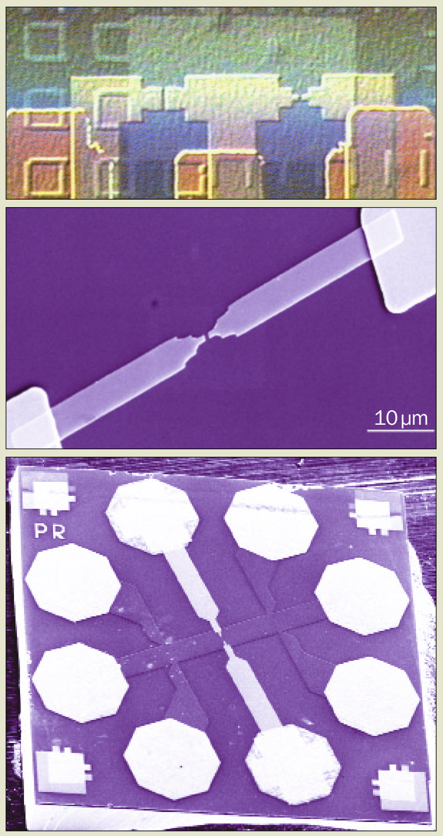
Physicists are learning how to move and manipulate electrons in one- and zero-dimensional systems, which could lead to a new generation of electronic devices

New directions with fewer dimensions

Karl Berggren and Michael Pepper

ANYONE who compares the power of today's desktop computers with those that were on the market 10 years ago will realize just how much consumers have benefited from progress made in semiconductor physics and technology. Engineers can now cram ever-higher densities of active components onto chips and give them much better functionality. Indeed, thanks to advances in technology, it is now possible to make semiconductor devices that are about as small as the wavelength of an electron.



The electrodes of a "split gate", which produces 1D electron flow (top). Similar behaviour can be created between two gold fingers (middle) in a quantum point geometry (bottom).

However, this work has also triggered a very active new field, in which physicists are learning how to move and manipulate electrons in a controlled fashion in one- or zero-dimensional systems. A number of major research institutions, companies and universities are now interested in this field, which has developed into an important part of nanotechnology. The "dimensionality" in this context refers to the number of degrees of freedom of electron momentum. An electron in a 1D system, for example, has its momentum fixed in two directions, while an electron in a zero-dimensional system is confined completely.

When it comes to studying electrons, semiconductors offer a major advantage in that they allow a remarkable variety of experiments to be carried out. These materials have also benefited from the enormous effort by industry to continually improve them. Thanks to high-resolution lithography and controlled-growth techniques, small features can now be created that allow the distribution of free electrons to be squeezed into any desired shape. As a result of this technological progress, semiconductors can now be made with such purity that electrons can flow inside them without really being scattered by impurities or imperfections. Therefore at low temperatures the conduction properties are basically determined by the chosen geometry of the device, which allows the electron distribution to be manipulated on a tiny scale. This in turn opens up new physics, continuing the progression of discovery driven by advances in technology.

Electrons in three and two dimensions

Electrons in a large block of material are free to travel in any direction they like, forming a 3D "gas". If, however, we create a thin slab of the material, the electrons can still travel freely in the plane of the slab, but their motion in the third dimension is restricted. The wavefunction of an electron in this dimension is represented by a standing wave. The situation is analogous to the "particle-in-the-box" concept taught in introductory quantum mechanics, in which a particle is confined between two rigid walls of infinite potential energy from which it cannot escape (figure 1*a*). The motion of the electron in the third dimension is quantized and can be represented by a "ladder" of levels of increasing energy, with the separation between the levels growing larger as the slab is made thinner. The electrons can occupy any of the levels that lie below a maximum energy known as the "Fermi energy", E_F. But if the separation of the levels is larger than E_F, then all the electrons will sit in the lowest level (figure 1*b*).

