Towards quantum processors?

May we one day be able to build processors that fundamentally operate based on quantum physics? This kind of device would use intrinsically parallel information processing, performing certain calculations radically faster than today's computers. The French CEA Quantronics Group is developing superconductor circuits that may well provide the building blocks for a quantum processor: quantum bits and quantum logic gates.

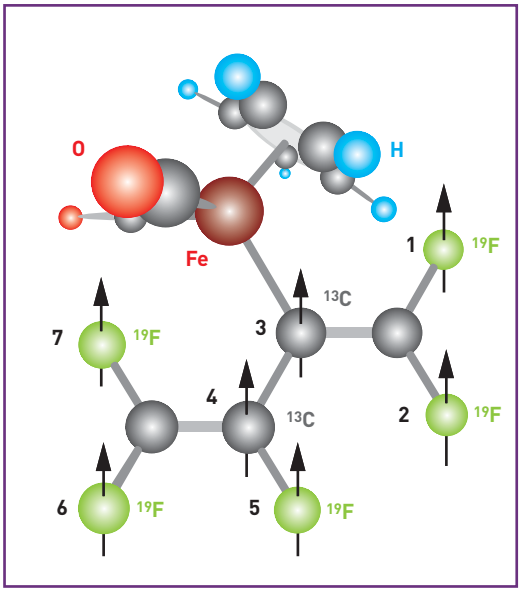
To better explain the specificities – and oddities – of quantum objects, the physicist Gamow imagined a world with highly **quantum** objects on our own scale. Among other weird events, a tiger relocated into space could be hit by a bullet shot in another direction. During the last decade, theorists have added a more realistic chapter to this rather over-imaginative story by putting forward plans for quantum machines, i.e. computers, that would function in the world as it is.

The quantum computer – a dream machine

Built on the laws of **quantum physics** (box B, ***A guide to quantum physics***), quantum computer could perform calculations way above the capabilities of today's computers, which can only perform serial processing of a dataset (See *Calculation and the quantum computer*).The power of quantum calculation stems from quantum mechanics intrinsic parallelism: if the input data supplied to a quantum processor is in a ***superposition state***, it outputs as the corresponding superposition of the processed data. Despite the obvious advantages that quantum mechanics appears to offer, few **algorithms** have so far been obtained, since generally all the gain is lost when reading the results of the calculation! The rapid disappearance of a system's "entangled" states, or **decoherence**, which is a set of physical properties that makes the world non-quantum at our scale, is the next major challenge to be faced when a quantum computer is built.

Quantum calculation was even considered a curiosity until 1994, when the American Peter Shor discovered a quantum algorithm for factoring large integers. This result had a huge impact, as the current algorithms used in cryptosystems are exactly based on the difficulty of factorization. Yet even more significant was that in 1996, Peter Shor teamed up with other theorists to prove that quantum algorithms could be made robust in terms of decoherence, although with heavy redundancy.

The flourishing theoretical research triggered by this series of discoveries has naturally generated a battery of all-round research into physical systems that could run these quantum algorithms. First off, this ideal system has not yet been discovered, but major progress has nevertheless been achieved in several fields. Based on highly quantum systems such as nuclear **spins** (the foundations of **nuclear magnetic resonance**, **NMR**), or **ions** trapped in cavities (quantum optics), several teams have already built elementary **logical gates**. Using high-resolution NMR developed for chemistry, Isaac Chuang and co-workers from the MIT successfully implemented a factorization algorithm for the integer 15. This was achieved by designing and synthesizing a molecule with seven coupled "nuclear magnets". However, NMR cannot lead to a processor with large numbers of quantum **bits** (qubits) since the effective signal decreases rapidly with the number of qubits under study. Furthermore, it would be extremely difficult to synthesize a **molecule** with enough coupled nuclear spins to "play" a large number of algorithms. Chains of trapped ions handled individually by laser pulses are closer to the concept of a quantum processor as they form a single system in which qubits are handled and read individually and coupled among themselves. However, it appears equally difficult to integrate ion traps into circuits.



MIT/quanta group

The molecule with seven "nuclear magnets" used by the MIT's "Quanta" group to calculate the factorization of the integer 15.

Thus, these demonstration experiments, while showing promise, run up against a serious problem: manageable systems will still be too small to support useful algorithms. In fact, these microscopic approaches are seriously lacking the flexible adaptability of electronic circuits designed and built using microelectronics. This flexibility is an essential factor in building complex circuits, and without it, the future of the quantum computer remains heavily compromised. But why isn't an electronic circuit generally

just as quantum as an atom? Because an electronic circuit, which already contains a large number of atoms, connector wires, etc., is constantly "monitored" by its environment - the currents and voltages in the circuit wiring become quantities that are clearly-defined at any point in time, obeying the rules on the conventional (non-quantum) world. It is therefore impossible to put the circuit in a superposition of states corresponding to the various currents in order to take advantage of quantum parallelism.
In order to generate a quantum electronic circuit, it has to be uncoupled from its environment without breaking the connections that make it able to operate and be quantified! This is the challenge met by the **superconductor** circuit recently manufactured by a team at the Solid-state Physics Unit at the CEA Solid-state, Atoms and Molecules Research Department (Drecam). This circuit was named *quantronium* to underline its resemblance with real and highly quantum atoms.

Quantronium, an artificial atom

The quantronium developed by the Quantronics group at CEA Saclay(1) comprised an superconductor aluminium loop with three **Josephson junctions** (figure 1). A Josephson junction is a barrier separating two superconducting **electrodes** by an insulation layer so thin that electron pairs (in superconductors, the electrons are coupled in **Cooper pairs**) can "**tunnel**" through. Two small junctions outline an "island" with low **capacitance**. The island is so small that it requires a substantial amount of energy to add just a single pair of electrons, which thermal fluctuations cannot supply at low temperature. These charge states are coupled with small Josephson junctions at the left of the schema, and qubit charges, marked $|0\rangle$ and $|1\rangle$, are the combinations. The third junction is much larger, and is used to read the quantum state of the system. Superconductivity fulfils several roles in the system. First, it provides a quantum-level structure with a doublet isolated from the other two levels, the two qubit levels. Then, the electrons are all paired off and there is no longer any thermal random motion of the electrons at low temperature, which would generate a major source of decoherence for the qubit.
The level structure of quantronium, which is an artificially-manufactured atom, is governed by the **electrostatic** charge coupled to the island and by the magnetic field flux travelling through the loop. These control parameters are analogues of electrical and magnetic fields for an atom. The advantage of the quantronium over previously-studied circuits is that is presents a working point where the circuit is almost perfectly decoupled from its environment, even though the wires are still present. This working point is reached when the energy differential between the two states $|0\rangle$ and $|1\rangle$ is unresponsive to subtle variations in the control parameters. In return, at this working point the states do not inject current into the loop or the bonding wires, which precludes any quantification, but the state of the qubit can still be manipulated by pulsing the **gate** coupled to the island with microwaves tuned into the transition frequency between states $|0\rangle$ and $|1\rangle$ of the qubit, in the same way that laser pulsing applied to an atom can change its quantum state. The qubit state can then be read by applying a current pulse able to trigger or not (depending on the qubit state) a voltage at the measurement gate contacts. In fact, by sending a current through the circuit, which is like sending a flux through a circuit loop, the currents circulating in the loop can be identified for each quantum state. Since these currents are different (even opposite signs) for the two quantum states, the superconductor current travelling through the measurement junction will depend on the qubit state. If the supercurrent exceeds the critical current at the measurement junction, a finite voltage appears at the circuit contacts. The two qubit states can therefore be discriminated by measuring the voltage. In the experiments performed, the probability P of observing a finite voltage, called switching probability, follows the probability of the qubit being in state $|1\rangle$. It is this probability P that is measured in experiments and that tests the state of the qubit.
Using this measurement system, a majority of experiments that can be performed on transition between two **atomic levels** were able to be reproduced on quantronium. Thus, applying a microwave pulse frequency tuned to the qubit transition makes it possible to prepare $a|0\rangle + b|1\rangle$ -type superposition of the two quantum states. The two coefficients can be complex numbers. Starting out with state $|0\rangle$, it can evolve periodically with pulse duration, switching to state $|1\rangle$ after a half-period of oscillation, then back to $|0\rangle$ at the end of a full period. These oscillations, which are coherent with the two quantum states (figure 2), have been called Rabi oscillations since they were first performed in atomic physics by Isaac Rabi. Observing *Rabi oscillations* provides proof of the manipulation of a quantum system.

