Quantum electronics: the physics and technology of low-dimensional electronic systems into the new millennium

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Quantum electronics: the physics and technology of low-dimensional electronic systems into the new millennium

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In 1947, a research team at the Bell Telephone Laboratories in New Jersey demonstrated a new electrical amplifier, the 'transistor'. Unlike the prevailing vacuum-tube amplifiers, the transistor was a solid-state device built from a piece of semiconductor crystal. Its invention sparked a revolution in electronics and communication technology that continues to rage unabated 50 years later. But one of the most striking aspects of the progress of semiconductor science over the last 50 years is how the commercially driven technological developments in semiconductor devices have occurred alongside advances in fundamental physics obtained from investigation of the same semiconductor devices. The basic building blocks of computer and communication technologies are perfect for the study of electrons and their interactions with each other and with their environment; the fundamental interactions of one of nature's most fundamental particles.

This paper develops the symbiotic relationship between the technological and the fundamental aspects of these electronic systems and reviews recent highlights of semiconductor physics and technology. I will also look, however, at a future generation of microelectronic devices in which the fusion of molecular biology, chemistry and physics will produce breathtaking results.

Keywords: semiconductors; electronic devices; nanostructures; quantum physics; correlated electrons; molecular and biomolecular electronics

1. The transistor

In the late 1930s, Mervin Kelly, the visionary director of research at Bell Telephone Laboratories, dreamed of eliminating the slow, bulky, unreliable vacuum tubes and electromagnetic switches upon which his telephone network relied, and replacing them with small, low-power, solid-state devices. In fact, since vacuum tubes were incapable of responding to high frequencies, Bell scientists had been forced to return to the temperamental crystal detectors used at the beginning of the century in radio receivers. These devices, discovered by Ferdinand Braun in 1874, permitted current flow in one direction only and comprised a piece of semiconductor crystal, such as galena (lead sulphide) or silicon, sandwiched between two metal electrodes. One electrode was a fine metal wire known as the 'cat's whisker' and it was something of a fine art to position the whisker correctly to obtain a strong signal (see, for example, Sah 1988; Riordan & Hoddeson 1997; Seitz & Einspruch 1998).

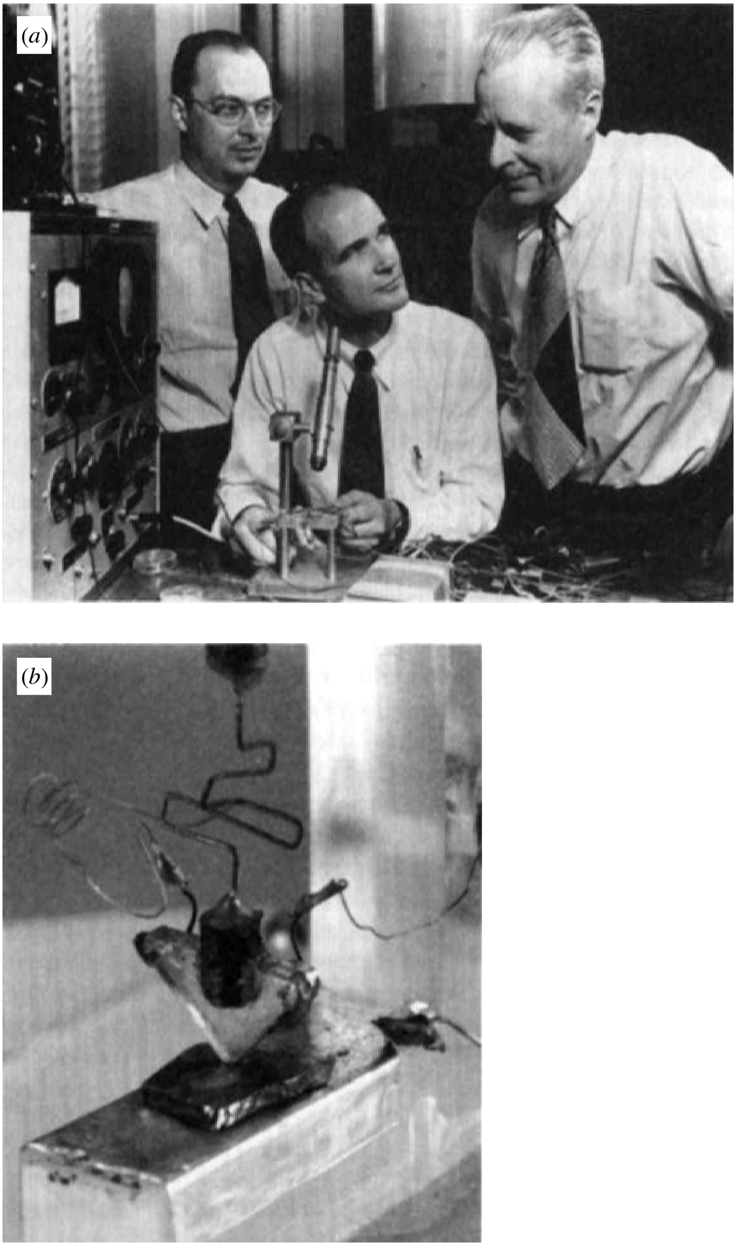

Figure 1. (*a*) (Left to right) John Bardeen, William Shockley and Walter Brattain in 1948 (Lucent Technologies). (*b*) Brattain's first bipolar point contact transistor (courtesy of AT&T archive).

The vacuum tube invented in 1904 by John Fleming comprised an evacuated glass tube containing two electrodes. It rectified current since electrons could only flow from the negative cathode to the positive anode. In 1906, Lee De Forest incorporated a mesh of fine wires called the 'grid' as a third electrode around the cathode. The

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grid potential controlled the tube current analogous to a valve regulating water flow through a pipe. Owing to the difficulty of obtaining a good vacuum, vacuum tubes did not really begin to replace crystal detectors until the 1920s, but soon became an integral part not only of wireless, but also telephone systems, television and, ultimately, computers. The copper–copper oxide rectifier (another metal–semiconductor junction) also began to be used in radio receivers in the 1920s as an alternative to cat's-whisker detectors.

In 1945, Kelly assembled a team to perform fundamental solid-state physics research. One member, Walter Brattain, had worked on copper-oxide rectifiers for many years and envisaged incorporating a third electrode, analogous to the vacuum-tube grid, to make a solid-state switch or amplifier. The team also included theoretical physicist John Bardeen, and was to be led by William Shockley (figure 1*a*).

(*a*) *Semiconductors*

The fundamental properties of semiconducting materials and the ways in which they differed from metals and insulators were only beginning to be appreciated at this time. One hundred years earlier, while performing his seminal investigations of electricity and magnetism at the Royal Institution, Michael Faraday identified a series of materials distinct from metals in that they conducted electricity poorly and possessed a strong temperature-dependent conductivity that improved (rather than degraded) when heated. Although much theoretical understanding of electrical conduction in solids had been provided in the 1920s by Felix Bloch, Rudolf Peierls and Alan Wilson inter alia, semiconductor samples were polycrystalline and contained impurities that affected their properties unpredictably. Silicon and germanium were still thought by many to be metals. And, although metal–semiconductor junctions had been used for many years in cat's-whisker detectors and copper-oxide rectifiers, they would not begin to be understood until the work of Walter Schottky and Nevill Mott in the late 1930s.

Bloch applied the emergent quantum mechanics to electrons in a crystal lattice and showed that those with certain energies could be diffracted by the periodic potential. A series of energy bands separated by 'forbidden' energy gaps are formed and electrons are constrained to energies within the bands. Wilson developed band theory further in 1931 and explained the distinction between metals, semiconductors and insulators in the following way (figure 2*a*). The most energetic electrons in a metal partly fill a band (the conduction band) up to an energy called the 'Fermi energy'. Under the influence of an electric field, the Fermi electrons acquire energy from the field and scatter into the adjacent empty states in the band. Their ability to respond to the field in this way results in an electric current. In an insulator, however, the most energetic electrons lie at the top of an energy band (the valence band). There are no empty states close in energy to scatter into and so insulators cannot conduct. However, the size of the band gap separating the filled valence band from the empty conduction band is crucial. At low temperatures, intrinsic semiconductors insulate since all electrons fit snugly in the valence band, but the band gap is sufficiently small that, at ordinary temperatures, some electrons are thermally excited into the conduction band, resulting in a certain degree of conduction. Two important consequences of band theory should be noted.