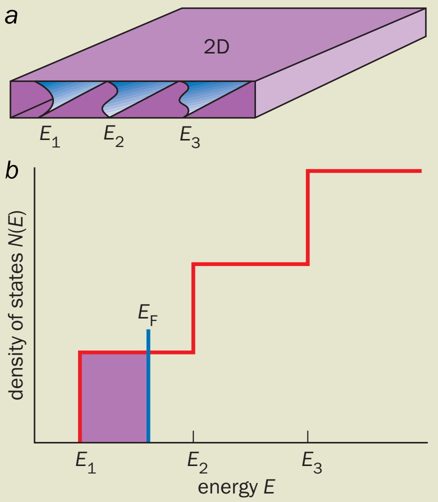
The first attempts to study electrons in fewer than three dimensions took place in the 1970s and early 1980s when David Poole from the Cavendish Laboratory in Cambridge and the present authors examined the behaviour of electrons in the conducting region of a gallium-arsenide field effect transistor. As this region became thinner, we noticed a change in the nature of the energy levels, which indicated that the electrons were no longer free to move in three dimensions – but instead just two.

It turns out that we can also alter the energies of the different levels by applying a magnetic field. If the field is applied parallel to the slab, then the gap between the levels grows larger, which leaves fewer and fewer energy levels below E_{F} for the electrons to occupy. In other words, the electrons steadily become more confined as the applied field is increased. Eventually only the lowest energy level contains any electrons and the system is – to all intents and purposes – two dimensional (figure 1*b*).

Two-dimensional electron gases can also be created naturally using a number of semiconductors. The first such system was investigated in the 1960s by Alan Fowler and Frank Fang at IBM's T J Watson Research Center at Yorktown Heights in New York. In a series of pioneering experiments, Fowler and Fang proved the existence of a 2D electron gas using the "inversion" layer of electrons on the surface of oxidized p-type silicon in a metal-oxide-silicon transistor.

A more recent and widely used system is the gallium-arsenide aluminium gallium-arsenide (GaAs/AlGaAs) heterostructure. It contains a 2D electron gas at the interface between the two materials, which have similar properties. There is little disorder in this region, which means that electrons are scattered much less than they are in silicon and are highly mobile. The system plays a valuable role in the modern optoelectronics industry and has been used for a number of important experiments in physics, notably the discovery in 1982 of the "fractional quantum Hall effect" by Daniel Tsui, Horst Stormer and Arthur Gossard at Bell Laboratories in the US. Tsui and Stormer shared the 1998 Nobel Prize for Physics with Robert Laughlin for "their discovery of a new form of quantum fluid with fractionally charged excitations".

1 Making a 2D electron gas



(*a*) In an infinitely large conductor, electrons can travel freely in all directions and form a 3D electron gas. In a thin slab of the material, however, the motion of the electrons across the slab is quantized. The lowest three energies – E_1, E_2 and E_3 – are shown, along with the wavefunction of the electrons at each energy. The electrons can, however, still travel freely in the plane of the slab. (*b*) The density of different states that an electron can occupy, $N(E)$, increases step-like as a function of energy, E. Applying a magnetic field parallel to the slab makes the energy levels move further apart. Eventually only the lowest energy level (E_1) lies below the maximum possible energy that the electrons can have – the Fermi energy E_{F}. When only the lowest state is populated (purple region), the electrons are confined to just two dimensions.

From two dimensions to one

So how can we study electrons in just one dimension? This is a question that the authors and their colleagues began considering in the early 1980s. At first sight, one might imagine that the most convenient way of studying the 1D behaviour of electrons would be to use organic polymer materials, in which electrons move along the long, thin "backbone" of the molecule. However, it turns out that it is better to begin with a 2D electron system and try to narrow the conducting channel by adjusting appropriately patterned controlling "gate" electrodes.

We began with silicon, but later obtained better results using gallium arsenide and aluminium gallium arsenide, with its 2D layer of electrons at the interface between the two semiconductors. We took a thin film of this layered material and placed a "source" and "drain" at either end and a split "gate" in the middle (figure 2). As the negative voltage on the gates was increased, we found that it reduced, or "squeezed", the area available to the electrons that travel from the source to the drain. Eventually just a single line of charge was produced. What was remarkable was that we could move this line of electrons across the semiconductor at will simply by making the voltage on the two gates slightly different. Although it was possible to reduce the width of the channel to zero, most of the interesting phenomena occurred when it was 10–100 nm wide. This technique, which can transmit a pattern of confinement to the underlying electron gas, has proved to be incredibly powerful and flexible.