The coherence time of quantronium

For a qubit to be usable, one of the superposed states has to hold much longer than the duration of a 1- or 2-qubit operation. The **coherence** time of a superposed state is therefore an essential feature of a qubit. Coherence time is measured by preparing a superposed state $(|0\rangle + |1\rangle)$ by applying a microwave pulse. The state obtained is then left to evolve freely for a time Δt, then exactly the same pulse is repeated, after which the qubit state is read. This experiment, called *Ramsey fringes* in atomic physics, generates a beat signal that varies with time t (unlike the difference between switching and microwave frequency) and whose amplitude decreases with loss of coherence of the superposition $(|0\rangle + |1\rangle)$ (Figure 3). Coherence time thus determined is optimal at the point where the energy differential between the two states is unresponsive to subtle changes in the control parameters, and where a coherence time of 500 nanoseconds (ns) represents around 10^{-4} coherent oscillations in the qubit. Shorter than the theoretical predictions, it is limited in the experiment performed by noise interference: hot-electron noise and flux

(1) See Denis Vion, et al., *Science* **296**, 886 (2002) and the thesis written by A. Cottet, which can be found at www-drecam.cea.fr/drecam/spec/Pres/Quantro/index.htm

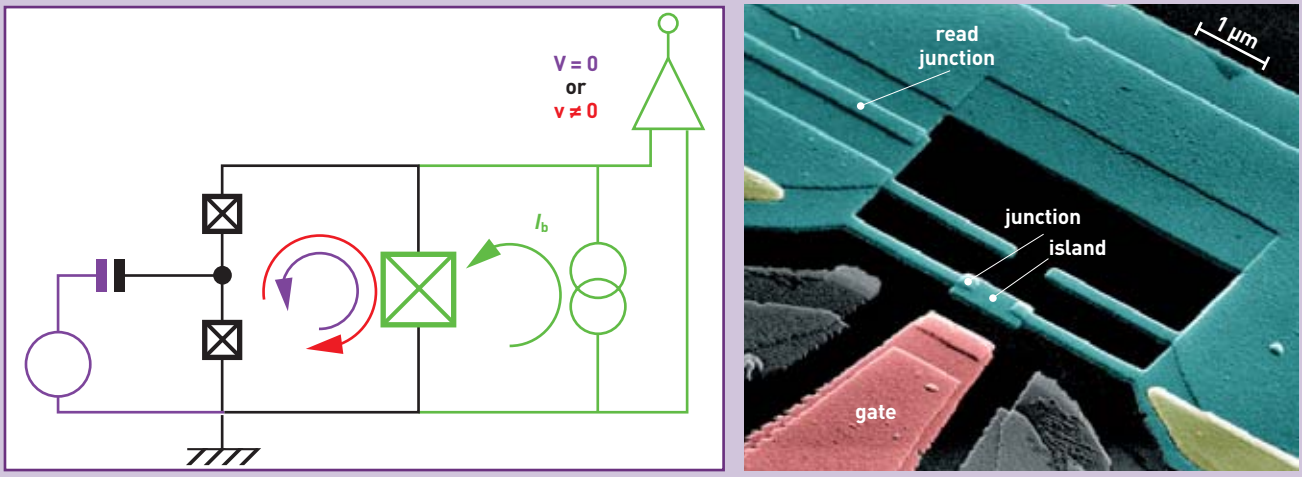


Figure 1.
Schematic diagram and electron microscope image of the central part of quantronium. Two small Josephson junctions (boxed crosses) forming a small island, and a read junction (to the right), are inserted into a loop. Grey areas in the image are (superconducting) aluminium layers covered to create the Josephson junctions. The quantronium control parameters are the gate voltage of the electrode capacitively coupled to the island, and the magnetic flux across the loop. For the qubit, the read current I_b is equal to an additional flux that develops the loop current of the two qubit states (blue arrow for $|0\rangle$, red for $|1\rangle$). When the I_b reaches the critical superconductor current at the read junction, the switching probability to a finite voltage state becomes higher for state $|1\rangle$ than state $|0\rangle$. The two qubit states can therefore be discriminated by measuring the voltage at the circuit contacts.

noise through the circuit loop. The coherence time is already longer than the duration of a one qubit operation (typically 2 ns), and longer than the predicted time for a 2-qubit operation. Furthermore, there is significant room for expansion.

NMR comes in as reinforcements

Quantum calculation will require very precise random operations from each qubit of a processor. By combining microwave pulses with $\pi/2$ phase shifts, the Quantronics group has demonstrated that it is possible to trigger random qubit transformations. Moreover, by also using the so-called composite-pulse NMR, which instead of a single pulse applies a series of pulses, the group also demonstrated that a transformation could be made robust in terms of experiment flaws such as an offset quantum transition frequency[2].

Furthermore, it is possible to counteract residual decoherence to improve the coherence time of the qubit using other methods also inspired by NMR. First, from the spin-echo technique: a microwave pulse corresponding to a reversal in qubit state makes it possible to counterbalance the decoherence exerted during two identical periods. A signal can thus be obtained for longer times than coherence time. Applying constant microwave excitation to a gate also increases the effective coherence time of a superposition of states. These rudimentary "error correction" methods will eventually be replaced by quantum error-corrector codes, although

(2) Collin et al., *Physical Review Letters* **93**, 157005 (2004).

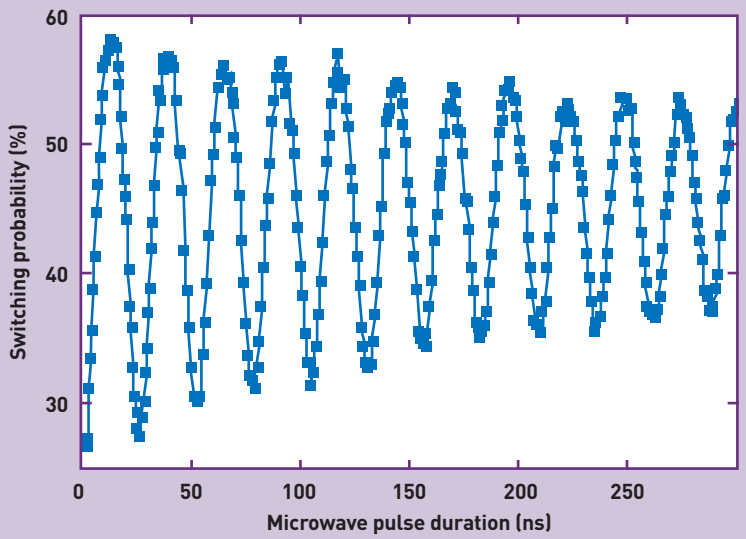


Figure 2.
Switching probability following a microwave pulse of variable duration. The curve shows coherent oscillations in qubit state between $|0\rangle$ and $|1\rangle$. These oscillations are called Rabi oscillations, named after the same experiment in atomic physics. The qubit is constantly within a superposition of its two quantum states.

