Nanoelectronics

Jessamyn Fairfield explains how nanomaterials obey fundamentally different physical laws than bulk materials and why this offers up a host of exciting future applications.

physicsworld Discovery

Nanoelectronics

Nanoelectronics

Jessamyn A Fairfield
National University of Ireland, Galway, Republic of Ireland

IOP Publishing

ISBN 978-0-7503-1568-5 (ebook)

DOI 10.1088/978-0-7503-1568-5

Version: 20180301

Physics World Discovery
ISSN 2399-2891 (online)

British Library Cataloguing-in-Publication Data: A catalogue record for this book is available from the British Library.

Published by IOP Publishing, wholly owned by The Institute of Physics, London

IOP Publishing, Temple Circus, Temple Way, Bristol, BS1 6HG, UK

US Office: IOP Publishing, Inc., 190 North Independence Mall West, Suite 601, Philadelphia, PA 19106, USA

To my father Eric Fairfield,
who taught me how to think and write about science.

Contents

Abstract

Nanomaterials are changing the world we live in, and one of the most exciting applications they can have is the creation of new electronic devices. But what are they, how can we build devices from them, and how can nanoelectronics give us new ways to interact with light, our environments and even our brains? This ebook will explore the unique physics of different types of nanomaterials, and lay out different devices that harness this unique physics to create optoelectronic components, chemical sensors, and novel paradigms for memory and computing. After outlining the current state of the art, the final section looks to grand challenges and opportunities in nanoelectronics.

Author biography

Jessamyn A Fairfield

Jessamyn A Fairfield is a lecturer in the School of Physics at the National University of Ireland Galway. She received her bachelor's degree from the University of California Berkeley (2005) and her PhD in physics from the University of Pennsylvania (2011), completing her postdoctoral research at Trinity College Dublin. Her research is focused on electronic devices made from nanowires and nanocrystals that emulate synaptic behaviour, for incorporation into medical implants and interfaces. In addition to research and teaching, she is a writer, comedian and public speaker. She runs Bright Club in Ireland, the research and comedy variety night, and appears frequently on the radio talking about science.

Nanoelectronics

Jessamyn A Fairfield

1 Introduction

What is a nanomaterial? Nanomaterials are defined as having at least one dimension on the nanoscale, of size less than a thousand nanometres. Materials at this scale have properties that are significantly different than bulk materials, due to physical effects such as quantum confinement that only occur at low length scales. Many naturally occurring materials contain nanoscale structures, such as bone, shell and butterfly wings. These structures can lead to fascinating and beautiful interactions with light, as seen in figure 1 for butterfly wings imaged using optical and electron microscopy. While nanostructured materials are mechanically interesting and can be used to make hydrophobic coatings and structural colour, the electronic properties of these materials are especially intriguing and are the focus of this book.

When the size of a nanomaterial shrinks below a certain point, changes in its electrical and optical properties arise due to quantum confinement. This happens when the diameter of a material is smaller than the de Broglie wavelength for electrons in that material, leading to shifts in the electronic band structure. The atomic levels of the material change, becoming quantized and also changing the wavelengths at which light is absorbed or emitted.

These nanoscale effects have high relevance for electronic applications. Quantum confinement and interface effects lead to nanoscale systems where dominant modes of conduction can include thermionic, tunnelling, hopping, space charge limited conduction, and blockades and resonant effects also often play a role. Tunability of the electronic response of a material based on size, and the sensitivity of these materials to both light and other stimuli, have enabled many applications such as solar cells, sensors, memory devices, water purification, and novel forms of logic and computation.

Nanomaterials can demonstrate quantum confinement in one, two or all three spatial dimensions. Depending on the degree of confinement, this can result in materials that are effectively two-dimensional, one-dimensional or even zero-dimensional. We will first discuss these types of nanomaterials, how they can be synthesized, and their unique advantages and disadvantages.