First, the electrical properties of semiconductors can be tailored by incorporation of extrinsic impurities. In fact, once the dopant concentration exceeds a threshold,

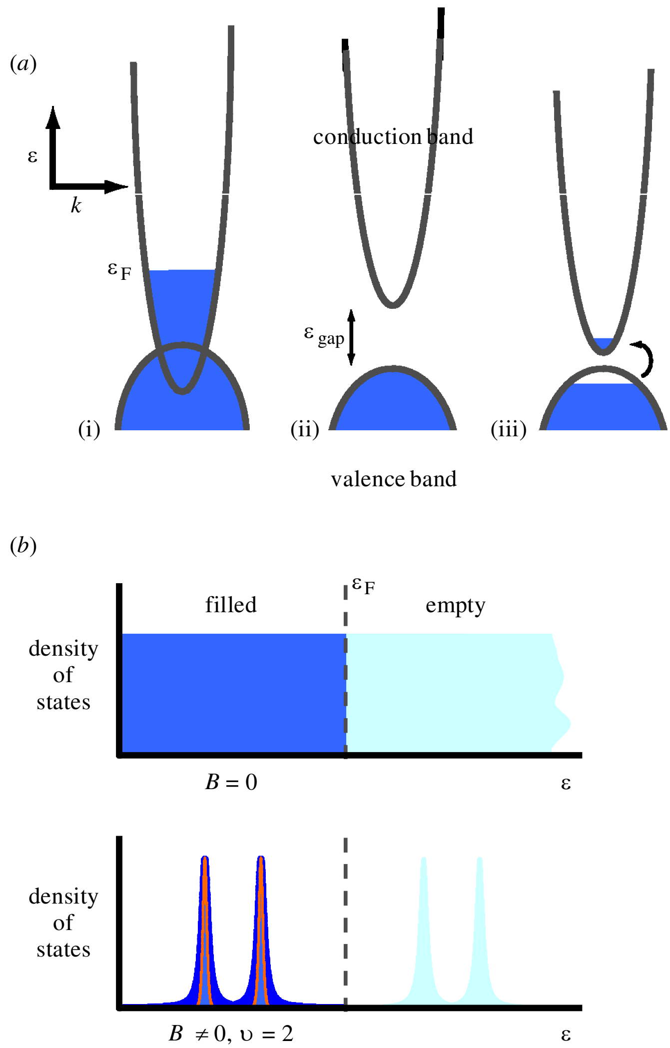

Figure 2. (a) Schematic band arrangement in (i) a metal, (ii) an insulator, and (iii) a semiconductor. Grey lines show the conduction and valence band dispersion curves (plots of electron energy ε against electron momentum k). The mid-blue regions indicate energy states that are occupied by electrons. In a metal, electrons completely fill the valence band and partly fill the conduction band up to the Fermi energy (ε_F). In an insulator, electrons completely fill the valence band, which is separated from the empty conduction band by the 'band gap' (ε_{gap}). A semiconductor is similar but the band gap is much smaller (typically a few electron volts), allowing some electrons to be thermally excited into the conduction band at room temperature. (b) Schematics showing the density of two-dimensional electron states as a function of electron energy ε for zero magnetic field ($B = 0$) and for finite perpendicular magnetic field ($B \neq 0$). The field splits the continuum of allowed energy states into a ladder of discrete Landau levels, which are broadened by impurity scattering. Electrons in states at the Landau level centres (mid blue) can conduct, those in states at the tails (dark blue) are localized. The system shown is at filling factor $\upsilon = 2$, since exactly two Landau levels are filled.

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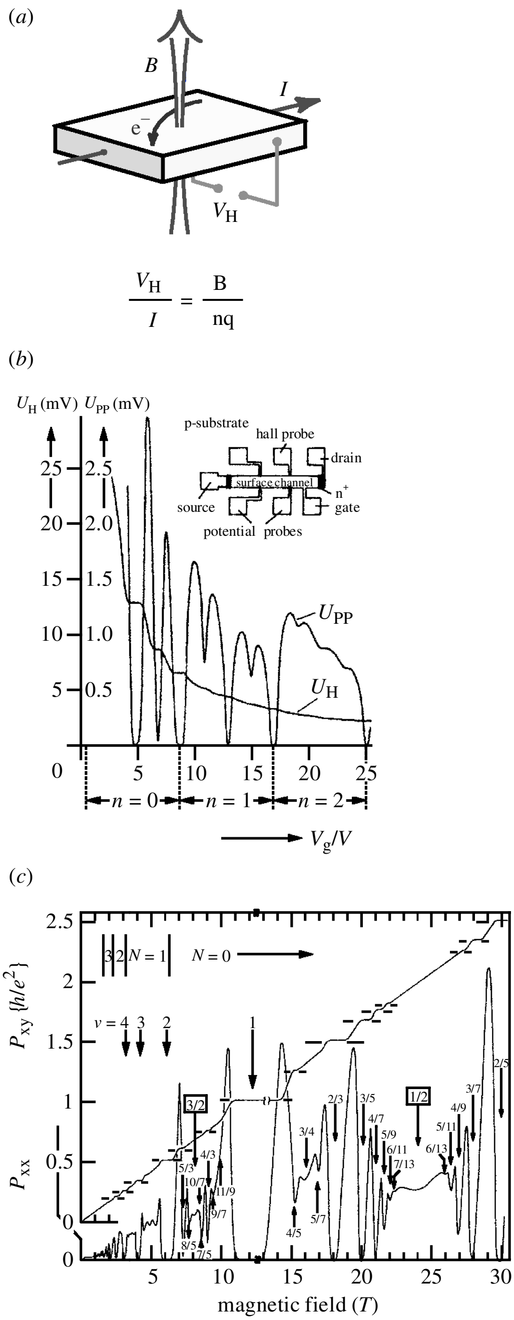

Figure 3. The Hall effects. (a) Schematic of how a current of electrons (charge $q = -e$) or holes (charge $q = +e$) is deflected by a perpendicular magnetic field B to produce a Hall voltage V_{H}. (b) The first demonstration of the integer quantum Hall effect (IQHE); quantized steps are observed in the Hall resistance concomitant with minima in the oscillatory sample resistance (von Klitzing *et al.* 1980). (c) Overview of the rich spectrum of IQHE and fractional quantum Hall effect states observed in a GaAs–$\mathrm{Al}_x\mathrm{Ga}_{1-x}$As heterojunction (Willett *et al.* 1987).

the semiconductor undergoes a transition to a metal, but one with a much lower conduction electron density than elemental metals such as copper (Mott 1949). Second, band theory gave an explanation of 'hole' transport. Just as a few drops of water can trickle along an otherwise empty tube, air bubbles in a tube nearly full of water can also move. A nearly full valence band can conduct, but the current appears to be carried by *positively* charged particles, holes. Conduction by this anomalous particle had been observed in studies of the 'Hall effect', discovered in 1879 by Edwin Hall, who found that the current in a thin film of gold was deflected by a perpendicular magnetic field resulting in a transverse voltage (figure 3*a*). Although the Hall voltage polarity is consistent with conduction by negative electrons in most materials, some studies suggest conduction by positive particles. The Hall effect became a useful means for determining carrier type (electrons, n-type; holes, p-type) and concentration in semiconductors, but was to have a glorious future. As we shall see, 100 years later, it would be central to two Nobel physics prizes.