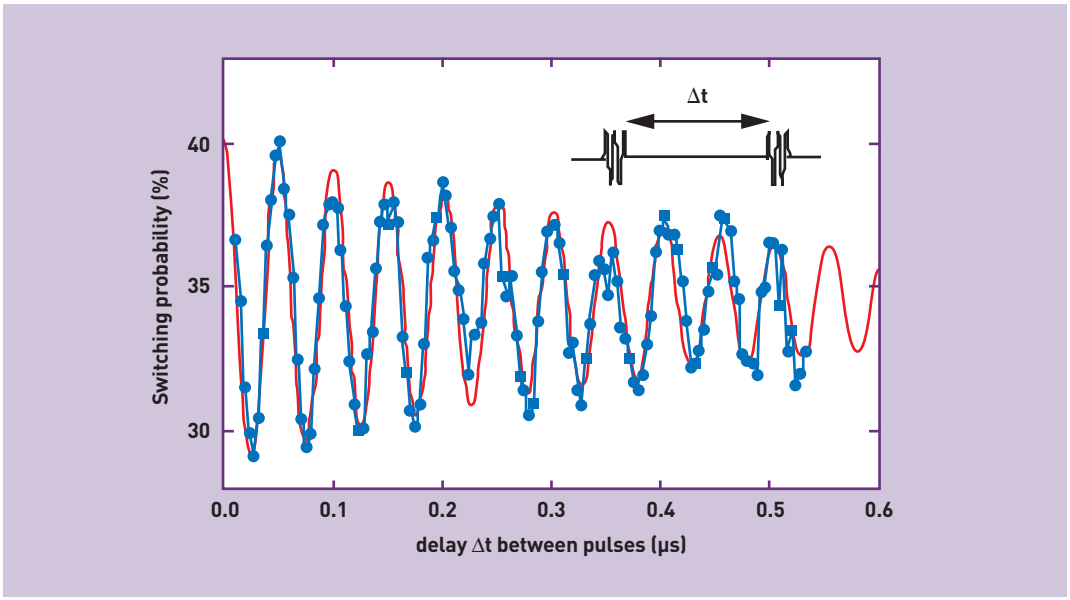


Figure 3.
Determination of quantronium quantum coherence time based on a fall-off in oscillations measured after two Rabi pulses distanced by time Δt. The probability of the qubit being in state 1 (points) oscillates with the difference frequency of the microwave and the qubit switching frequency between its two states. These oscillations are called Rabi fringes, named after the same experiment in atomic physics. They characteristically level off in a time equal to the quantum coherence time of the qubit superposition states. Adjustment by a smoothed sine curve gives a coherence time of 500 ns, which corresponds to around 10^4 coherent oscillations of the qubit.

these codes remain outside our grasp on circuits that can be produced with currently-available technology.

Towards quantum processors

While quantronium is the first functional example of a qubit manufactured with an electronic circuit, other circuits – superconductors or otherwise – are currently being developed. The results obtained with quantronium demonstrate that is possible to counter decoherence and make a genuinely quantum electronic circuit. We are close to being able to manufacture processors with a handful of qubits, which, while rudimentary, will essentially work using the resources of the quantum world. Perhaps more important is the fact that following this avenue of research will open up further insight into the astonishing laws of quantum physics, and better define the frontier between the quantum and classical worlds.

> Daniel Estève
Quantronics Group
Materials Science Division
CEA Saclay Centre

Calculation and the quantum computer

The theoretical basis of the quantum computer has been established, and the first experiments are conclusive, but researchers are still a long way from actually conceiving of the real architecture of a quantum computer. Will they one day make "qubits" the silicon of tomorrow?

In his 1998 novel *Timeline*, the bestselling American science-fiction writer Michael Crichton used **quantum** computers to calculate the space-time manipulation required for time travel. A fad? A trend? Impossible to ignore the plethora of scientific and popularized material published on the subject over the last ten years. Researchers have so far established the theoretical working principles of these rather futuristic machines, invented the new dedicated **algorithms** needed, thought about a possible architecture, and even tried some prototypes.

What's so special about quantum computers? The answer is that, theoretically, they can provide the solutions to problems that no conventional computer could possibly resolve. Computer scientists categorize problems by their "complexity" which is basically how the number of time steps required by the computing algorithm varies as a function of the problem "size". For exam-

ple, for the multiplication of two numbers, this size is the number of figures in the largest allowable number. In 1936, Alan Turing and Alonzo Church, the pioneers of computing, speculated that, for a given task, any computer needs a number of steps that does not vary more than the polynomial of the size of the problem. "Hard" problems are problems that can only be resolved after and exponential number of steps, for example 2^N steps for a problem of size N. "Easy" problems can be resolved in a polynomial time. When an easy problem of size 100 doubles, the number of steps required to resolve it can double, or else increase by a factor of 4, 8 or even 1024. In contrast, for a hard problem, the number of steps required increases by a factor of $2^{100} \simeq 1.3 \cdot 10^{30}$! One example of an important hard problem is finding the prime factors of large numbers. Many cryptographic algorithms are based on the difficulties in resolving this task. While progress in conventional computing has made it possible to "crack" 40 **bit** keys, 512 bit cryptographic keys will theoretically remain unbreakable. Unless a quantum computer (QC) finds the solution!

The fundamentals

As its name suggests, quantum mechanics (Box B, ***A guide to quantum physics***) are at the core of QCs. It therefore makes sense to revise the guiding principles. Every object or isolated system of objects is described by a function called a **wavefunction** $|\psi\rangle$. Physicists say that the object is in **quantum state** $|\psi\rangle$. This function varies in time according to the **Schrödinger equation**

$$i\hbar \frac{d}{dt}|\psi\rangle = \hat{H}|\psi\rangle$$

which itself depends on the Hamiltonian(1) $\hat{H}$ of the system (where $\hbar$ is **Planck's constant**).
Starting with this equation, the Hamiltonian has to be applied for a certain time in order to allow the system's state to evolve in the required direction. The Hamiltonian is related to the system's classical energy; most of the time a "force" is applied to the system. For example, an electrical field can be applied to an **electron**, and the momentum will evolve with the acceleration of the electron.
Then comes the measurement postulate, which is far less intuitive. It states that if we measure one of the "observables" characterizing a particle, such as its position or orbital momentum, we "collapse" the wavefunction into one of the states specific to this observable, called *eigenstate*. Any other state can be expressed as a combination of these base states. Before going further, it is important to note that the Schrödinger equation is linear: the evolution of a **superposition** of eigenstates over time is a superposition of these same evolved states.
The idea that a computer based on the principles of quantum would be far more powerful than any conventional computer possible was first put forward by Richard P. Feynman in 1982, and researchers have since developed on this idea. The potential architecture of a quantum mechanical computer can be conceived as similar to that of conventional computers. Take a system where we choose two quantum states and call them state $|0\rangle$ and state $|1\rangle$, with the system in one of these states representing its corresponding number. If we calculate its evolution correctly, we can make sure the system never enters into any other state, even if one exists.