doi:10.1088/978-0-7503-1568-5

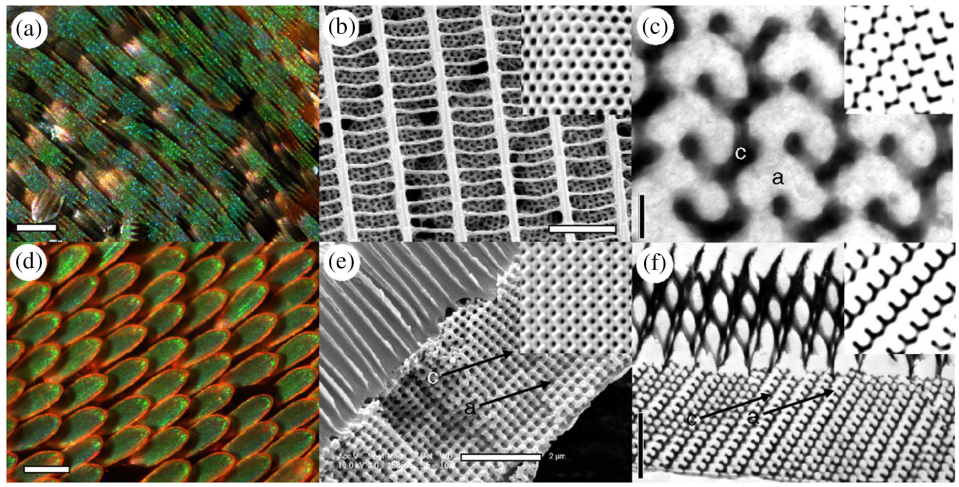

Figure 1. Structural colour-producing nanostructure in lycaenid (a)–(c) and papilionid (d)–(f) butterflies. (a) and (d) are optical images, while (b) and (c), (e) and (f) are electron micrographs. Reproduced with permission from Saranathan V *et al* 2010 *Proc. Natl Acad. Sci.* 107 11676–81. Copyright 2010 Proceedings of the National Academy of Science.

2 Background

Zero-dimensional materials

Nanomaterials confined in all three dimensions are called nanoparticles, and if they retain their crystal structure they are called nanocrystals. The spatial confinement of electronic states leads to modifications in band structure and energy levels that are unique to nanoparticles. Although these particles have only been well understood in recent decades, their use in artistic pursuits is ancient. Metal nanoparticles were used to lend colour to glass, as in the Lycurgus Cup crafted in Rome during the 4th Century which is green when light is shone on the cup from outside and reflected back (reflective light) but red when illuminated from within or behind (transmitted light), a phenomenon known as the dichroic effect. Many stained-glass windows also incorporate metal nanoparticles, whose free electrons have a resonant interaction with incident light at certain wavelengths (more on this later).

Controllable and reproducible synthesis of nanocrystals can be achieved either via a 'top-down' method of carving nanocrystals out of larger bulk materials, or a 'bottom-up' method of chemical assembly one atom at a time. Top-down methods include lithography and electrical migration, but these can have major problems with surface roughness and distortion of the crystal lattice. There are many bottom-up methods to create nanocrystals, including chemical synthesis, vapour deposition and sol–gel methods. Some of these synthesis methods may deposit a layer on the surface of the synthesized nanomaterials, which often acts as a passivation layer preventing further aggregation and helping to keep the nanoparticles in colloidal suspension. The passivation layer is chemically useful and can be tuned to enhance the chemical functionalization of the nanomaterial, adding sensitivity to specific

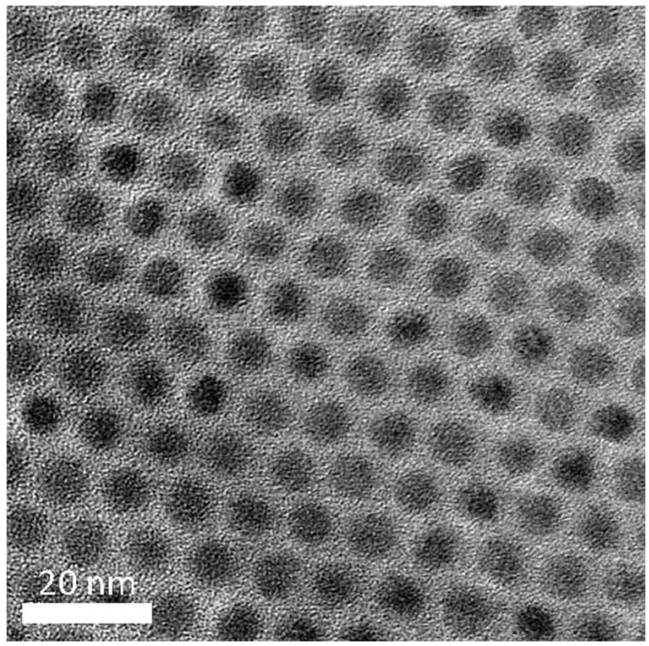

Figure 2. Transmission electron micrograph of lead telluride nanocrystals in an array, where the nanocrystals appear dark. Adapted with permission from Ko D K, Urban J J and Murray C B 2010 *Nano Lett.* **10** 1842–7. Copyright 2010 American Chemical Society.

molecules. However, the passivation layer can also act as a significant barrier to charge transfer. Figure 2 shows nanocrystals which have self-assembled into an array imaged using transmission electron microscopy, where each individual nanocrystal appears dark. Some nanocrystals appear darker than others because their crystal lattices have differing orientations in the film.

The unique traits of nanocrystals enable many useful applications. The wavelength selectivity of nanocrystals makes them excellent optical tags for biological studies. Nanocrystals are small enough to enter cells and subcellular processes, and can then be stimulated to fluoresce by external light. They can also be used to convert light to electricity or vice versa as light emitting diodes, lasers or solar cells.