The first indications of 1D confinement in a gallium-arsenide heterostructure were given in 1985 through low-temperature experiments carried out by Trevor Thornton and colleagues at the Cavendish Laboratory. They studied how electron waves interfere with each other after being repeatedly scattered from the tiny number of residual impurities present in the channel. The interference makes it harder for the electron waves to spread out and raises the material's resistance in a way that is unique to each dimension. They also found that the mutual interaction of the electrons changes the way in which the scattering occurs. These "quantum corrections" to electron transport are very important in all three dimensions.

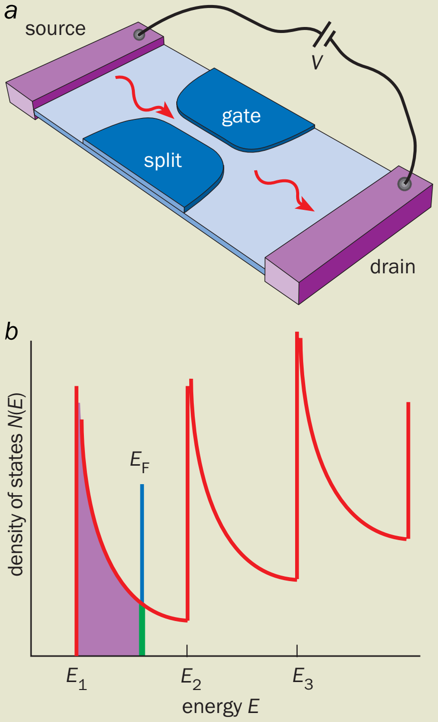
Although these early experiments showed that the electrons had been successfully confined to one dimension, they did not directly demonstrate the discrete 1D levels produced by the confinement of the electrons. There were two possible ways of investigating this further. One was to apply a magnetic field normal to the conducting plane, which would increase the separation of the energy levels and leave fewer levels occupied. The other was to eliminate the scattering. In both cases one would not investigate the subtle quantum corrections but would directly observe how the resistance varied with the occupation of the quantized levels.

Applying a magnetic field to unconfined electrons makes them rotate in cyclotron orbits of ever-tighter radius as the field increases. But the electrons in a 2D layer are spatially confined because of the electrostatic squeezing from the split gates. The magnetic field therefore squeezes the electrons even more, increasing their energy and pushing the energy levels further apart. The electrons now have fewer levels that they can occupy – a phenomenon known as "magnetic depopulation". As the levels depopulate, "peaks" and "valleys" in the resistance can be observed at particular values of the magnetic field. The periodicity of the resistance allows the nature of the confining potential and the nature of the 1D wavefunctions to be derived.

Our observation of these effects in 1986 provided definitive evidence that we had obtained the first controllable 1D quantization of electron states. The work showed that any imperfections in the channel were not significant enough to broaden the energy levels and so obscure the 1D quantization. This technique of magnetic depopulation is now widely used by many researchers to study the energy distribution of the levels for different confinement potentials.

The other way of sharpening the energy levels – eliminating electron scattering – can be achieved by shortening the split gates to less than about 3 µm in length. The exact distance depends on how perfect the semiconductor is, although the magnetic-depopulation experiments can be performed with gates about 15 µm long. The virtual absence of scattering, which means that the electrons move "ballistically", sharpens and separates their 1D energy levels. It also produces a fascinating effect – unique to 1D physics – in which the 1D resistance of the electrons becomes quantized.

2 Creating a 1D line of charge



(*a*) A schematic view of a device that can create a 1D line of charge from a 2D layer of electrons lying at the interface between gallium arsenide and aluminium gallium arsenide (cyan region). Electrons are first made to flow (red arrows) by applying a voltage, *V*, between the source and the drain. Steadily increasing the negative voltage on the gates reduces the area available for the electrons to flow through until only a single line of charge remains. The line of electrons can be moved at will simply by changing a gate voltage. (*b*) The density of states, $N(E)$, as a function of energy, *E*. The flow is 1D when the electrons occupy only the lowest level (purple region). The narrow window (green) at the Fermi energy, E_F, of width $\Delta E = eV$, where e is the charge on an electron, indicates which states contribute to the net current flow. Below this energy, equal numbers of electrons flow in both directions, which means that they contribute zero net current.