(*b*) *The field effect*

In 1945, Shockley started working on a mechanism now known as the 'field effect'. The aim was to modulate the current in a thin silicon film by an electric field produced by a surface metal plate (the 'gate'). As a concept, the field effect extends back to the beginning of the century. Nevill Mott recounts how his father, Charles, attempted to observe the effect with J. J. Thomson at the Cavendish Laboratory between 1902 and 1904, shortly after Thomson discovered the electron in 1897 (Mott 1986). This experiment failed since they tried to modulate the current in a metal (rather than a semiconductor), in which the electron density is too high for the effect to be observable. Shockley and collaborators were unaware of its pedigree until they tried patenting the idea and discovered that Julius Lilienfeld had preempted them with three patents filed in the late 1920s for field-effect semiconductor devices. Although it is not clear whether Lilienfeld built any of his devices, his structures are remarkably prescient of successful devices fabricated over 20 years later.

Shockley's failure to observe the field effect led Bardeen to propose that electron traps ('surface states') form at semiconductor surfaces, which prevent the gate field penetrating. In 1947, Brattain and co-worker Robert Gibney discovered that an electrolyte such as water between the semiconductor and the gate neutralized the surface states. Brattain and Bardeen found they could just modulate the current flow from a tungsten point contact into silicon, and later germanium, by using a water drop to both neutralize the surface states and, via a second electrode, act as a gate. They were concerned, however, about the frequency response. The device had to operate at audible frequencies for telecommunications, but the sluggish response of the electrolyte restricted operation to a few hertz. They replaced the electrolyte with a thin layer of germanium oxide, but this washed off, and, with both electrodes pushed into the surface, they discovered a new effect and invented the first transistor: the *bipolar point-contact transistor*.

(*c*) *Two transistors*

Brattain and Bardeen found that the current between one electrode (the 'collector') and the germanium slab (the 'base') could be controlled by the potential on the second electrode (the 'emitter'). They proposed that minority carriers (holes) were injected into the germanium by the emitter. A small emitter–collector hole current not only resulted in a larger collector–base electron current, but also modulated it (Bardeen & Brattain 1948). After further work, the bipolar point-contact 'transistor' (named by Bell Laboratories colleague John Pierce, who is also credited with the aphorism 'Nature abhors the vacuum tube') was operating at 1 kHz with a power gain of several hundred per cent; figure 1*b* shows a demonstration transistor that Brattain constructed in December 1947.

Shockley, feeling rather left out, worked feverishly on a device in which the emitter and collector would be consolidated inside the semiconductor, eliminating the clumsy and electrically noisy point contacts. He proposed a sandwich structure comprising a p-type region (the base) encased by two n-type regions (the collector and emitter) (figure 4*a*). Small changes in the base bias lead to exponential changes in the emitter–collector current, analogous to a dammed river in which a small variation in the height of the dam produces a large change in water flow. Physical chemist, Gordon Teal, realized that eliminating grain-boundary scattering would lead to more reproducible behaviour, and, together with Morgan Sparks, he developed a technique for pulling single-crystal germanium directly from the melt. They could change the doping between n-type and p-type by adding small amounts of appropriate elements, such as gallium or antimony, to the melt, and, in 1950, successfully fabricated Shockley's *bipolar junction transistor*. Shockley, Bardeen and Brattain ultimately received the Nobel physics prize for their 'investigations on semiconductors and the discovery of the transistor effect' in 1956.

(*d*) *Transistor computing*

Shockley immediately appreciated the transistor's potential for computing. In a 1947 interview he pointed out, 'For applications of this sort there are difficulties in applying vacuum tubes because of their size and the heat that they produce. It seems to me that in these robot brains the transistor is the ideal nerve cell.'

The desire to build a 'robot brain' has entertained engineers for several hundred years (see Shurkin (1996) for a thorough history of computing). During the 17th and 18th centuries, a series of (often untrustworthy) machines were built to perform simple arithmetic, and the story of Charles Babbage's two unrealized visions—his difference engine (figure 5*a*), a machine designed to calculate mathematical tables in a preordained manner, and his analytical engine, a programmable machine remarkably prescient of modern computers, which was designed to perform calculations according to instructions entered on punched cards—is well known. Analogue machines built around winches and pulleys gave way to more reliable electromechanical operation in 1944 with the IBM automatic sequence controlled calculator (the Mark I), designed by Howard Aiken. Researchers had also turned to vacuum tubes to increase switching speed, albeit reluctantly. The COLLOSSUS, built in Britain's Bletchley Park in 1943 by a team including Alan Turing, was one of the first electronic computers. It employed 1800 vacuum tubes and was used exclusively for wartime cipher decryption. The first electronic digital computer was built at the University of Pennsylvania in 1946. The electronic numerical integrator and computer (ENIAC), used over 17 000 tubes, weighed 30 tons, and consumed nearly 200 kW. The ENIAC could add 5000 numbers per second and was used to calculate artillery shell trajectories. Williams (1998) notes that the energy required to calculate the trajectory of a shell

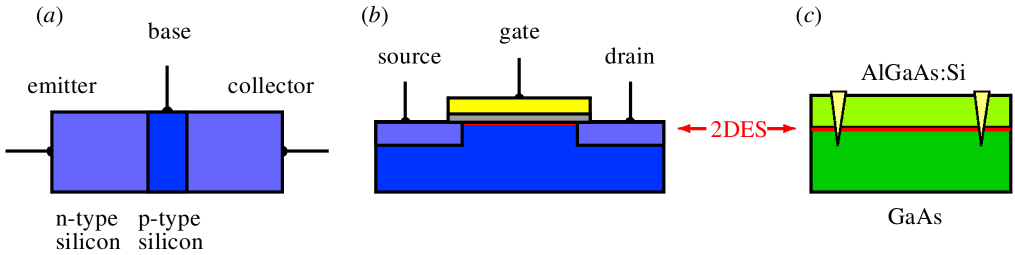

Figure 4. Schematic of (*a*) the bipolar junction transistor, (*b*) the silicon MOSFET, (*c*) the GaAs–$Al_xGa_{1-x}As$ heterojunction. A two-dimensional electron system (2DES) is formed in the MOSFET and in the heterojunction.

was comparable with the explosive discharge needed to fire the shell itself! When the US Army decommissioned the ENIAC nine years later because of operational expense, it was still the world's fastest computer. Figure 5*b* shows the first public demonstration of the automatic computing engine (ACE) in 1950, one of Britain's earliest general-purpose stored-program computers. Based on a design by Alan Turing and built at the National Physical Laboratory, it used 800 tubes and could add 15 000 numbers in 1 s.

Although the transistors of the early 1950s switched more slowly than vacuum tubes, it was clear that the inherent disadvantages of the latter (bulkiness, high power consumption, the requirement of continuous power, warm-up time, large heat production, frequent failure), would lead to their demise. The first purely solid-state digital computer was the transistorized digital computer (TRIDAC) built by Bell Laboratories in 1954 for the US Air Force. It employed 700 point-contact transistors and rivalled digital vacuum-tube computers such as the ENIAC in computational speed. Figure 5*c* shows an early British transistor computer, the Elliot 803, from 1963.

In 1955, Shockley left Bell Laboratories to set up his own company in the San Francisco Bay area where he once lived. Shockley Semiconductor Laboratory opened in February 1956, seeding the growth of high-technology companies in the area of California now known as Silicon Valley. Although Shockley recruited an excellent team, his company was not a success and many of his personnel resigned the following year to form Fairchild Semiconductor nearby, under the leadership of Robert Noyce and Gordon Moore.