One-dimensional materials

Nanomaterials confined in two of the three spatial dimensions retain some quantized properties but also have a bulk dimension. One example is nanowires. These structures can be comprised of metals, semiconductors, insulators or even polymers or other organic materials. How they are fabricated is strongly material dependent, but similar to nanoparticles, nanowires can either be defined via a top-down lithographic process or assembled in a bottom-up process. Chemical synthesis, vapour–liquid–solid deposition and chemical vapour deposition are the most common bottom-up methods for synthesis. Similar to nanocrystal synthesis, many

of these nanowire synthesis methods can deposit a surface passivation layer which affects both the chemical and electronic properties of the nanowires.

In addition to nanowires, which are effectively bulk crystals that are nanoscale along two axes and macroscale along one axis, another form of one-dimensional nanostructure is the carbon nanotube. Carbon nanotubes, which had been demonstrated several times in the literature but took off after Sumio Iijima's seminal paper in 1991, consist of a sheet of hexagonally bonded carbon rolled up into a hollow cylinder. Single-walled carbon nanotubes have only a single layer, and multi-walled carbon nanotubes (which are considerably easier to synthesize) have multiple nested layers of carbon. Nanotubes can be created via several bottom-up processes, such as arc discharge, chemical vapour deposition and high-pressure carbon monoxide disproportionation. The sp^2 bonding structure of carbon nanotubes results in extraordinary mechanical strength and high thermal conductivity. Electrically, carbon nanotubes can be either metallic or semiconducting along the tubular axis, depending on the angle of the crystal lattice with respect to that axis. Because of confinement in two dimensions, they exhibit ballistic conduction which leads to very high current densities. Nanotube type can be determined spectroscopically, by examining the fluorescence and Raman signature of the nanotubes. Control of nanotube type has been a major focus of research, but there are currently many industrially available high-quality nanotubes of various types, and they are making their way into more and more applications.

One-dimensional nanostructures such as nanotubes and nanowires are useful for a variety of applications, such as adding mechanical strength to composites. They can also be used as photonic waveguides and collectors in optoelectronic generators and collectors. However, they are extremely interesting as electrical components. Nanowires and nanotubes can be individually contacted electrically to create circuit elements that can be used to probe basic transport physics in a single dimension. They can also be combined to act as networks of elements, exploring percolation thresholds and network topology as they relate to conductivity. A network of nanowires that has been electrically contacted is shown in a scanning electron micrograph in figure 3. Since the image was taken using charge carriers, the technique of passive voltage contrast causes the nanowires connected to ground and the probes to appear dark, highlighting the exact current path through the material. Because one-dimensional nanostructures such as nanowires and nanotubes have one non-confined axis, they provide better conductivity than nanocrystal-based networks, although somewhat less optical tunability.

Two-dimensional materials

Nanomaterials confined in only one spatial dimension are sheet-like structures that are effectively two-dimensional. Graphene, a sheet of hexagonally bonded carbon, was the first two-dimensional nanomaterial to emerge, having been accidentally produced for decades before being officially 'discovered' in 2004 by Andre Geim and Konstantin Novoselov. The crystal lattice structure of graphene is shown in figure 4. A slew of other two-dimensional nanomaterials have now emerged, based on

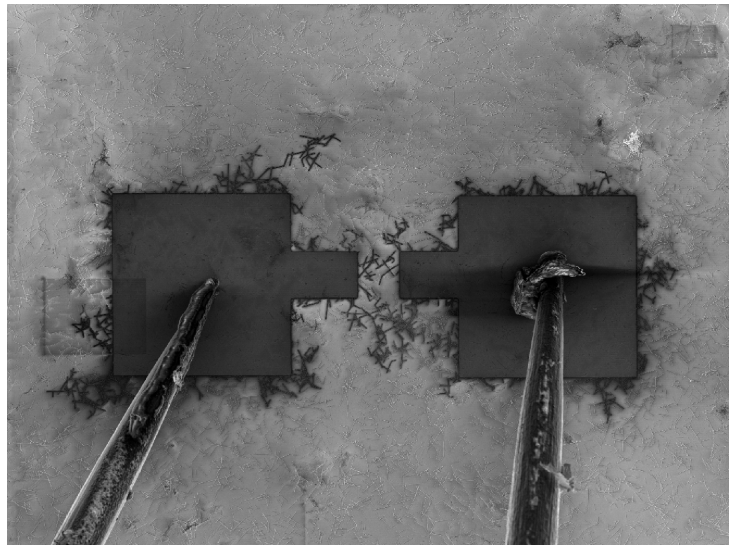

Figure 3. A network of silver nanowires contacted by two electrodes and probes on the left and right of the image. Passive voltage contrast is used in this scanning electron micrograph to show electrical conductivity through the centre of the nanowire network.

materials such as molybdenum disulphide (MoS_2), molybdenum diselenide ($MoSe_2$), silicon (Si), germanium (Ge) and boron nitride (BN). Although these materials are effectively two-dimensional, they can also be deformed or functionalized in the third dimension.