Quantized 1D resistance

The quantization of an electron's resistance can be understood quite simply in semiclassical terms. When a voltage V is applied between the source and the drain, it generates a current $I \sim v\mathcal{N}(E)eV$, where v is the velocity of the electrons, $\mathcal{N}(E)$ is the density of states and e is the charge on an electron. But since $v \sim \sqrt{E}$ and $\mathcal{N}(E) \sim 1/\sqrt{E}$, the two terms cancel and the resistance (V/I) depends only on e and Planck's constant, h. It turns out that each quantized energy level has a resistance – termed the "quantized resistance" or "quantum point-contact resistance" – of $h/2e^2 \approx 12.9\ \mathrm{k\Omega}$. When we have n levels, each acts independently, rather like resistors in parallel, and the total resistance is simply $h/2ne^2$.

This effect was first observed in 1987 by David Wharam and co-workers in Cambridge, and by Bart van Wees and co-workers at the Delft University of Technology and Philips Research Laboratories in Eindhoven, although it had previously been predicted by the late Rolf Landauer and Marcus Buttiker at IBM in the US and by Joe Imry at the Weizmann Institute in Israel. It can conveniently be observed by measuring the resistance between the source and drain as a function of the split-gate voltage, which alters the channel width.

Increasing the negative voltage on the gate makes the gate narrower and increases the number of energy levels above the Fermi energy. This in turn reduces the number of levels that are free for the electrons to occupy. The conductance – the inverse of the resistance, i.e. $2ne^2/h$ – therefore drops in a series of steps as the voltage becomes increasingly negative (figure 3*a*). Advances in semiconductor technology have now made it possible to observe almost 30 one-dimensional quantized energy levels contributing to current flow.

Strangely, the quantum of conductance is not $2e^2/h$ but just e^2/h. The reason is that an electron carries an intrinsic angular momentum, or "spin", that can point in one of two directions – up or down. In the absence of a magnetic field, the two directions are equivalent and both spins contribute the same amount (e^2/h) to the conduction, which therefore totals $2e^2/h$. However, when a magnetic field is applied, each spinning electron acts as a tiny current that is affected by the field according to the spin direction. The factor of 2 therefore disappears and the quantum of conductance is just e^2/h.