(*e*) *Silicon, silicon dioxide, the integrated circuit and the microprocessor*

Although Texas Instruments began as a geophysical company, in 1952, Vice-President Pat Haggerty decided that transistors were the future. Gordon Teal joined Texas from Bell Laboratories at the end of 1952 and devoted his crystal-growth expertise to the fabrication of single-crystal silicon. By 1954, Teal and his team had produced the first silicon bipolar junction transistor (figure 4*a*). Silicon is more reactive than germanium and was more difficult to work with, but has a larger band gap and so its electrical properties are less sensitive to temperature. Germanium transistors fail if heated to 70 °C, making them insufficiently robust for military applications, for example.

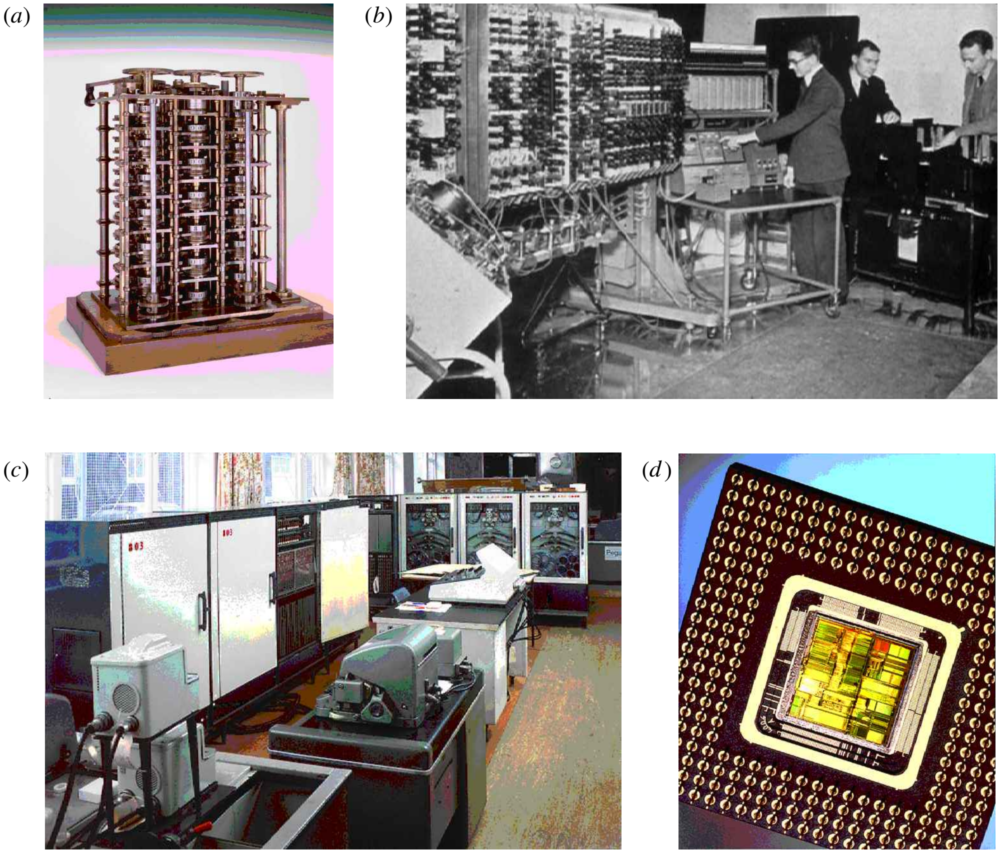

Figure 5. A brief history of computing! (*a*) Demonstration portion of Charles Babbage's difference engine no. 1 (1832); (*b*) the first public demonstration of the ACE vacuum-tube computer (1950); (*c*) the Elliott 803 computer, an early transistor computer (1963); (*d*) Intel Pentium microprocessor (1993); the package dimensions are 5.5 cm^2. (Science Museum/Science & Society Picture Library.)

By the end of the 1950s, tens of millions of transistors were produced each year, finding applications as diverse as office equipment and satellites. However, as circuits became more complicated they were increasingly difficult to assemble, since each discrete component had to be individually wired to the next. The possibility of consolidating the components into a single 'integrated' structure started to crystallize with a series of key developments that have engendered the massive integration and miniaturization of high-speed switching, logic, and memory circuitry over the last 40 years.

The breakthrough came in 1958. Jack Kilby at Texas realized that if conventional circuit elements such as resistors, diodes and capacitors were made from silicon, they could be incorporated with transistors on a single silicon substrate. As well as miniaturizing circuits by consolidating the circuit elements and doing away with the interconnecting wires, this procedure would eliminate assembly errors. Kilby used photographic techniques to pattern the silicon wafer, introducing precise concentrations of dopants to specific areas and depths by the heat diffusion of appropriate metals (a technique demonstrated in 1951 by John Saby at General Electric, which allowed the fabrication of the diffused-base bipolar junction transistor). However, at the same time, Robert Noyce at Fairchild was also considering the interconnection problem, realizing the absurdity of separating individual transistors fabricated on a silicon wafer only to subsequently reassemble them with soldered wires. In 1959, his colleague Jean Hoerni proposed coating the silicon surface with a thin layer of silicon dioxide (SiO_2), which, unlike Brattain's GeO_2 layer, provided an insoluble, insulating protective sheet. This allowed the photographic patterning of fine interconnecting wires on the SiO_2 surface, with holes etched through the SiO_2 to allow access to the transistors beneath.

However, SiO_2 was discovered to have a further significant property: it passivates the silicon surface states, allowing the electric field from a gate electrode on the SiO_2 surface to penetrate the silicon channel below. And so, at Bell Laboratories in 1960, the field-effect transistor (the MOSFET, metal-oxide-semiconductor field-effect transistor; figure 4*b*) was finally produced. MOS technology would prove cheaper and capable of higher device packing densities than its bipolar junction counterpart, and the complementary MOSFET (CMOS), developed in the late 1960s, which comprises an n-type and a p-type MOSFET in series, has progressively replaced the junction transistor in integrated circuits. Since CMOS technology only draws power when switching, it has led to the high component packing densities found in present-day circuits, which would otherwise be prevented by the devices overheating (but even a modern 'room-temperature' CMOS silicon microprocessor operates above 100 °C, heated by its internal power dissipation!).

The early 1970s heralded two further developments: semiconductor memory and the microprocessor. In 1968, Noyce and Moore left Fairchild to found Intel and started making semiconductor memory circuits. Although the magnetic data-storage systems that replaced punched card storage in the 1950s are still used today for archival purposes, the 1 kbit capacity memory chips of the early 1970s pioneered cheap compact storage of vast quantities of information. A modern 256 Mb CMOS dynamic random-access memory (DRAM) chip may contain several hundred million transistors with 0.25 μm features packed in a postage-stamp sized area (Fowler 1997). The microprocessor combines key computer circuitry in one versatile programmable chip. Intel's first 4004 microprocessor in 1971 contained 2300 transistors with features as small as 10 μm, and a clock speed of 108 kHz. The Intel *Pentium* launched in 1993 (shown in figure 5*d*), had 3.1 million transistors with 0.8 μm features and a 60 MHz clock speed. The *Pentium II Xeon* processor, launched in January 1999, had 7.5 million transistors with 0.25 μm features and operated at 450 MHz. By the time this article is published in January 2000, the 733 MHz *Pentium III Coppermine* processor will be available, which has 28 million transistors with 0.18 μm features. No doubt, this processor will be superseded just as rapidly.

2. The physics

The fundamental solid-state physics research that resulted in the invention of the transistor has progressed as rapidly as the advances in microelectronics that it engendered. The versatility of semiconductor technology—its ability to create devices in which the optical and electronic properties can be easily tailored—makes semiconductor systems important for basic physics research too. In this section, I review a few prominent themes from a vast literature. The most famous discoveries are, perhaps, the integer and fractional quantum Hall effects discovered in the two-dimensional electronic systems inherent in silicon MOSFETs and gallium arsenide heterostructures. In addition, an entire field of mesoscopic physics has emerged in which the subsequent electrostatic confinement of these two-dimensional systems into one-dimensional wires, one-dimensional rings and zero-dimensional boxes, for example, has allowed the investigation of quantum electronic transport through nanometre-scale architectures of ever-increasing complexity.