Graphene has a very high mechanical strength, much like carbon nanotubes, as well as good thermal conductivity and a high resistance to gas transfer through its confined axis. Electrically, it has a very unusual band structure, acting as a gapless semiconductor with very high electron mobility but no gap between the conduction and valence bands, and hence limited optical response. Other two-dimensional materials have bandgaps, enabling optical interactions, but lower electrical conductivity.

These materials can be produced using a variety of methods, such as exfoliation from bulk, chemical vapour deposition, and sonication and centrifugation in suspension. Many are optically transparent and thus useful for transparent conductor applications such as graphical displays. They can also be combined into layered composites, with other two-dimensional materials or with one- or zero-dimensional nanostructures to exploit the properties of each. Each dimensionality has distinct features, but they all obey different physical laws due to their nanoscale.

3 Current directions

Harnessing light

The unique band structure of many semiconducting nanomaterials can lead to interesting interactions between light and charge carriers in the material. A photon incident on a material with a bandgap can lead to the excitation of an electron–hole

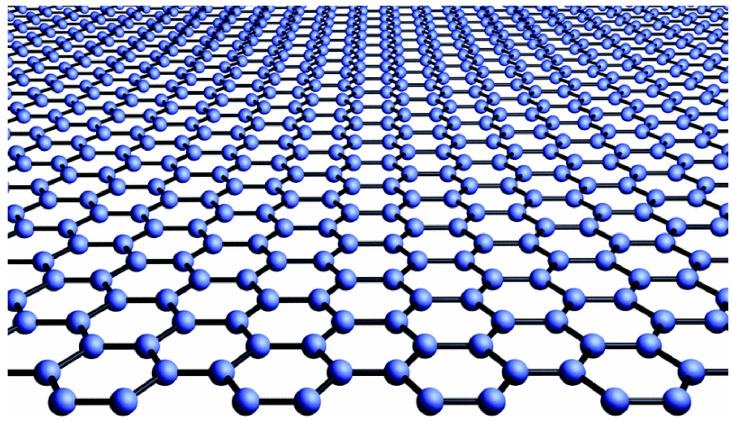

Figure 4. Hexagonal crystal lattice structure of graphene. Reproduced with permission from Novoselov K S 2011 *Rev. Mod. Phys.* **83** 837–49. Copyright 2011 American Physical Society.

pair, depending on the wavelength of the photon and the energy value of the bandgap. Once these charge carriers have been generated in the material, they must be transported through it to a part of the device that can collect and measure charge carriers in order to contribute to photocurrent for the device. A similar process happens in reverse when current is injected, which can result in photons being emitted from the nanomaterial. If photogenerated electron–hole pairs are not separated from each other quickly enough, they will drift diffusively until they recombine, which can happen on the scale of picoseconds in a nanoscale material. Hence, field-driven transport away from the site of charge generation is very important in semiconducting optoelectronic nanomaterials.

In metallic nanostructures a different yet equally interesting light–matter interaction occurs, if the wavelength of incident light induces a resonant oscillation in free charge carriers within the nanomaterial. This resonance induces quantized plasma oscillations in the carriers, called 'localized surface plasmon resonance'. It can result in a strongly enhanced electric field around the nanostructure, especially if there is a sharp edge or point to the nanostructure. The exact wavelength of light that induces this effect depends on the size of the nanostructure and the material, but it is a common feature of metallic nanomaterials that can be used to enhance electric field and hence current extraction. Surface plasmon resonance can also be used to enhance the signal from light-based techniques such as Raman spectroscopy, leading to surface-enhanced Raman spectroscopy, a useful tool for detecting even single molecule spectroscopic signatures.

The exact size of the nanomaterial is critical to optoelectronic effects in both semiconducting and metallic nanocrystals. The direct correlation between nanocrystal size and the wavelengths at which light can be absorbed, emitted or resonant means that tuning the nanocrystal size also tunes nanocrystal electronic properties. So for example, when chemically synthesizing cadmium selenide (CdSe) nanocrystals, stopping the reaction earlier leads to a smaller nanocrystal which emits higher