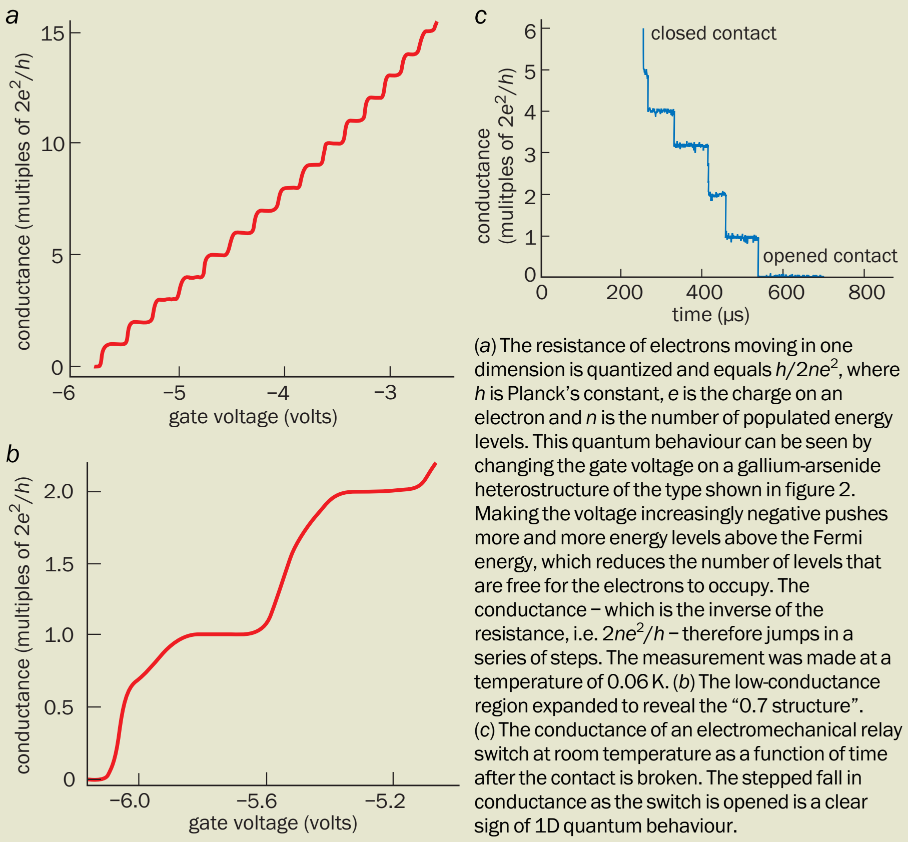
Applications of 1D systems

The simple split-gate configuration mentioned above has now become the building block of nanosystems, which leads to some interesting effects. For example, two such channels placed in series behave very differently to how one might expect given Ohm's law. It turns out that the total resistance is not just the resistance of the first channel plus that of the second. Instead it is simply equal to the greater of the two resistances. This unusual property arises because the resistance in the ballistic regime is inversely proportional to the number of 1D levels – in other words the lower-resistance channel has more levels than the higher-resistance channel. Since electrons fill the 1D levels up to the Fermi energy, the additional levels in the lower-resistance channel lie above the Fermi energy of the other channel. Electrons in these extra levels therefore cannot pass through the lower-resistance channel. The bottom line is that the channel with fewer levels dictates the resistance of the two channels in series.

Further patterning of the split gates by high-resolution electron lithography can convert a 2D electron gas into a system in which the electron wavefunction is quantized in all three dimensions. This creates a small "dot" of electrons surrounded by insulating regions. Electrons can only enter the dot by quantum mechanically tunnelling through these regions. A controllable quantum dot of this type was first fabricated in 1988 by Charles Smith and colleagues in Cambridge, who unexpectedly found that its resistance oscillated as the dot was made bigger or smaller.

Soon afterwards, Leonid Glazman and Robert Shekhter, who were then based in Kharkov in the former Soviet Union, showed that these oscillations were due to the fact that electrons can only enter the dot one at a time. The "Coulomb repulsion" between electrons in the dot means that a fixed energy of e^2/C is needed to add each new electron to a dot, where C is its capacitance. This phenomenon of "Coulomb blockade" – and of single-electron transport – in split-gate-defined quantum dots has been investigated in detail, particularly by Marc Kastner and co-workers at the Massachusetts Institute of Technology. Researchers believe that such systems could be used as memory chips or active elements in

3 Resistance of electrons moving in one dimension



(*a*) The resistance of electrons moving in one dimension is quantized and equals $h/2ne^2$, where *h* is Planck's constant, *e* is the charge on an electron and *n* is the number of populated energy levels. This quantum behaviour can be seen by changing the gate voltage on a gallium-arsenide heterostructure of the type shown in figure 2. Making the voltage increasingly negative pushes more and more energy levels above the Fermi energy, which reduces the number of levels that are free for the electrons to occupy. The conductance – which is the inverse of the resistance, i.e. $2ne^2/h$ – therefore jumps in a series of steps. The measurement was made at a temperature of 0.06 K. (*b*) The low-conductance region expanded to reveal the "0.7 structure". (*c*) The conductance of an electromechanical relay switch at room temperature as a function of time after the contact is broken. The stepped fall in conductance as the switch is opened is a clear sign of 1D quantum behaviour.

quantum information processing.

The simple 1D channel can also be thought of as a waveguide for electron waves, an application that many researchers have looked at in detail. For example, corrugating the metal split gates can locally change the width and potential of the confined electron gas. This sudden change of the potential reflects the electron waves in a controllable manner. Interference between incoming and reflected waves can be used as the basis of an electron interferometer.