(1) The Hamiltonian is an operator (an operation that acts on one function by changing it into another function) that correlates strongly with the classical energy system it describes.

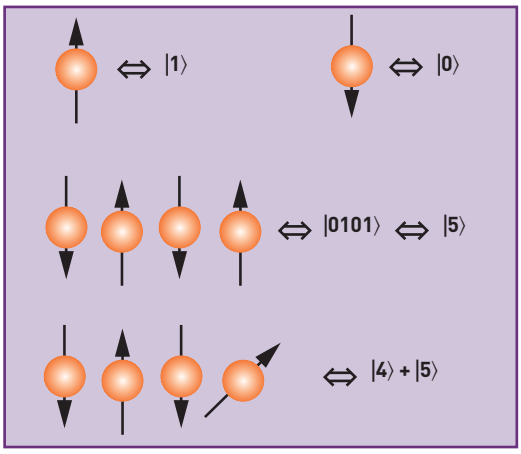


Figure.
Representation of numbers by a qubit, here by magnetic spin. The up-spin means "1", the down-spin means "0". The 4-qubit register is used to represent the figure 5. If the least significant qubit is in a superposition state, its spin is horizontal and the register represents the superposition of 4 and of 5. Most of the other superposition states require the entanglement of several qubits, which cannot be visualized simply.

Quantum parallelism

This element is called a *quantum bit*, or qubit for short. What sets it apart from a conventional bit? It can exist in a *continuum* of states: any superposition of two base states works fine. The qubit thus becomes the fundamental building block of a quantum computer, in the same way a two-position switch, which can store one bit, is fundamental to a classic computer. More qubits can be used to represent absolutely any number (Figure 1). For example, if we take 3 qubits and set one to the left in state $|1\rangle$ while the other two are in state $|0\rangle$, we get the number 4 in binary notation, i.e. $|100\rangle$.
We can create simple **logic gates** by acting on a single qubit or on qubit pairs, and then building more complex arithmetic operations, like the architect of a classical computer builds a CPU using **semiconductor** circuits performing elementary logic operations such as "no", "and" and "or".
By applying complex transformations, any arithmetical operation can therefore be done on the qubit registers. A register with N qubits will have 2^N base states: $\underbrace{|\underbrace{00\ldots00}_{N}\rangle, |00\ldots01\rangle \ldots |11\ldots11\rangle}_{2^N}$. Therefore, if we prepare the state containing the superposition of all the possible states and then run any kind of calculation on this state, we will do this calculation for all the possible 2^N values of its argument in one simple step! A classical computer, though, would take infinitely more time to so the same thing. This is an example of "quantum parallelism", a fundamental concept in quantum computing that was first presented by David Deutsch in 1985.
Unfortunately, these results can only exist within the superposition of all the possible values of the func-

tion to be calculated: should we want to measure its value, we can only recuperate a *chance* possibility, as the wavefunction would collapse into a superposition of states corresponding to the value measured. It would be far more useful to "distill" several useful pieces of information on this function into a single number, put this number into one of the quantum registers, and then measure the result. In 1994, Peter Shor suggested a way of finding a period of a function. When we calculate all the values of a periodic function, the states surviving in the superposition after the measurement will repeat periodically. For example, for a periodic function with period T, if we measured a value y such as $f(3) = y$, the following states would present as: $|\psi\rangle = |3\rangle + |3+T\rangle + |3+2T\rangle + \cdots$. We know how to then extract the useful information from a periodic sequence, using the **Fourier transform**. Following this transformation, we reach a state that is the superposition of the frequency harmonics $1/T\rangle, |2/T\rangle \cdots$. The number of steps required is a polynomial function of the size of the problem, while it increases exponentially for a classical computer. This demonstrates a problem where a quantum computer is far more powerful than its classical older brother (at least in theory), and the Church-Turing thesis is refuted.

The algorithm used to find the period of a function can also be used to resolve the problem of factorization mentioned previously. There are not, at present, many algorithms where quantum computers can outdo classical computers. Lov K. Grover devised one to perform a basic search in a non-ordered database, with decrease in number of steps of the order of $\sqrt{N}$. Feynman suggested another domain in which quantum computers would beat classical computers: the simulation of quantum systems, which requires extremely high calculation power. The state of a system with N base states is represented by a point in 2^N-dimensional space in order to track the quantum evolution of even simple systems with, for instance, 30 base states, 2^{30} complex numbers have to be followed!

The fight against decoherence

In order to build a QC, certain requirements must first be met, including being able to reinitialize the computer and to measure the state of each qubit. The most serious hurdle is the criterion of weak **decoherence**. States of superposition are easily destroyed by interaction with the environment, but for operation of QC this process must be slow. Fortunately, in 1995 Peter Shor and Andrew Steane suggested quantum-error-correcting codes, which work in a similar way to the error-correction methods used in classical computers and data transmission. The system uses redundant information which it combines with real data to detect any errors and correct them. Quantum-error-correction is more complicated that in classical mode, for several reasons. First off, errors are not **discrete**, but can be randomly small. In other words, the QC is an *analogue* device in which errors can easily accumulate. Error correction renders the QC digital. It therefore appears possible to build a quantum computer if the elementary units forming it can remain error-free for around 10^4-10^5 operations.

CEA/DSM/Drecam/Quantronics Group/Yuvanoe

Artist's impression of a microphotograph of quantronium, the first electronic circuit comprising a qubit. The graphical object at centre symbolizes the superpositions of states 0 and 1 in which this bit can be prepared.

Three CEA teams in the frontline

Now that the operating principles behind a quantum computer have been laid down, the next question how to implement them. The number of proposed qubits increases at least every month, if not every week. At the CEA, three teams are leading their research in this direction, within the Department of Fundamental Research on Condensed Matter. The most advanced of these is the Quantronics Group, which uses the quantronium device developed at Saclay (see *Towards quantum processors?*) and studied, along with its variants, by many other research teams. This circuit is able to bypass the difficulty in obtaining weak decoherence at the same time as high-precision control of the qubit using base states that can be made relatively unresponsive to random magnetic and electrical fields created by substrate impurities. The operation of a single "quantronium" qubit has been demonstrated with a respectable decoherence time of 0.5 microseconds, which is enough to perform around 8,000 operations without error. The two-qubit-gate operation is expected to be demonstrated some time soon.

