в разделе НАУКА / Электронные публикации
и в электронной мультимедийной библиотеке ELiS

Издательский центр
Пермского государственного
национального исследовательского университета
614990, г. Пермь, ул. Букирева, 15