1D electrons in other systems

Research into 1D physics is not restricted to gallium arsenide. Other materials and technologies have also been incorporated into experiments, showing that the basic crystal structure often affects the quantization. For example, David Wharam and Gerhard Abstreiter at the Technical University in Munich, Germany, have used silicon, which has a conduction band that is unusual in that it contains two possible directions for an electron to follow. The ballistic conductance therefore rises in steps of $4e^2/h$ – rather than $2e^2/h$ – which is interesting because it illustrates the role of the crystal lattice.

Meanwhile the Nobel laureate Herb Kroemer, Evelyn Hu and co-workers at the University of California at Santa Barbara have examined the 1D behaviour of electrons in indium arsenide. This material has a very narrow gap between the conduction and valence bands, which means that the electrons have a small "effective mass". Since the separation of the quantized energy levels is inversely proportional to the effective mass, the electrons are strongly confined in one dimension. This could allow the 1D behaviour of electrons to be studied at room temperature as it is in principle possible to obtain energy levels that are separated by more than the thermal energy at 300 K. However, such measurements would only work if the electrons do not scatter due to thermal vibrations, which might otherwise smear out the quantization.

New techniques for forming 1D semiconductor channels have also been developed. Rather than using a metal, Klaus Ensslin and colleagues at the ETH Zurich in Switzerland have used an atomic force microscope to oxidize a split pattern in the semiconductor; removing the pattern then leaves 1D regions. Poul-Erik Lindelof and his group at the University of Copenhagen, meanwhile, have etched doped layers over a channel to produce particularly clearly defined regions of 1D electrons.

Other researchers have been able to create 1D channels by modifying conventional semiconductor growth techniques. David Ritchie, Stuart Holmes, Mark Leadbeater, Jeremy Burroughes and colleagues at the Cavendish Laboratory and the Toshiba Cambridge Research Laboratory, for example, have shown that very narrow 1D regions can be made by using pre-patterned layers. Similar work at Bell Laboratories in the US has been carried out by Loren Pfeiffer and co-workers.

The 1D behaviour of electrons is a widespread phenomenon that can occur in very different systems – and at room temperature, provided conditions are appropriate. It can arise quite simply whenever electron wavefunctions overlap with each other in a single direction. For example, the tip of a scanning tunnelling microscope can be envisaged, crudely, as a small pyramid with one atom at the apex, two just beneath it and so on. As the tip is brought close to a surface and current starts to flow through it, the resistance is initially quantized because each atom provides a separate 1D pathway for the electrons to flow along.

One-dimensionality has also been produced by continuously stretching a metal wire. Just before the wire breaks, the thinnest region narrows atom by atom until it is just one atom wide at its tip. As each atom contributes one overlapping orbital, the very end of the tip, which is 5, 4, 3, 2, 1 atoms wide, has 5, 4, 3, 2, 1 one-dimensional channels. This narrowing, one atom at a time, quantizes the conductance. This effect, which was initially observed by Nicolas Garcia and colleagues at Consejo Superior De Investigaciones Científicas in Madrid, Spain, has been used to probe the mechanical nature of the metallic filament as it breaks. The resistance provides a measure of the shape of the filament as it varies with time.

One of the most surprising manifestations of one-dimensionality is exhibited by the resistance of an electromechanical switch. Frederic Ott and James Lunney at Trinity College Dublin, Ireland, measured how the resistance between the two contacts of a switch made from a variety of noble metals or alloys changed with time after the switch was opened. They found that the conductance fell in steps during the first millisecond after the switch was opened – a clear signature of quantum behaviour (figure 3*c*). As the pressure on the switch decreased, contact was lost one atom at a time. The resistance therefore fell steadily to a very low value until the switch was completely opened. What is remarkable is that the initial conducting region between the contacts was due to the presence of just one atom.

This experiment is so straightforward and physically meaningful that Edward Davis at Leicester University in the UK uses it in his undergraduate-physics lab class. This remarkable development shows just how far we have come from the early days, when a loss of dimensionality could only be shown with split-gate devices created by tricky high-resolution lithography with measurements performed at very low temperatures.

Enter the 0.7 structure

Ballistic quantization is a single-electron effect. In other words, the interaction between electrons – which is responsible for many effects such as superconductivity – plays no role here. However, interactions in one dimension ought to produce a measurable effect, as Joaquin Luttinger first pointed out in the 1950s. The electrons are, after all, so close together that one might imagine all sorts of unexpected consequences of the interactions between the electrons moving in one dimension.