CEA Saclay research engineers are also working on other proposition in partnership with *Royal Holloway College* of the University of London and several other international teams. This prototype is in many ways a combination of the other concept qubits. The qubits are formed by electrons floating on a thin layer of liquid helium covering the electrodes. An electron cannot enter the helium, but is weakly attracted to its surface. This attraction causes an analogue of a relatively large-sized hydrogen atom to form. Then, either the two lowest states of this artificial atom or the **spin** states of the electron (the approach favoured by Stephen Lyon at Princeton University) can be selected. The electric field of the electrodes is used to localize the electron at a specific site on the helium surface. The resonant frequency of the transition between the two lowest levels can be adjusted to between ~120 and ~200 GHz by changing the vertical electric field. This determines the maximum core

frequency of the computer, at about 10 GHz. Operations on a single qubit are done by tuning individual electrons in and out of resonance with the applied microwaves. Two-qubit operation is founded on **Coulomb interaction** between adjacent qubits. The major advantage this configuration has over other solid-state devices resides in the fact that the liquid helium is absolutely impurity-free, and serves to isolate the qubits from noise produced in the substrate. The decoherence time for orbital states is estimated at 100 microseconds. There is practically zero coupling between spin-states and environment: their decoherence time should therefore be at around a few seconds. The state of the electron can be measured with a highly-sensitive electrometer. Single-electron trapping has been demonstrated, but detection of the quantum state of a qubit and measurement of the decoherence time have yet to be achieved.

The state-of-the-art in quantum computers is the 7-bit processor highlighted in *Towards quantum processors*?. This is still far from impressive. Can we expect to see operational quantum computers any time in the near future? Who are the first customers likely to be? These remain difficult questions. Theoretically, a quantum computer can do everything a classical computer can, and more still. In fields such as cryptography, a QC has the potential to go way further. The answer to the question of whether it can raise market interest will depend on its ability to significantly out-perform classical devices in a few known key fields. It will also depend on new algorithms being devised so that it can demonstrate a fundamental advantage in relation to existing technology. Without this kind of breakthrough, quantum computing is going to find it extremely tough to rival the steadfast silicon-based technology.

Where reality meets sci-fi?

Timeline describes fictional events set in the year 2000: reality is certainly a long way behind the author's imagination. No billionaire has yet released the funding required to develop a quantum computer as fast as possible. But is that all that's slowing it down? Or is there fundamental problems prohibiting operation of a quantum computer?

Even if there are none, it is still an extraordinarily difficult task. Nevertheless, huge steps forward in other technologies give signs of hope. The first semiconductor transistor in 1947 measured several centimetres; in 2004, they have been scaled down to a point where tens of millions of transistors can be crammed into a far smaller volume. Hope persists that over the next half-century, a roomful of equipment today required to run a single qubit will be packed into the tip of a pen. And than, maybe, it will be possible to use them to teleport to friends or parents tiny but real copies of ourselves that can recount our latest vacation stories!

> Yury Mukharsky
Materials Science Division
CEA Saclay Centre

Semiconductor quantum dots

Most modern optoelectronic components use quantum wells capable of one-dimensional electron confinement. Quantum dots, though, which can confine electrons in all directions, make it possible to fabricate completely novel components for quantum processing, particularly in cryptography.

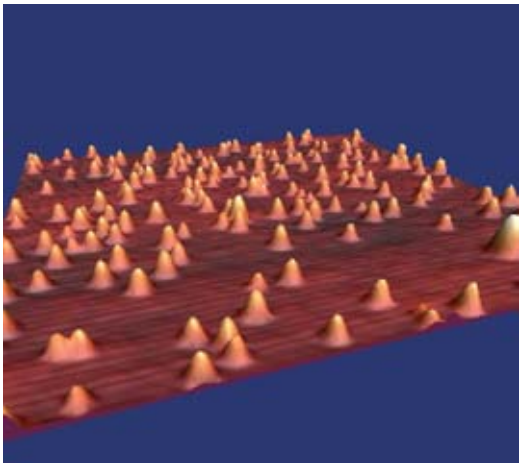
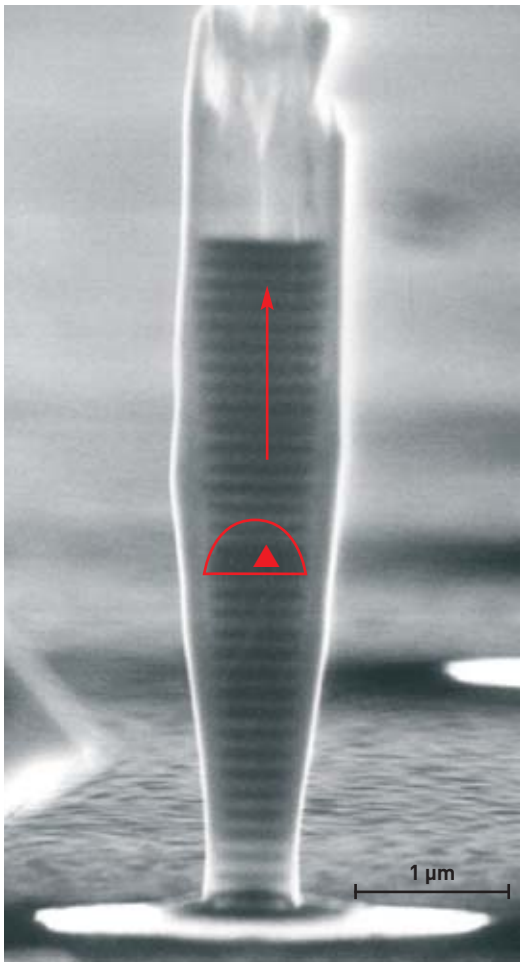


Image provided courtesy of L. Grenouillet and N. Gogneau

Figure 1. Atomic force microscopy image of an array of quantum InAs islands on GaAs. The image measures 1 µm by 1 µm, and the islands are 10 nm high by 50 nm wide.

Since the late 1970s, a major research effort has been led on the development of **semiconductor** heterostructures able to confine **electrons** at a scale of a few nanometres (nm). *Quantum wells*, which are fabricated by having a thin layer sandwiched between two layers with a wider **bandgap**, can confine electrons in one dimension. They have revolutionized **laser diode** performance and are used in most commercially-available optoelectronic components. A great deal of research is now focused on *quantum dots* (QDs), which are able to confine electrons in all dimensions. In contrast with quantum wells, QDs - like atoms - possess **discrete electronic states** and thus present an array of special properties.

In practice, an "electron box" has to be small enough to allow **quantum** effects to control their properties.



CEA

Scanning electron microscope view of a GaAs/AlAs micropillar. The centre of this optical microresonator houses the optical cavity surrounded by two Bragg mirrors made up of alternating layers of quarter-wave GaAs (grey layers) and AlAs (light layers) stacks. This micropillar has a diameter of 1 µm.

In general terms, a dot is considered "quantum" when its states have clearly spaced energy levels at the **quantum** scale of thermal energy kT (which is equal to 25 milli **electron volts** (meV) at a temperature of 300 K). This means that all the feature sizes have to be scaled down to below 10 nm. In objects this small, electronic state energies are strongly dependent on the size of the dot. Therefore, if we want to produce an array of dots with similar properties, the size has to be determined extremely accurately. For instance, size needs to vary less than 15% to ensure that the bandgap energy of the QDs fluctuates less than kT at 300°C.