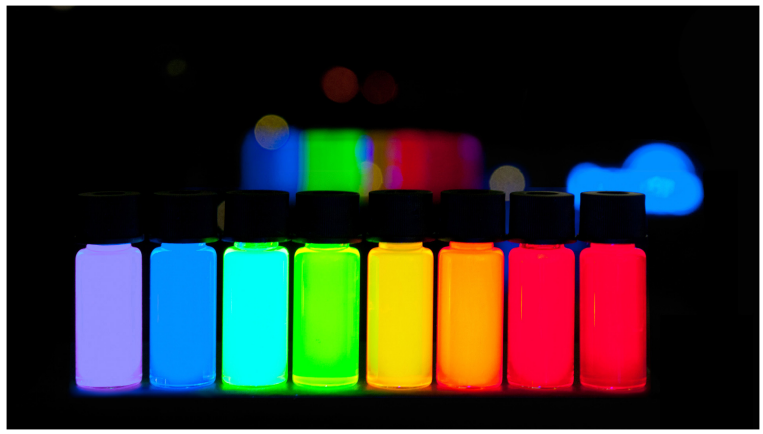

Figure 5. CdSe/zinc sulphide nanocrystals fluorescing in different colours based on their size. Smallest nanocrystals are on the left. CC BY-SA 3.0/Antipoff.

frequency, bluer light. Nanocrystals can hence either be selected for specific wavelength response or combined to yield controllable spectra, as shown in figure 5.

Nanocrystals are sometimes called 'artificial atoms' because the wavelength selectivity of their response is similar to that of single atoms. However, since nanocrystals are quasi-bulk materials, they have many more phonon interactions than single atoms can. This leads to the Stokes shift, which is the difference in wavelength between the absorption and emission wavelengths of a nanocrystal. Some loss of energy occurs to lattice vibrations, meaning the emission wavelength will always be slightly redder than the absorption wavelength. However, this loss is relatively small, and the unique light–electron interactions in nanomaterials have led to their widespread adoption in many optoelectronic applications, such as solar cells and light-emitting diodes.

While the light-sensitive nanowires described above can be assembled into arrays and thin films, it is also possible for individual nanowires and nanocrystals to have a multi-part structure. Core–shell nanostructures have different chemical composition in their interior than at their surface, which can add to quantum confinement or help mediate interactions with the environment. For example, the CdSe nanocrystals described above can be coated with a shell of another material, such as zinc sulphide (ZnS). CdSe/ZnS nanocrystals are very useful in optoelectronic devices with electrical contacts, made of elements such as gold, whose work function is closer to the bandgap of ZnS than CdSe. Additionally, core–shell nanostructures can be sintered together to improve electrical conduction without losing strong quantum confinement, which still exists as long as the nanocrystal cores are kept separate. Nanostructures can also have differing composition in different segments, e.g. striped nanowires with segments of different materials, or nanoscale tetrapods which may have a core of one material and four protruding legs made of another. These heterogeneous nanomaterials provide a means to make nanoscale p–n junctions and other circuits to enhance charge transport before carriers recombine.

Indeed, it is often the transport of photogenerated carriers that causes the biggest issue in nanoelectronics. The same quantum confinement that leads to wavelength selectivity in nanocrystals means that a charge carrier cannot be transported through a film of these nanocrystals without tunnelling through a large number of potential barriers. Conduction through a film of nanomaterials is similar to conduction through a large number of particles in a box, which means hopping-based transport that requires a high applied field for a relatively small extracted current. This issue can be addressed by coupling nanomaterials with poor conduction to other nanomaterials or a carrier material, such as a conducting polymer, which aids in charge carrier transport without affecting electron–hole generation.

Finally, periodic nanoscale structures can also lead to interaction with light for photonic crystals. Propagation of some frequencies of light can be forbidden in the band structure of these crystals, in one, two or three dimensions. Natural sources of structural colour, such as opalescent minerals, are effectively natural photonic crystals. But again, the source of the interaction is the similarity in size between the nanoscale structures and the wavelength of incident light. The butterfly wings shown in figure 1 are a form of naturally occurring photonic crystal, reflecting specific wavelengths of light and not others. Photonic crystals with nanoscale structure are used as thin-film optics, photonic crystal fibres and may eventually be used to implement all-optical computing.

Sensing the environment

In contrast to bulk materials, nanomaterials have a much larger surface area compared to their volume. This large number of surface states, and hence of dangling chemical bonds, makes nanomaterials very sensitive to their environment. Changes in the functionalization of the surface can cause nanomaterials to act as chemical sensors, whose electrical conductivity changes as molecules bind and unbind from the surface. If these changes are detectable by externally applied electrodes, a sensor can be built to measure variation in the behaviour of the nanomaterial. These effects can be similar to surface-enhanced Raman spectroscopy, as described above, but with a purely electrochemical effect rather than an optochemical effect.

One example of the use of surface states to perform chemical sensing with nanomaterials is an artificial nose based on graphene or carbon nanotubes, where the nanomaterial is functionalized with strands of DNA, electrically contacted and then used to detect chemicals in the environment, such as water, methanol and other compounds which affect the conductivity of the DNA-decorated nanomaterial when they bind to it. Volatile organic compounds related to food spoilage, nerve gas or the presence of explosives have been reliably detected using decorated nanotube sensors, as shown in figure 6. These can also be used to measure air quality or test biological fluids such as blood or urine for biomarkers. Graphene-based biosensors have been demonstrated using a field emission transistor geometry, where chemical binding to an exposed sheet of graphene modifies the conductivity in a buried conducting channel. These biosensors can be combined into an electronic assay, to give information about the quantity and binding of various chemical compounds in solution.