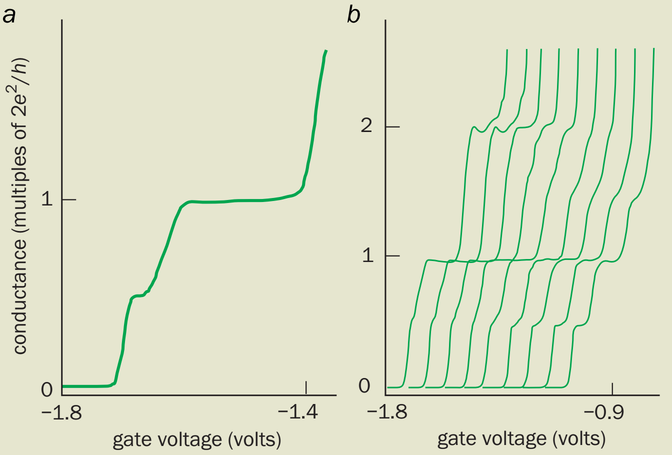
In order to enhance such effects – which would otherwise be hard to spot when dealing with so few electrons – many groups have tried to make better samples that contain as little structural and compositional disorder as possible. When measuring the conductance of a split-gate channel of the type shown in figure 2, Kalaricad Thomas and colleagues in Cambridge noticed a small blip in the conductance as the gate voltage was changed. Although such an anomaly had often been apparent to varying degrees in earlier data, these authors found that it became much stronger as the sample became more ordered, appearing as a separate plateau at a value near $0.7 \times 2e^2/h$, (figure 3*a*).

This so-called 0.7 structure in the graph drops smoothly with increasing magnetic field until it levels off at a value of $0.5 \times 2e^2/h$. This is half of the value that one would normally expect if the spin of the electrons have two equal but opposite values. What happens is that the magnetic field splits the energy of the two previously equal levels – a phenomenon known as "spin splitting". Only the lower of the two levels can be occupied, thereby removing the factor of two in the conductance and halving its value to just e^2/h. The unusual feature of this work is that there is still some residual spin splitting even in the absence of a magnetic field.

Measurements show that the 0.7 structure is not a ground state, which would be stable down to the lowest temperatures. Instead, cooling the sample makes the conductance rise towards $2e^2/h$ as the 0.7 structure vanishes. There is currently a lively debate about the origin of this effect, which appears to contradict a long-standing theorem devised by Elliot Lieb and Daniel Mattis. While working at IBM in 1962, the two predicted that spin splitting cannot occur in 1D systems in the absence of a magnetic field.

One solution to the dilemma could be that their theory applied to infinitely long systems rather than the nanostructures discussed here. It is most likely that the spin splitting arises from the quantum-mechanical exchange interaction between the electrons – the same interaction that makes iron magnetic. Indeed, measurements of the temperature difference between tiny regions containing a few electrons either side of the channel suggest that the interaction of spins does indeed lead to the 0.7 structure.

4 Spin splitting



(*a*) The formation of a small plateau in the conductance at 0.1 K of a 1D electron gas in a split-gate gallium-arsenide structure at e^2/h indicates the phenomenon of "spontaneous spin-splitting" (see text). (*b*) Applying a magnetic field in the plane of the electron gas broadens the plateau but does not alter the conductance at which it occurs. This effect shows that the field increases the energy between the two spin levels and that there is a spin splitting at zero field.

The 0.7 structure has been studied in detail by many researchers in addition to the present authors, including Robert Clark and his group at the University of New South Wales, by Lindelof and colleagues in Copenhagen, and by Charles Marcus and co-workers at Harvard University in the US. Many explanations have been proposed for this intriguing structure and especially why it should occur at this particular value of conductance. One possibility is that the energy difference between the two spin directions is not big enough to only allow one of them to pass through. What happens instead is that one electron is transmitted fully and the other only partially, with the magnitude of the transmission varying with temperature, although many alternative scenarios have also been envisaged.