(*a*) *The silicon MOSFET*

An n-channel silicon MOSFET is shown schematically in figure 4*b*. The n-type electrodes form rectifying contacts to the p-type substrate, and so no current flows in the absence of an appropriate positive gate bias. This induces electrons in the channel, establishing an n-type inversion layer at the semiconductor–oxide interface in an approximately triangular potential well. However, Robert Schrieffer (who subsequently shared Bardeen's second Nobel prize for the theory of superconductivity) pointed out in 1957 that these electrons might not behave classically, since they are constrained to a plane less than 10 nm thick, comparable with their quantum mechanical wavelength. The electron energy spectrum perpendicular to the interface is split into a set of energy levels—a realization of the textbook 'particle in a box' situation—and the electrons form a two-dimensional electron system (2DES), free only to move in a plane parallel to the interface. Measurements of these systems can reveal fascinating quantum mechanical phenomena (Ando *et al*. 1982; Pepper 1985).

A magnetic field perpendicular to a 2DES quantizes electron motion in the plane and splits the continuum of allowed energy states into a ladder of discrete levels known as Landau levels (figure 2*b*). Electron scattering off impurities broadens the levels and localizes electrons in the states in the tails. The number of levels filled at a given field depends upon the electron areal density and a dimensionless quantity, the filling factor υ, is quoted; if exactly one Landau level is filled, the system is at $\upsilon = 1$, and so forth. The quantization is manifest by the oscillatory behaviour of a number of physical properties including magnetic susceptibility (the de Haas–van Alphen effect), thermal conductivity, and electrical conductivity (the Shubnikov–de Haas effect). Magnetotransport measurements performed at IBM in the mid-1960s proved the two-dimensional nature of the inversion layer by showing the Shubnikov–de Haas oscillations to have a constant period as a function of electron density (Fowler *et al*. 1966). After Fang & Fowler (1968) showed the conductance of a dilute inversion layer to be thermally activated at low temperatures, Mott (1973) proposed this as an example of Anderson localization, and the subsequent study of electron localization and hopping conduction has proved a fecund area of research (Pepper 1985), which is still active today. Fang & Stiles (1968) measured the electron Landé g factor by tilting the magnetic field with respect to the 2DES, and found it not only to be different from the free-electron value but also dependent upon electron density. Janak (1969) suggested that this was a many-body effect and recognized that fundamental electron–electron interactions could play an important role in these devices.

(*b*) *The integer quantum Hall effect (IQHE)*

The most famous discovery, however, is the Nobel-prize-winning integer quantum Hall effect (IQHE) discovered in 1980, which is a consequence of the peculiar dynam-

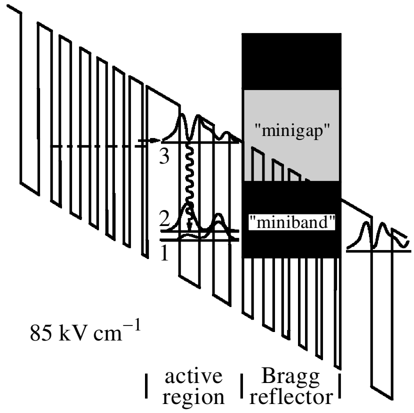

Figure 6. (*a*) Detail of the conduction band diagram of the $Ga_{0.47}In_{0.53}As$–$Al_{0.48}In_{0.52}As$ quantum cascade laser (Faist *et al*. 1995). The layered semiconductor structure produces 25 successive three-level active lasing regions, separated by Bragg reflectors. Under the influence of an electric field, electrons enter the upper lasing level of each active region from the left, and relax to the lower level, emitting a photon. The Bragg reflectors confine the electrons laterally in each upper lasing level by creating a band gap (called a 'minigap' to distinguish it from the semiconductor conduction–valence band gap) to the right. Population inversion is achieved by feeding the electrons that reach the lowest level of each active region into the upper lasing level of the next active region via the 'minibands'.

ics experienced by a 2DES in a strong magnetic field. In fact, to a certain extent the IQHE had been anticipated. Several researchers in the late 1970s found that when the Fermi energy lay in the localized states in the Landau level tails, the Hall conductance deviated from its expected gate bias dependence, and small plateaux were formed. Subsequent experiments by von Klitzing *et al*. (1980) showed the Hall plateaux could be significant and were quantized at resistance $h/ie^2 = 25\,813/i\ \Omega$ (where i is an integer equal to the filling factor at the plateau centre) to a very high accuracy, better than an astonishing one part in 10^8 (figure 3*b*). Concomitant with the Hall plateaux, the sample resistance tended to zero. The IQHE is now used internationally as a resistance standard and has generated a massive international research effort.

Classically, electrons in the bulk of a sample execute circular orbits in a perpendicular magnetic field. Electrons close to the edge, however, repeatedly strike the edge and bounce along in skipping orbits. Quantum mechanically, if the Fermi energy lies between Landau levels in the bulk, the only conducting states are at the sample edges because there the levels are forced up through the Fermi energy by the confinement potential. These 'edge states' are the quantum analogue of skipping orbits, but only conduct in one direction, and so electrons with forward and reverse momenta are physically separated on opposite sides of the device. For an electron to be scattered backwards, it has to cross the device, and so normal scattering events do not affect conduction. Edge states are ideal one-dimensional conductors (see below), each contributing conductance e^2/h. In a standard four-terminal measurement, there is no voltage drop *along* the device since there is no back scattering. The voltage drops *across* the device, producing a quantized Hall resistance h/ie^2, with i being the number of conducting edge states.

(c) The GaAs–$Al_xGa_{1-x}As$ heterojunction and layered semiconductor devices

Over the last 30 years, techniques have been developed to fabricate a number of high-purity, compound semiconductor crystals, such as gallium arsenide (GaAs), as well as layered devices called heterostructures. These comprise a series of different semiconductors grown sequentially one on top of the other, with the crystal lattice maintained throughout (epitaxial growth). The optical and electronic properties of the constituent semiconductors can be combined to tailor new structures with new properties. Molecular beam epitaxy (MBE) is perhaps the best-known growth technique, and is, essentially, a sophisticated form of high-vacuum evaporation, which allows the fabrication of near-perfect crystals with extremely abrupt changes in composition and doping.

The GaAs–$Al_xGa_{1-x}As$ single heterojunction (a heterostructure of just two materials) comprises a crystal of silicon-doped aluminium gallium arsenide ($Al_xGa_{1-x}As$) grown epitaxially on a crystal of GaAs (figure 4*c*). Electron transfer into the GaAs bends the GaAs conduction band into an approximately triangular potential well near the interface: the ionized silicon dopants hold the free electrons against the interface. The well width is similar to the electron wavelength, and, like the silicon MOSFET, a 2DES is formed. These 2DESs can be of extremely high quality owing to the crystalline purity and abruptness of the interface, and at low temperatures (*ca.* 1 K) electrons can travel many micrometres before scattering. Multilayer systems containing two or more 2DESs in close proximity (15–500 Å) are of importance because of the additional degree of freedom for interaction and transport between two-dimensional planes. The system comprising a 2DES close (*ca.* 100 Å) to a two-dimensional hole system is particularly interesting since the electrons and holes may pair to form excitons, which are predicted to undergo Bose–Einstein condensation into a new, possibly superconducting, ground state. A further step towards the realization of fully three-dimensionally engineered quantum structures can be achieved by incorporating a highly focused (50 nm) ion beam in an MBE system (Linfield & Ritchie 1997). A partly grown wafer can be lithographically patterned *in situ*, allowing a series of laterally patterned layers to be formed throughout the structure. Wafers can also be returned to the MBE machine after external processing for further growth.