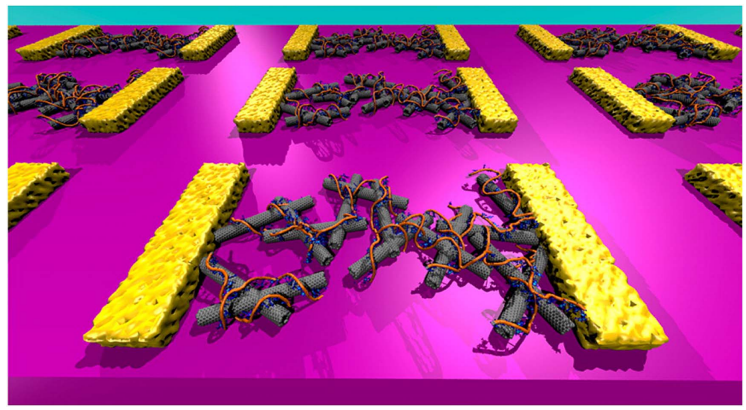

Figure 6. Vapour sensors based on functionalized carbon nanotubes. Reproduced with permission from Kybert N J, Lerner M B, Yodh J S, Preti G and Johnson A T C 2013 *ACS Nano* **7** 2800–7. Copyright 2013 American Chemical Society.

Direct electrical interaction with nanostructures can also yield important information about the local environment. There is currently intense interest in electrophoretic sequencing of DNA via translocation through a solid state nanopore, which can be created in silicon, graphene or other thin materials. These solid state nanopores emulate the very small biological pores which can be found in the lipid bilayer around cells and their nuclei. Macroelectrodes in solution on either side of a solid state nanopore drive an ionic current in the carrier solution through the nanopore. As the DNA passes through the nanopore, it physically blocks the ionic current through the nanopore, allowing detection of translocation events. Additional electrodes can be added across the nanopore to enhance sensitivity to DNA. While research in this area is ongoing, it is thought that noise in the electrical signal through the nanopore can eventually be lowered—by applying coatings, slowing translocation speeds and improving fabrication techniques—to enable base pair sensitivity for DNA sequencing.

Nanostructures are also increasingly being used to measure and interact electrically with biological tissue such as nerves and neurons. Nanomaterials have lower rigidity and feature sizes than their bulk counterparts, which are similar to those of biological materials. This minimizes the immune response that can occur when foreign objects are inserted into the brain. The current injection density of nanomaterials is also considerably lower than for traditional neural electrodes, reducing the risk of tissue damage due to excess current and power dissipation. Nanomaterials can either be used as coatings for traditional neural electrodes or as free-standing electrodes themselves, and excellent performance has been demonstrated from metallic, semiconducting and even polymer-based nanostructured neural electrodes. Three-dimensional nanoscale scaffolds have also been developed into which neurons can grow, providing both mechanical support and electrical sensing for neural cultures. While nanomaterials can sometimes be toxic to cells, a recent review of nanomaterial toxicity found it to be

highly material dependent, showing that nanomaterials can be selected for biocompatibility to develop safe and reliable biosensors.

Memory and computing

Traditional computers locate memory separately from processing, which leads to the so-called 'von Neumann bottleneck' where the speed at which information can be transferred from memory to processing and back again is a rate-limiting step for computation. Additionally, as the physical size of memory bits has shrunk, the importance of noise and nanoscale phenomena has grown correspondingly. Moore's law, a prediction made in 1965 that the number of transistors in an integrated circuit would double every two years, has basically ended due to the difficulty of nanoscale fabrication. While traditional computers have led to tremendous advances in computational ability and quality of life in recent decades, a computational paradigm based around the nanoscale could mean a new era of breakthroughs for our electronics and how we use them.

The stochastic nature of electronic devices made from nanomaterials initially appeared to be a problem to researchers. As discussed in previous sections, the high number of surface states on nanomaterials leads to a high sensitivity to surface chemical reactions, a large number of electronic trap states and hence an electrical conductivity that can be strongly affected by the surrounding environment as well as previous measurements. Nanoscale rearrangements in atomic structure, which would not noticeably affect the electronic properties of a macroscale solid, are all too evident in nanoscale materials, leading to issues with measurement reliability and logic operation reproducibility.