At the outset, engineering 10 nm objects with nanometric precision appears to be a major challenge. Objects are currently fabricated by a self-assembly technique, as illustrated in figure 1 for an indium gallium arsenide (InAs/GaAs - indium arsenide/gallium arsenide) system, which is far and away the most extensively studied. The atomic lattice is similarfor InAs and GaAs, but with very different interatomic distances between In-As and Ga-As ($\Delta a/a = 7$ %). When, during **epitaxy** deposition, an InAs layer is grown on a GaAs substrate, the layer has to adapt its shape to take on an in-plane interatomic distance identical to the substrate's one. When the layer deposited exceeds 0.6 nm of InAs, a dense array of 3D quantum islands of InAs (10 to 1,000 islands/µm^2) forms spontaneously. This 3D surface morphology permits indeed to relax efficiently the elastic energy of the deformed InAs layer. By coating these InAs islands with a layer of GaAs, InAs can be embedded in the GaAs, which has a much larger bandgap than InAs. This forms *potential wells* for the electrons, thus forming an array of QDs. The size and shape of the quantum islands can therefore be largely engineered by adjusting the growth conditions. Thus, the emission wavelength of InAs/GaAs QDs can be tuned to between around 0.9 and 1.6 µm. Optimized growth processes can control the size to within 10%. A remarkable feature of this "natural" nanofabrication process is that it proves significantly more effective than the "**top-down**" approaches based on electronic lithography, which were therefore abandoned in the mid-1990s. It has been extended to a range of other semiconductor materials such as Si/Ge and GaN/AIN (figure 2).

A non-isolated "artificial atom"

Optical **spectroscopy** is the preferred tool for probing the electronic properties of semiconductor nanostructures. Although the effects of quantum confinement can already be observed in most sets of QD assemblies, it is particularly useful to be able to study a *single* quantum dot in order to control any inhomogeneous enlargement due to size dispersal. At low temperatures (T<50 K), a single QD presents an **emission line** and **absorption lines** which are both spectrally very narrow (a few microelectron volts). This feature highlights the discrete energy states of the box, earning it the name "artificial atom" often used when talking about QDs. However, this artificial atom is not isolated. Raising the temperature dramatically increases the emission line (~10 meV at 300 K), resulting from the coupling of this localized electronic system to the vibration modes of the **crystal**. Another QD-specific property is their ability to harness several electron-hole pairs in an extremely small space of about 100 nm^3. The emission wavelength of a QD, X_n, is highly dependent on the number n of electron-hole pairs that it contains, due to the strong **Coulomb interaction** between trapped holes and electrons (figure 3).

Image provided courtesy of B. Daudin and J.-L. Rouvière, DRFMC/SP2M

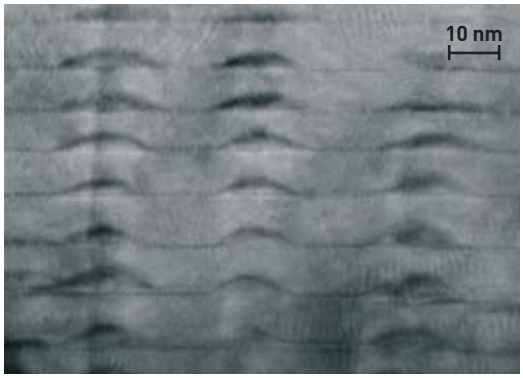


Figure 2.
GaN quantum dots (grey areas) in AlN, fabricated by molecular beam epitaxy. Cross-sectional view taken from under a transmission electron microscope.

Outlook in application

Historically, QD applications were first studied in optoelectronics in the early 1980s because of their potential advantages for laser diodes. Hope was rai-

C Molecular beam epitaxy

Quantum wells are grown using Molecular Beam Epitaxy (from the Greek *taxi*, meaning order, and *epi*, meaning over), or MBE. The principle of this physical deposition technique, which was first developed for growing III-V semiconductor crystals, is based on the evaporation of ultra-pure elements of the component to be grown, in a furnace under ultra-high vacuum (where the pressure can be as low as $5 \cdot 10^{-11}$ mbar) in order to create a pure, pollution-free surface. One or more thermal beams of atoms or molecules react on the surface of a single-crystal wafer placed on a substrate kept at high temperature (several hundred °C), which serves as a lattice for the formation of a film called epitaxial film. It thus becomes possible to stack ultra-thin layers that measure a millionth of a millimetre each, *i.e.* composed of only a few atom planes.

The elements are evaporated or sublimated from an ultra-pure source placed in an effusion cell (or Knudsen cell; an enclosure where a molecular flux moves from a region with a given pressure to another region of lower pressure) heated by the Joule effect. A range of structural and analytical probes can monitor film growth *in situ* in real time, particularly using surface quality analysis and grazing angle phase transitions by LEED (*Low energy electron diffraction*) or RHEED (*Reflection high-energy electron diffraction*). Various spectroscopic methods are also used, including Auger electron spectroscopy, secondary ion mass spectrometry (SIMS), X-ray photoelectron spectrometry (XPS) or ultraviolet photoelectron spectrometry (UPS).

As *ultra-high-vacuum* technology has progressed, molecular beam epitaxy has branched out to be applied beyond III-V semiconductors to embrace metals and insulators. In fact, the vacuum in the growth chamber, whose design changes depending on the properties of the matter intended to be deposited, has to be better than 10^{-11} mbar in order to grow an ultra-pure film of exceptional crystal quality at relatively low substrate temperatures. This value corresponds to the vacuum quality when the growth chamber is at rest. Arsenides, for example, grow at a residual vacuum of around 10^{-8} mbar as soon as the arsenic cell has reached its set growth temperature.

The pumping necessary to achieve these performance levels draws on several techniques using ion pumps, cryopumping, titanium sublimation pumping, diffusion pumps or turbomolecular pumps. The main impurities (H_2, H_2O, CO and CO_2) can present partial pressures of lower than 10^{-13} mbar.

sed that a QD array would present a very narrow gain curve typical of systems with discrete electronic levels, in contrast with quantum wells where the electrons inserted in are distributed thermally within a *kT-width* bandstate. This better use of inserted electrons was expected to lead to a substantial improvement in the threshold current[1], maximum modulation frequency and temperature stability of laser diodes. Ten years after the first quantum dot laser was demonstrated, this hope has largely faded. Indeed, the band gain for an array of real QDs is significantly broadened by both QD size fluctuations and more intrinsic phenomena such as crystal vibration coupling.

Today, it is clear that QD lasers are not ready to replace quantum well lasers, but will rather fulfil certain technological niche applications. Start-ups like Zia Laser in the USA or NL nanosemiconductor in Germany are looking to market InAs QD diode lasers at 1.3 µm for fiberoptic communications interconnects. These components are engineered on GaAs substrate and offer highly temperature-stable properties and therefore can forego a thermal regulation module, which is an advantage over conventional laser diodes based on InGaAsP quantum wells on Indium phosphide (InP) wafers.