But if the 0.7 structure is due to spin splitting, can the splitting be increased so that a conductance of e^2/h is observed in the absence of a magnetic field? Further work by Thomas and colleagues has shown that this can be the case. They found that if the carrier concentration is reduced, it is possible for the 0.7 feature to move down to e^2/h and stay at this value as the temperature becomes very low, indicating that it is a stable ground state. So in the absence of a magnetic field, the electrons in the system take only one spin direction – in other words they are fully polarized (figure 4).

Conclusions and consequences

One lesson from this field is that technological advances are not just an end in themselves but can also stimulate new discoveries in physics. The 1D physics generated by the early semiconductor studies has become increasingly sophisticated and subtle. More elaborate split-gate patterns have been produced and 1D electron flow has been observed in a range of other systems. Richard Newbury and colleagues in New

South Wales have shown that curved split gates can be used to confine an electron gas in less straightforward configurations. For example, a bowl-like "stadium" shape has been used to investigate chaotic behaviour in the transport of electrons.

Complex quantum behaviour can also be investigated as technology and lithographic techniques advance. Moty Heiblum and colleagues at the Weizmann Institute of Technology in Israel have measured the phase of the wavefunction of electrons moving in one dimension. They have created an array of gates that force the electron gas into a ring shape where the electrons enter the ring and can then cross it by choosing one of two arms. They placed a quantum dot in one of the arms and measured the phase difference of the electron waves traversing the two arms of the ring as the number of electrons in the dot changed one at a time. Groups led by Robert Westervelt in Harvard and Charles Smith in Cambridge, meanwhile, have directly observed the quantized 1D wavefunctions using scanning probe microscopes. Such techniques promise to take the manipulation and observation of single-electron phenomena in one dimension a stage further.

Combined quantum structures are highly relevant to the emerging technologies of quantum information processing, in which the control and manipulation of electron spins and wavefunctions play a central role. The ability to control the spin of 1D electrons without applying a magnetic field could be a crucial impetus to the field. One-dimensional systems in which the movement of electrons can be precisely controlled could well form a basic unit for the complex quantum-information-processing systems of the future.

Further reading

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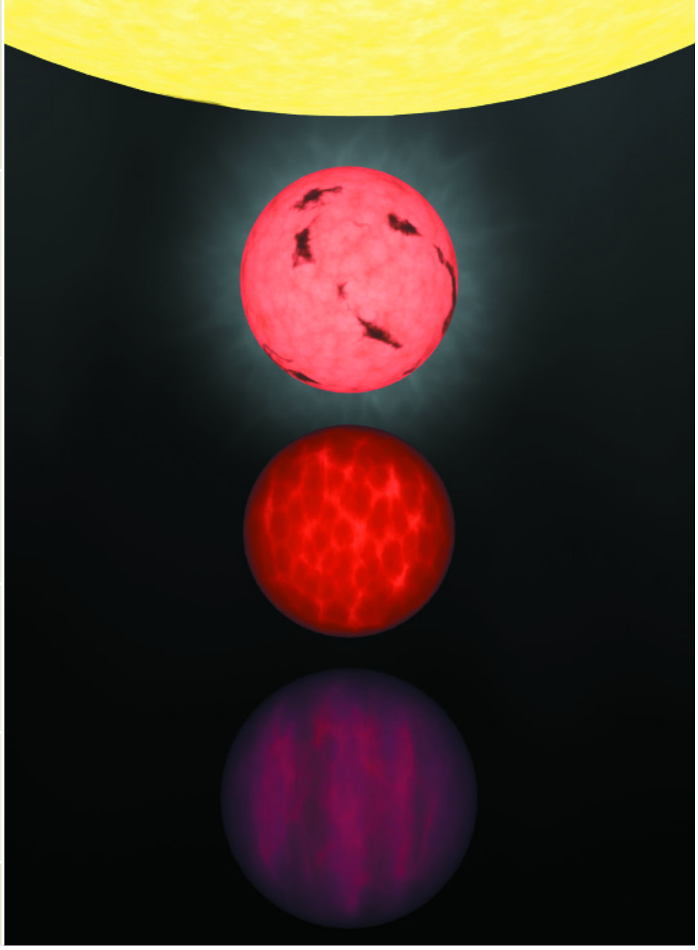

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