Compound semiconductors such as GaAs are of technological importance, since, unlike silicon, they have a direct band gap and can emit light efficiently. They are the basis for solid-state lasers and light-emitting diodes, essential for fibre-optic telecommunications and compact disc players *inter alia* (see Kelly 1995). The quantum cascade laser (Faist *et al.* (1995); see also figure 6) demonstrates the versatility of MBE compound semiconductor growth and its ability to engineer sophisticated optical devices. Compound semiconductor transistors also switch faster than silicon MOSFETs and are exploited in mobile telephones.

(d) The fractional quantum Hall effect (FQHE), an electron liquid

Two years after the discovery of the IQHE, Daniel Tsui and Horst Störmer of AT&T Bell Laboratories observed Hall plateaux and resistivity minima at *fractional* filling factors $\upsilon = 1/3$ and $\upsilon = 2/3$ in studies of GaAs–$Al_xGa_{1-x}As$ heterojunctions grown by Arthur Gossard (Tsui *et al.* 1982). It was clear that although the results were phenomenologically similar to the IQHE, this effect had a different origin and fundamental electron–electron interactions could be responsible. In common with the IQHE, the temperature dependence of the resistivity minima was activated, suggesting that energy gaps had opened in the density of states. But these gaps lay in the lowest Landau level where none were anticipated. Theoretical understanding was provided by Laughlin (1983), who developed a beautifully simple wave function to describe the ground state of a many-electron interacting system. He found the pair distribution function had characteristics of a liquid and showed that at $\upsilon = 1/q$ (where q is an odd integer), many-body interactions cause the 2DES to condense into a new incompressible macroscopic quantum liquid. At very low filling factors, the distribution function became solid-like with the electrons forming a Wigner crystal (see below). The condensation opens an energy gap separating each ground state from the lowest excited states, hence the activated conduction. But most remarkable of all, the elementary excitations across these gaps were found to be quasi-particles carrying fractional charge $\pm e/q$.

Many more FQHE states have been observed subsequently. Figure 3*c* shows the rich spectrum of IQHE and FQHE structure observed in a subsequent investigation (Willett *et al*. 1987). Each series of FQHE states was originally described as a hierarchy in which the quasi-particles of a 'parent' state condensed to form a weaker 'daughter' state. However, Jain (1989) proposed that the FQHE energy gaps arise from Landau quantization of new fermionic particles called 'composite fermions' (which are composites of electrons and magnetic flux quanta), generated dynamically by electron–electron interactions at high magnetic fields. The FQHE is the IQHE of composite fermions! Although most investigations of the FQHE have been by magnetoresistance measurements, other techniques such as photoluminescence, surface acoustic wave propagation, and inelastic light scattering have produced unique insights. Recent studies have particularly concentrated on investigation of the fractional charge, the role played by electron spin, and the properties of composite fermions. The FQHE is the signature of a completely unanticipated macroscopic quantum phenomenon and earned Tsui, Störmer and Laughlin the 1998 Nobel physics prize.

(*e*) *The electron solid*

In fact, interest in the low-temperature, many-body ground states of an interacting electron system extends back to a proposal by Eugene Wigner in 1934 for a dilute three-dimensional crystalline electron state. Although the electron density in GaAs–$Al_xGa_{1-x}As$ heterostructures is too high for a Wigner solid to form even at absolute zero (the zero-point electron motion is sufficient to shake the crystal apart), a transition to an electron solid is anticipated at high magnetic field (figure 7). The electrons are each confined to a progressively smaller area with increasing field and the system minimizes its potential energy by forming a lattice structure: a magnetically induced Wigner solid (MIWS). (A classical 2D Wigner solid can be observed in the dilute electron system formed when electrons are suspended above the surface of a dielectric such as liquid helium). As we have seen, however, the application of a strong perpendicular magnetic field has other profound effects on the 2DES ground state; the single-particle gas-like IQHE and the many-body liquid-like FQHE can be formed, and competition between the correlated states (FQHE versus MIWS) is of particular interest. A variety of experiments has mapped the liquid–solid phase boundary, providing strong evidence that the main MIWS phase occurs immediately

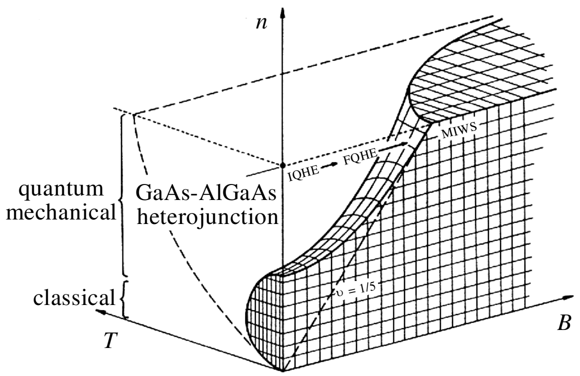

Figure 7. Schematic phase diagram for the electron solid (hatched). The axes are electron areal density (n), temperature (T) and magnetic field (B). At zero magnetic field (n, T-plane), a classical Wigner solid is only anticipated at low temperatures for clean, dilute electron systems. If n is too high, the electron zero-point motion prevents the electrons from crystallizing, even at absolute zero. Under the influence of a magnetic field, the 2DES passes first through the IQHE and FQHE regimes, ultimately crystallizing into a MIWS.

beyond the $\upsilon = 1/5$ FQHE state, but it is broken into 1 μm domains (approximately 25 lattice spacings) pinned by residual impurities. Electrical transport of a pinned crystal can be problematic and so there has been interest in optical techniques, such as magnetophotoluminescence, to provide a local experimental probe.

(*f*) *Nanostructure physics*

Electrons can be further constrained to patterned geometries in the two-dimensional plane by etching vertically into the device or by imposing electrostatic confinement. Electrostatic patterning has the advantages of better resolution and a controllable degree of confinement. If the additional confinement is extreme, the two-dimensional electron energy will become quantized in the confining direction and an electronic system of lower dimensionality, such as a one-dimensional wire or a zero-dimensional box, will form. The investigation of such systems has led to a wealth of new physics because the electrical, optical and thermal properties of electronic systems depend strongly upon their dimensionality. Electron-beam lithography is the key fabrication technique and uses the beam of a scanning electron microscope to write directly into an electron-sensitive resist. The exposed resist is chemically modified and can be selectively removed to allow metal gate deposition of submicrometre resolution onto the semiconductor surface. Under an appropriate bias, the two-dimensional electrons lying below and to the side of the gate structure are depleted and the remaining electrons are constrained to flow around the geometry described originally by the electron beam. The electrostatic lateral confinement of a two-dimensional system into a one-dimensional channel was established in 1982 in n-type silicon MOSFETs (Dean & Pepper 1982; Fowler *et al*. 1982), after Pepper demonstrated the electrostatic squeezing of a three-dimensional system into a two-dimensional system (Pepper 1978). Two heavily doped p-type regions defined a long