However, examination of the theoretical underpinnings of electronic components provides a different perspective on this innate nanoscale phenomenon. Introductory physics courses present three fundamental equations relating electrical phenomena in basic devices:

$$\mathrm{d}V = R\mathrm{d}I \tag{1}$$

$$\mathrm{d}Q = C\mathrm{d}V \tag{2}$$

$$\mathrm{d}\varphi = L\mathrm{d}I \tag{3}$$

These equations relate the voltage V, current I, flux φ and charge Q in a (1) resistor, (2) capacitor and (3) inductor—the three simple circuit elements covered in introductory electromagnetism. Current and charge, as well as flux and voltage, are subject to time relations as follows:

$$\mathrm{d}Q = I\mathrm{d}t \tag{4}$$

$$\mathrm{d}\varphi = V\mathrm{d}t \tag{5}$$

However, from a mathematical perspective, symmetry between these four variables would seem to imply that there should be a circuit element that relates flux to charge in some way. This missing element was first predicted in 1971 by Leon Chua, who called it the 'memristor' and posited that it should satisfy:

$$d\varphi = M\,dq \tag{6}$$

The memristor as Chua proposed would have a 'memristance', a resistance dependent on the flux history of the device. But although the mathematical foundations for the memristor were clear, the physical mechanisms that could lead to a real memristor were not. However, as electronic devices based on nanomaterials were developed, it became evident that memristance is a natural feature of nanoelectronics. Changes in surface functionalization, electronic trap state population and dopant concentration can all lead to conductivity which varies with device history, the hallmark of memristance.

The memristor was experimentally 'discovered' in a landmark 2008 paper by Dmitri Strukov and colleagues, which pointed out that memristance had already been observed in a variety of nanoscale physical systems, such as thin films of titanium dioxide. This research catalysed an avalanche of studies creating memristive devices in various transition metal oxides whose conductance can be tuned. The hallmark of memristance is a hysteresis loop in current–voltage measurements, as shown in figure 7.

Memristance is related to another nanoscale conduction effect, resistive switching. Resistive switching occurs in many transition metal oxides, where the field-induced motion of dopants does not occur uniformly but instead results in the formation of nanoscale conducting filaments through the oxide. Once formed, these filaments demonstrate Ohmic conduction, but can be ruptured at high current due to

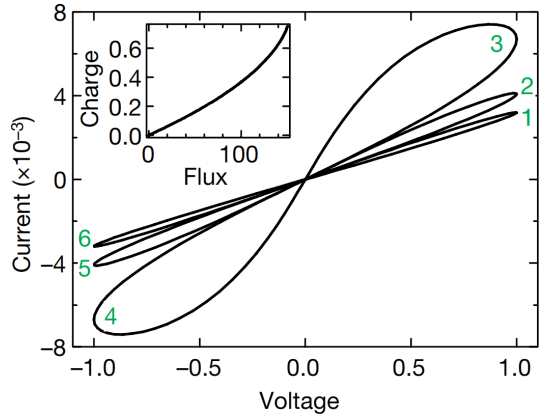

Figure 7. Simulated current–voltage curves for an ideal resistor. Reproduced with permission from Strukov D B, Snider G S, Stewart D R and Williams R S 2008 *Nature* **453** 80–3. Copyright 2008 Nature Publishing Group.

Joule heating. Post-rupture, most of the filament is still present and can be reformed, allowing the filament to act as a current-controlled switch between high and low resistive states. Resistive switches can have very high on/off ratios between resistive states, up to 10^5, and are reliable over a large number of switching cycles. However, the exact location of conducting filaments in the film is stochastically determined in most device geometries, and not easy to directly control.

Memristive behaviour, whether 'digital' as with resistive switching or 'analogue' as with dopant front motion in a semiconductor, can be used to implement random-access memory (RAM). Two-level and multi-level memories have been demonstrated with various materials, using the conductive state as a variable instead of spin as in traditional silicon-based RAM architectures. Nanoscale memristors can also be useful as the basis for 'stateful' computing and alternative logics, like material implication, which involve local storage of the memory state to perform calculations.

Perhaps the most promising potential application of nanoscale memristive devices is 'neuromorphic' computing, which aims to emulate the electrical behaviour of neurons and synapses. Neuromorphic devices can be implemented in thin film-, nanowire- and nanocrystal-based devices, to demonstrate synaptic timing dependence, long term potentiation and other basic neuroelectrical functions. These devices can then be networked, using either top-down fabrication or bottom-up assembly techniques, to create a large number of randomly arrayed nanoelectronic devices whose connections strengthen and weaken over time in response to external stimuli, which can be optical or electronic in nature. These fault-tolerant networks of nanoelectronics emulate the topology and connectivity of the brain more faithfully than traditional silicon-based neuromorphic devices can, which may lead to their superiority in brain-like computational tasks such as pattern recognition and associative memory. While this field is still relatively young, neuromorphic computing has the potential to take advantage of innate features of nanomaterials to construct electronics that exploit them to their full potential.