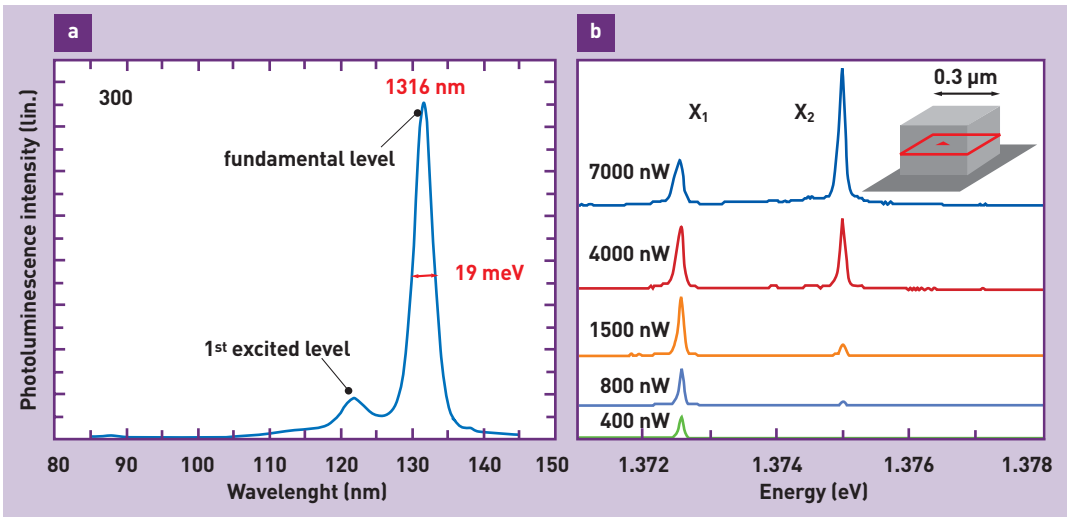


Figure 3.
a) emission spectrum at 300 K of an array of InAs/GaAs quantum dots (courtesy of the thesis written by V. Célibert).
b) emission spectrum variation at 4 K of a single QD isolated into a lithographed pattern (diagram in insert) in relation to excitation energy. At low excitation, the QD contains one electron-hole pair at most, and presents a single emission line (X_1). Line X_2, which appears at higher excitation, is emitted by the QD when it contains two electron-hole pairs.

The promising prospects of single-photon source

The highly specific properties of QDs can also be applied to developing pioneering new optoelectronic components. One of these is the single **photon** source (SPS), whose active environment is formed of a single QD placed in an optical microcavity(2). An SPS is a component that is able to emit, in a controlled way, light pulses containing a one single photon. Currently, development efforts are mainly driven by the potential for innovation in quantum cryptography which codes information into quantum objects and uses the principles of quantum physics to ensure the information exchange processes are absolutely confidential. It is expected that in the longer term, SPSs will probably become also important components of metrology applications.

Figure 4 shows the operating principle underlying the application of SPSs to QDs. Pulsed **optical pumping** or electrical pumping are used to excite matter in the region of an isolated QD; this stimulates the QD to capture several electron-hole pairs (figure 4a). These pairs then go through radiative recombination sequences, with each photon being emitted at a specific energy X_n. Spectral filtering can then select the unique X_1 line of the QD, to prepare one pulse containing a single photon for each pumping cycle.

The spontaneous emission of a QD is generally omnidirectional. For the SPSs to become really useful, single photons have to be efficiently collected and prepared in a given state (propagation direction, spatial mode, **polarization**). The most powerful approach developed thus far involves inserting the QD into a micropillar, like the one shown on p. 25. This optical microcavity, which confines the photons in three dimensions at the wavelength scale, possesses discrete modes. The optical confinement considerably enhances the interaction between electromagnetic field and emitter. Making the QD resonate with one of the confined modes generates a sharp increase in the spontaneous emission of the QD (a phenomenon known as the P*urcell effect*) and high photon collection efficiency in this electromagnetic mode. First developed in 2001 at the CNRS Laboratory for Photonics and Nanostructures (LPN), this SPS system is already demonstrating very promising results for quantum cryptography.

Conceptually speaking, the SPS is the first optoelectronic component that works based on a quantum cavity electrodynamic effect, in this case the Purcell effect. This preliminary results have paved an exciting future for developments in the association of QDs and very small semiconductor microcavities ($V \sim \lambda^3$). Under particular conditions, spontaneous emission becomes reversible, and the atom/cavity coupling evolves deterministically, even without applying any driving electromagnetic field. This system is set to open up very promising perspectives for quantum information processing. In addition, thanks to spontaneous emission control by optical microcavities, microlaser threshold currents will be significantly scaled down. The predicted room temperature threshold current should be far lower than one microampere when QDs are inserted into ultimate-sized optical microcavities ($V \sim (l/2)^3$), a startling comparison with the value of just a few milliamperes obtained with a standard laser diode. In terms of potential applications, miniaturizing and cutting the threshold current of laser sources are the first steps towards the integration of high-density *intra-chip* optical interconnects into electronic circuits. Autonomous optical micro-sensors are also often cited as potential innovation applications for the biomedical and environmental sciences.

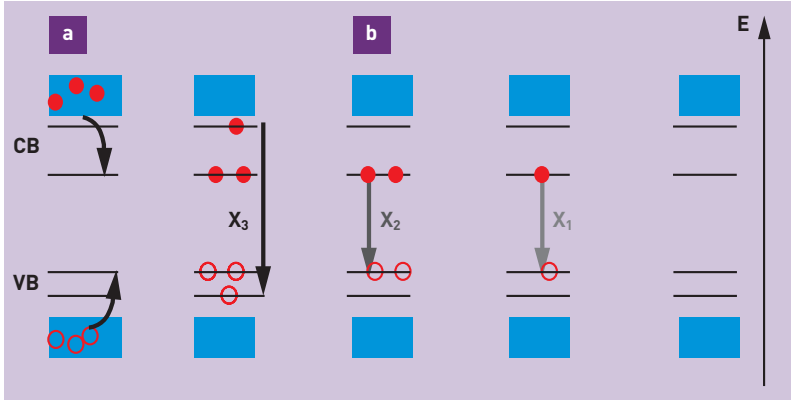
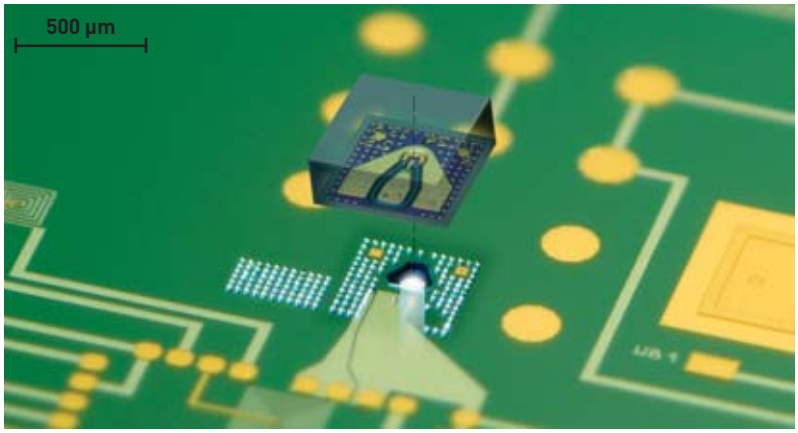


Figure 4.
Diagram view of the conduction band (CB) and valence band VB) states of the quantum dot (lines) and the GaAs lattice (grey continuum), together with the protocol followed to generate a single photon with a quantum dot. a) optical or electrical GaAs excitation, and capture of electrons and holes (illustrated as red circles) by the QD. b) captured electron-hole pairs recombining one-by-one, emitting at each stage a photon whose energy depends one the number of residual pairs in the QD. Spectral filtering of the emission line X_1 for targeting a single photon.



Artechnique

Photomontage showing flip-chip assembly on a silicon optical bench of a wide-wavelength laser based on a VCSEL (Vertical Cavity Surface Emitting laser)-type quantum dot. This product was developed as part of the joint laboratory research project CLOVIS partnering the CEA-Leti and Intexys.

> **Jean-Michel Gérard**
Materials Science Division
> **Philippe Gilet**
Technological Research Division
CEA Grenoble Centre

(1) Threshold current: minimal amperage that when injected into a semiconductor laser can trigger a laser action.