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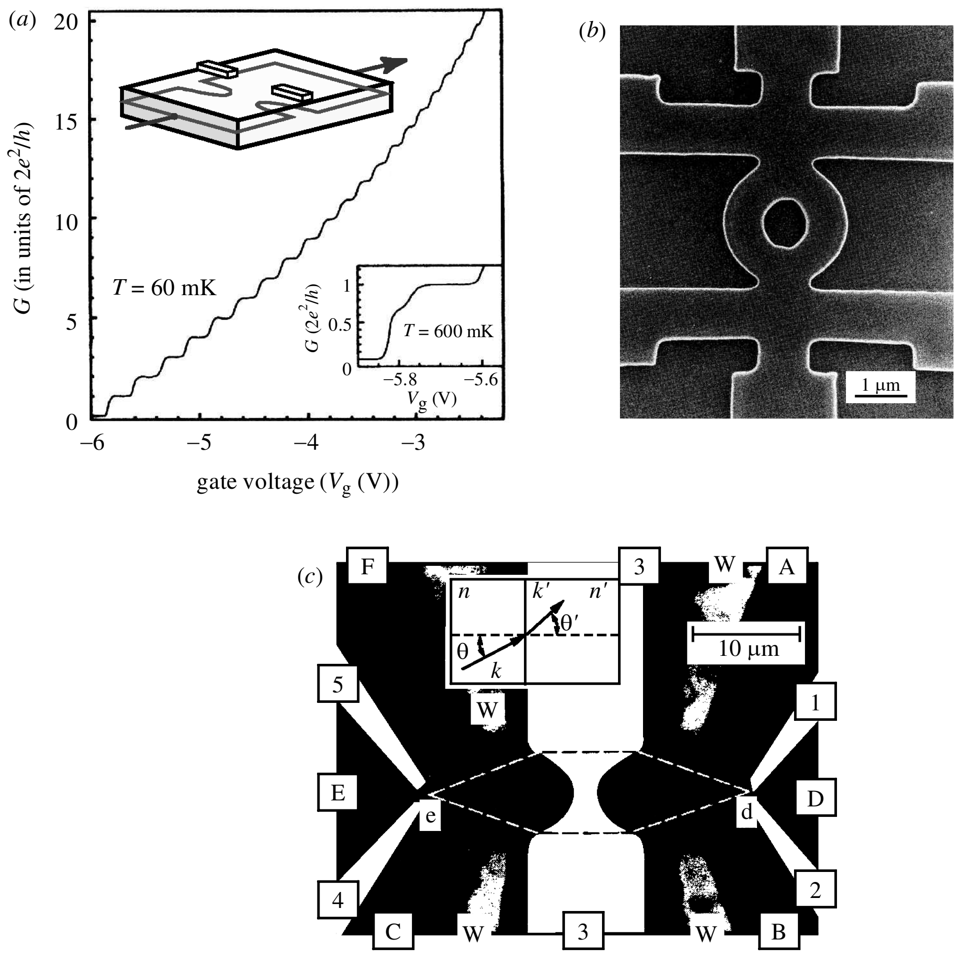

Figure 8. (*a*) Quantized conductance of a ballistic one-dimensional channel. The upper inset shows the schematic surface metal 'split-gate' geometry; a negative gate bias squeezes the two-dimensional electrons into a one-dimensional wire (grey outline). The lower inset shows the conductance feature at 0.7 ($2e^2/h$), attributed to a spontaneous zero magnetic field spin polarization (Thomas *et al.* 1996). (*b*) Resist geometry (before metallization) of an Aharonov–Böhm ring (Ford *et al.* 1988). (*c*) Gate geometry of an electrostatic lens device (Spector *et al.* 1990).

(5–10 μm), narrow (1–2 μm) channel controlled by a thin surface gate. Application of a bias to the p-type regions electrostatically squeezed the conducting channel and a transition between two-dimensional and one-dimensional variable-range hopping conduction was observed. This technique was subsequently extended to the GaAs–$Al_xGa_{1-x}As$ system with the first variable-width one-dimensional wire demonstrated by Thornton *et al.* (1986). A surface metal 'split gate' fabricated by electron-beam lithography comprised two rectangular gates separated by 0.7 μm, which defined a channel 15 μm long (figure 8*a*, upper inset). A negative bias squeezed the 2DES electrons into a one-dimensional wire, confirmed by measurements of appropriate

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corrections to the sample conductivity. This was independently developed by van Wees *et al.* (1988) and Wharam *et al.* (1988) to produce shorter channels (*ca.* 1 μm) and, in doing so, they discovered a new type of conduction. At low temperatures, electrons could pass through the constriction without scattering. This ballistic conduction is very different from customary diffusive solid-state electron transport, in which electrons repeatedly scatter off of phonons, impurities and defects. Figure 8*a* shows the conductance of a recent ballistic one-dimensional channel. As the channel becomes narrower, the conductance decreases. But it does so stepwise with the conductance quantized at $2ie^2/h$, with i an integer. When the channel width becomes comparable with the electron wavelength, a series of one-dimensional subbands form, which transmit the electrons. In one dimension, there is a cancellation of the energy dependence of the density of states and the electron velocity, with the result that each occupied subband contributes a fixed conductance $2e^2/h$ (the factor of 2 reflects the electron spin degeneracy). Recently, Thomas *et al.* (1996) identified further structure at $0.7(2e^2/h)$, suggestive of a spontaneous zero magnetic field spin polarization (figure 8*a*, lower inset).

The field of nanostructure physics has exploded over the last 15 years with the investigation of a vast array of ingenious geometries. Three are outlined here (see Beenakker & van Houten (1991) and Smith (1996) for further examples). Electron interference was investigated by the ring structure in figure 8*b* (Ford *et al.* 1988). Since the relative phase of electrons travelling around the two arms depends upon the magnetic flux though the ring (Aharonov–Böhm effect), conductance oscillations of period h/eA (where A is the ring area) are observed as the field is swept, resulting from the periodic constructive and destructive electron interference. A related structure is the zero-dimensional quantum box, in which a small puddle of electrons is formed, coupled capacitatively to the neighbouring two-dimensional regions. Owing to its small capacitance (*ca.* 10^{-18} F), electrons can only traverse the dot individually at low temperatures (the Coulomb blockade), resulting in periodic conductance peaks. This sensitive device has been incorporated in more complicated circuits as a non-invasive probe of other quantum transport and already forms the basis of a prototype single-electron transistor. Finally, figure 8*c* shows an electrostatic lens (Spector *et al.* 1990). The 2DES is partly depleted under the lens-shaped gate, reducing the Fermi electron momentum in this region. Electrons fired from the left are diffracted and focused into the constriction on the right (note that this is achieved by a structure shaped like an optically diverging lens).

3. The future

In the late 1960s, Gordon Moore proposed that microprocessor complexity (number of components per area) would double every 18 months. And, indeed, 'Moore's law' has so far been obeyed. However, it is predicted that the prevailing silicon technology will not be susceptible to this exponential progression in miniaturization (and associated circuit capability) for more than a further ten years. With the enormous capital investment and expertise already tied up in silicon technology, it is natural to develop existing proven technology. However, even relatively direct developments (for example, changing circuit interconnects from aluminium to the better conducting copper, or pushing photolithography to progressively smaller wavelengths into the deep ultraviolet) require a large investment in time and money.

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Since a modern silicon fabrication plant costs around $2 billion (and has increased exponentially with time, Moore's second law), a point will be reached where small improvements no longer outweigh the necessary investment. Furthermore, device dimensions are already approaching the limit where quantum effects will interfere with their operation: the MOSFET oxide thickness has been gradually reduced to *ca.* 5 nm; at 2 nm, quantum tunnelling through the oxide impairs performance, particularly for DRAMs (Fowler 1997). Of course, this technology may simply saturate. Other materials systems such as GaAs (which, as we have seen, have some operational advantages over silicon, but the technology for which is expensive) or layered silicon–germanium structures (which have the prospect of combining the flexibility of band-gap engineering with silicon CMOS compatibility; see Paul (1999)) may play a larger role.

However, I want to look well into the future. As devices become smaller and approach the quantum limit, quantum mechanical effects, rather than being deleterious, will become central to device operation (Feynman 1986). New electrical and optical characteristics will emerge and be exploited, and the quantum mechanical phenomena prized by physicists will enter the public domain. Already, several computing schemes have been proposed in which the quantum mechanical state of a two-level system (for example, the nuclear spin orientation of dopant atoms embedded in a semiconductor) encodes binary information (Kane 1998). The interaction between these systems (called 'quantum bits' or 'qubits'), and, hence, the operation of the computer, is purely quantum mechanical. Such quantum computers are predicted to outperform classical computers, although their realization promises to be a formidable task.