4 Outlook

Nanomaterials obey fundamentally different physical laws than bulk materials, experiencing quantum confinement and other non-bulk effects. They can be used to construct electronic devices that can produce or detect light, for solar cells or optical computing elements. Charge transfer in nanomaterial composites is full of energy barriers to transport, however, clever use of ligands and parallel conduction paths can help to address this issue. The high surface area of nanomaterials also makes them exquisite chemical sensors, able to respond electrically to adsorption of trace surface compounds, or integrated into bio-characterization systems such as nanopore sequencers. While the inherently stochastic nature of these materials prohibits their use in traditional computing architectures, they enable a whole range of memristive computation and logic operations. These tuneable nanoelectronic systems can be integrated with light and even biological environments, enabling electronic interfaces and controls.

From an industrial perspective, nanomaterials have already reached commercial use for their outstanding mechanical properties, yet implementation in electronic devices has been slower to develop. The complex landscape of electronic behaviour seen in nanomaterials has taken decades to understand. However, traits that were previously seen as roadblocks to industrial use—intrinsic memory, barriers to charge transport, reproducibility—are now informing unique approaches to nanoelectronic device design and entirely new applications. In coming decades we are likely to see nanomaterial-driven revolutions in light-based computing, gas sensing, DNA sequencing and bio-inspired computation. These revolutions will change our relationship with the world around us and ourselves, as surely as the silicon revolution has. As Herbert Kroemer said in his Nobel Prize acceptance speech in the year 2000: 'The principal applications of any sufficiently new and innovative technology always have been—and will continue to be—applications created by that technology'.

Additional resources

1. For an example of a naturally occuring nanostructure see: Saranathan V *et al* 2010 Structure, function, and self-assembly of single network gyroid (I4132) photonic crystals in butterfly wing scales *Proc. Natl. Acad. Sci.* **107** 11676–81.
2. Nanocrystals, their synthesis, and their use in solar cells are well described in this review: Garcia de Arguer F P, Armin A, Meredith P and Sargent E 2017 Solution-processed semiconductors for next-generation photodetectors *Nat. Rev. Mater.* **2** 16100.
3. Structural and electronic properties of nanowire heterostructures are covered in this review: Hyun J K, Zhang S, and Lauhon L J 2013 Nanowire heterostructures *Annu. Rev. Mater. Res.* **43** 451–79.
4. A full and accessible review of graphene and other 2D nanomaterials is given in Konstantin Novoselov's Nobel lecture: Novoselov K S 2011 Nobel lecture: graphene: materials in the flatland *Rev. Mod. Phys.* **83** 837–49.
5. For an overview of charge transport in nanoscale systems and its various mechanisms, this article is helpful: Thijssen J M and Van der Zant H S J 2008 Charge transport and single-electron effects in nanoscale systems *Phys. Status Solidi* b **245** 1455–70.
6. Surface plasmon resonance in nanomaterials and its possible applications are well described in this paper: Luther J M, Jain P K, Ewers T and Alivisatos A P 2011 Localized surface plasmon resonances arising from free carriers in doped quantum dots *Nat. Mater.* **10** 361–6.
7. Functionalizing nanomaterials with biomaterials for chemical sensing is explored here: Kybert N J, Lerner M B, Yodh J S, Preti G and Johnson A T C 2013 Differentiation of complex vapor mixtures using versatile DNA-carbon nanotube chemical sensor arrays *ACS Nano* **7** 2800–7.
8. The use of solid state nanopores for DNA translocation and ultimate sequencing is demonstrated in high resolution here: Rosenstein J K,

Wanunu M, Merchant C A, Drndic M and Shepard K L 2012 Integrated nanopore sensing platform with sub-microsecond temporal resolution *Nat. Methods* **9** 487–92.

9. For more detailed explanation of nanomaterials as interfaces for biological systems, please see: Fairfield J A 2017 Nanostructured Materials for Neural Electrical Interfaces *Adv. Funct. Mater.* 1701145.
10. A crucial link between the two-terminal resistance switching behaviour found in nanoscale systems and Leon Chua's then hypothetical memristor was found in 2008: Strukov D B, Snider G S, Stewart D R and Williams R S 2008 The missing memristor found *Nature* **453** 80–3. This paved the way for other memristive devices.
11. An early paper positing that nanoscale junctions could be used as an artificial synapse helped establish modern neuromorphic device design: Jo S H, Chang T, Ebong I, Bhadviya B B, Mazumder P and Lu W 2010 Nanoscale memristor device as synapse in neuromorphic systems *Nano Lett.* **10** 1297–301. More neuromorphic behaviours have been demonstrated by other groups since.
12. Associative memory in a nanowire device is demonstrated in the following paper: O'Kelly C J, Fairfield J A, McCloskey D, Manning H G, Donegan J and Boland J J 2016 Associative enhancement of time correlated response to heterogeneous stimuli in a neuromorphic nanowire device *Adv. Electron. Mater.* **2** 1500458.