Why not build upwards: assemble atoms and molecules individually into appropriate three-dimensional configurations? Researchers have been looking to fabricate circuit elements on the ultimate molecular scale for many years now, and a range of molecular attributes including electrical, optical and mechanical properties, nuclear spin, conformation, lock-and-key recognition, inter alia, could be exploited for switching and memory functionality. There is already progress in the study of individual molecules (Reed *et al.* (1997) measured the conductance of a single benzene ring spanning the two gold faces of a break junction), and in the fabrication of molecular circuit elements (Martin *et al.* (1993) demonstrated a molecule that rectifies current). Many molecules, such as polyacetylene (the simplest conjugated polymer), intrinsically semiconduct on polymerization (owing to their conformation, a peculiarity of one-dimensional conductors addressed by Peierls) but can be 'doped' into conduction using halogens or alkali metals to remove or add electrons into the π-orbitals. Polymers are already exploited commercially for advanced large-area electroluminescent displays, for example, and have been demonstrated to be susceptible to the field effect in polymer-channel transistors (Burroughs *et al.* 1988). The optoelectronic properties of a number of molecules have attracted attention. For example, the robust, naturally occurring protein, bacteriorhodopsin found in the bacterium *Halobacterium salinarium*, functions as a light-induced proton pump under anaerobic conditions. Its high second- and third-order polarizability, and its large two-photon absorptivity, have led to suggestions that it could form the basis of a three-dimensional optical memory in which photons from two lasers spatially address individual bits within the three-dimensional bulk. The field of molecular electronics is gaining momentum and crossing traditional disciplinary boundaries (for a review, see Petty *et al.* (1995)).

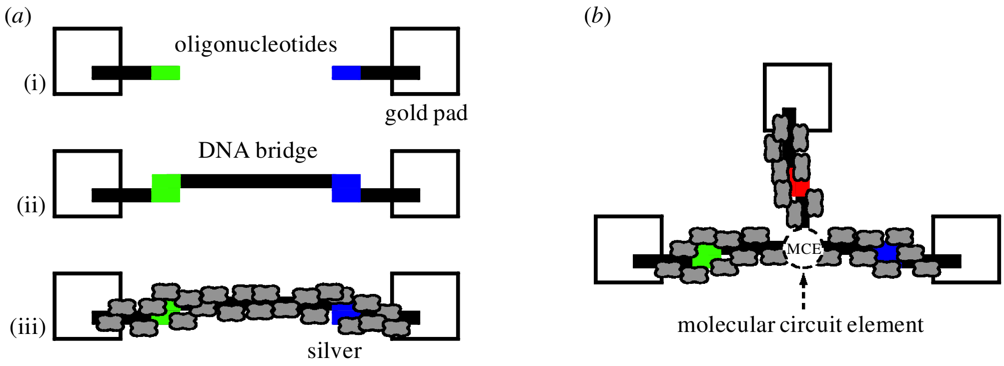

Figure 9. (*a*) Two gold-surface bound oligonucleotides can be hybridized with a strand of complementary DNA to form a template that can nucleate a 100 nm thick conducting silver wire (Braun *et al.* 1998). (*b*) This technique has the potential to self-assemble complex nanoscale conducting networks, incorporating functional molecular circuit elements.

Perhaps the most exciting prospect, however, involves one of the most fundamental molecules of life itself. The selective self-assembly and molecular recognition properties inherent to DNA (deoxyribonucleic acid) might be exploited to engineer complex supramolecular networks with exotic electrical and optical properties. DNA has been used to organize colloidal particles into macroscopic crystal-like aggregates and to control the conformation of semiconductor nanoparticle assemblies. However, a recent experiment has shown that a strand of DNA can be hybridized with two surface-bound oligonucleotides to form a template that can nucleate a 100 nm thick conducting silver wire. This procedure might be a solution to the nagging problem of how functional molecules can be connected to each other and to the outside world (although their incorporation into existing CMOS is a likely first step). Braun *et al.* (1998) evaporated two gold electrodes 12–16 μm apart onto a clean glass slide and attached a 12-base oligonucleotide to each electrode via a derivatized disulphide group, each oligonucleotide comprising a different specific base sequence (figure 9*a*). The two oligonucleotides, and, hence, the electrodes, were bridged (monitored by fluorescence spectroscopy) by hybridization with a 16 μm long λ-DNA strand possessing two 12-base sticky ends. Each end was complementary to one of the oligonucleotide sequences. A highly selective localization of silver ions along the DNA was performed via a silver–sodium ion exchange process and the subsequent formation of silver complexes with the DNA bases. These complexes seeded metallic silver aggregates along the DNA skeleton to form, ultimately, a 100 nm wide conducting granular silver wire connecting the two electrodes. This is well below the width achievable with standard, industrial processing technology. Furthermore, the use of a DNA polyanion in this way is not limited to the assembly of metal wires; Braun *et al.* (1998) fabricated a poly-(*p*-phenylene vinylene) (PPV) filament by attaching a positively charged pre-PPV polymer to the stretched DNA and subsequently treating it to form a highly photoluminescent PPV wire.

It is clear that this technique has the potential to self-assemble far more complicated structures. By incorporating functional molecules with such oligonucleotides, entire networks may be built up, which could be interconnected electrically by DNA-assembled metallic wires or by conducting conjugated molecules (figure 9*b*), or even optically. Entire three-dimensional microprocessors and memories might be created by combining molecular circuit elements (transistors, capacitors, diodes, etc.) in this way.

I believe, however, that it is a mistake to focus exclusively on the way existing technology operates and to try to create alternative schemes that operate in essentially the same manner. New devices reveal new physics. New devices will have new methods of operation. Some of these are predicted and sought, others will be discovered by serendipity. Shockley, Bardeen and Brattain tried to develop the field-effect transistor but instead discovered minority carrier injection, and, subsequently, the bipolar transistor, and this work was grounded in years of fundamental experimental and theoretical research on copper oxide rectifiers, semiconductors, and the 'esoteric' theories of quantum mechanics. If the concept of a self-assembled biomolecular computer seems far-fetched, remember that it may take a long time for ideas to become technologically feasible and reach fruition. Nearly a century passed between J. J. Thomson's original search for the field effect and it finally achieving widespread use in the microprocessor, but it happened.

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> It is certainly impossible for any person who wishes to devote a portion of his time to chemical experiment, to read all the books and papers that are published in connection with his pursuit; their number is immense, and the labour of winnowing out the few experimental and theoretical truths which in many of them are embarrassed by a very large proportion of uninteresting matter, of imagination, and of error, is such, that most persons who try the experiment are quickly induced to make a selection in their reading, and thus inadvertently, at times, pass by what is really good.
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> Michael Faraday (1826)

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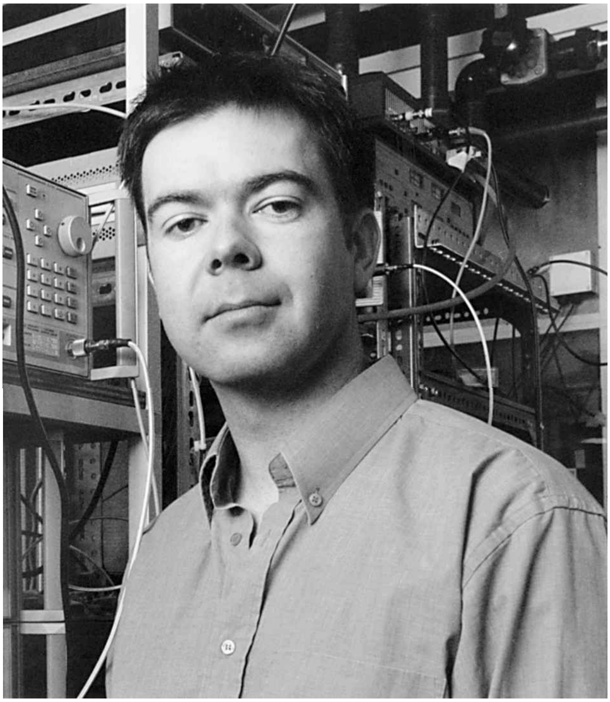

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