(2) Optical cavity: space between two laser mirrors holding the modes generated by the existence of static light waves inside the cavity. Each mode has a different frequency.

A From the macroscopic to the nanoworld, and vice versa...

In order to gain a better idea of the size of microscopic and nanoscopic* objects, it is useful to make comparisons, usually by aligning different scales, *i.e.* matching the natural world, from molecules to man, to engineered or fabricated objects (Figure). Hence, comparing the "artificial" with the "natural" shows that artificially-produced **nanoparticles** are in fact smaller than red blood cells.

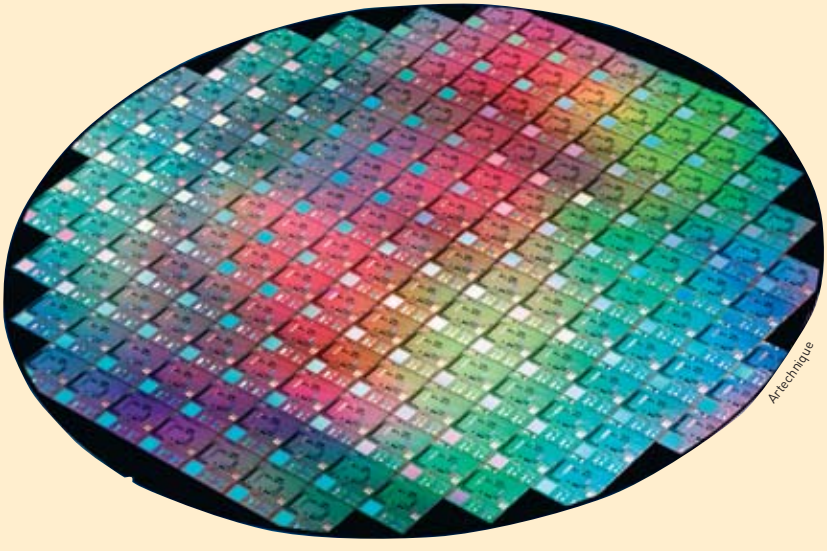
Another advantage of juxtaposing the two is that it provides a good illustration of the two main ways of developing nanoscale systems or objects: ***top-down*** and ***bottom-up***. In fact, there are two ways into the nanoworld: molecular manufacturing, involving the control of single **atoms** and the building from the ground up, and extreme miniaturization, generating progressively smaller systems.

Top-down technology is based on the artificial, using macroscopic materials that we chip away using our hands and our tools: for decades now, electronics has been applied using **silicon** as a substrate and what are called "**wafers**" as workpieces. In fact, microelectronics is also where the "top-down" synthesis approach gets its name from. However, we have reached a stage where, over and above simply adapting the miniaturization of silicon, we also have to take on or use certain physical phenomena, particularly from **quantum** physics, that operate when working at the nanoscale.

The bottom-up approach can get around these physical limits and also cut manufacturing costs, which it does by using component **self-assembly**. This is the approach that follows nature by assembling molecules to create **proteins**, which are a series of amino acids that the super-molecules, *i.e.* **nucleic acids** (**DNA**, **RNA**), are able to produce within cells to form functional structures that can reproduce in more complex patterns. Bottom-up synthesis aims at structuring the material using "building blocks", including atoms themselves, as is the case with living objects in nature. Nanoelectronics seeks to follow this assembly approach to make functional structures at lower manufacturing cost.

The **nanosciences** can be defined as the body of research into the physical, chemical or biological properties of nano-objects, how to manufacture them, and how they self-assemble by auto-organisazation.

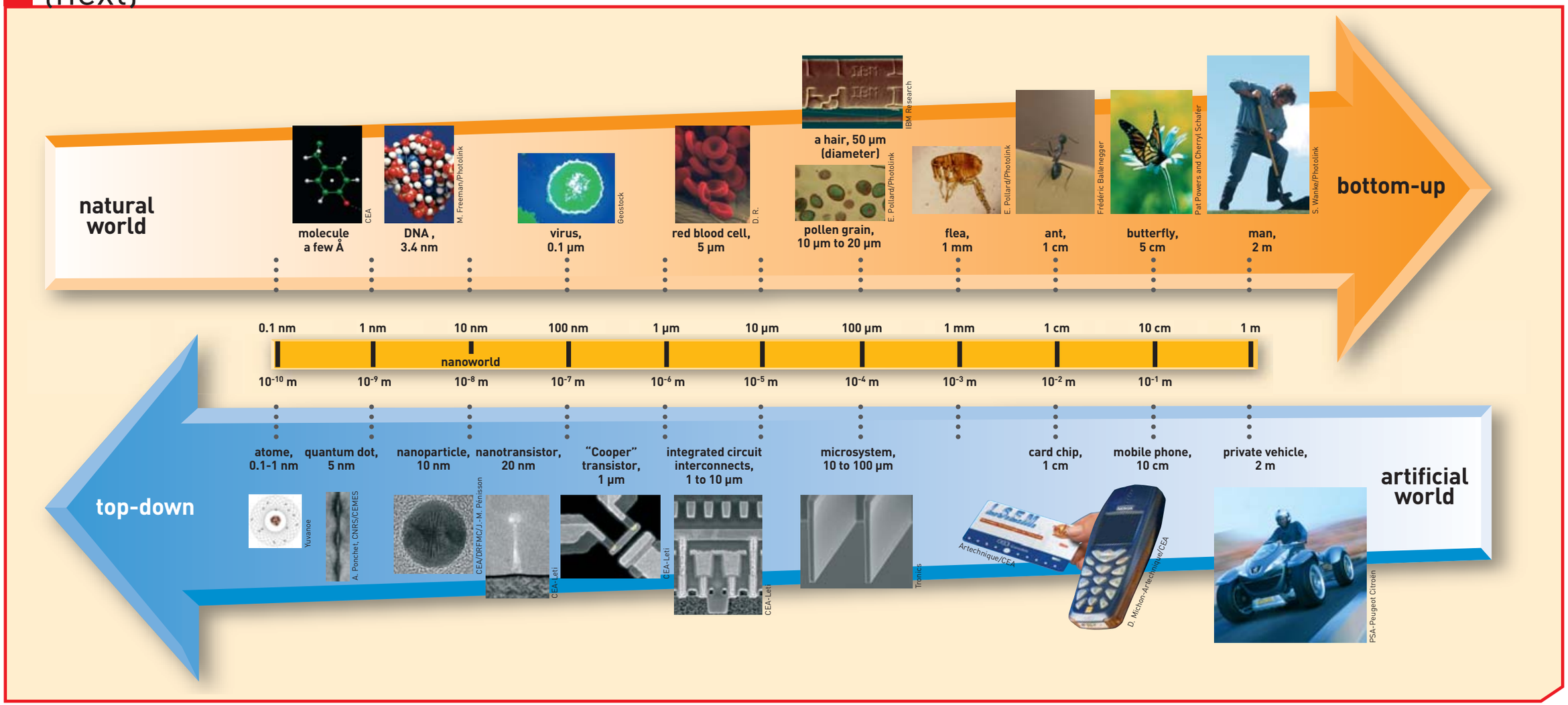
Nanotechnologies cover all the methods that can be used to work at molecular scale to reorganize matter into objects and materials, even progressing to the macroscopic scale.



300-mm silicon wafer produced by the Crolles2 Alliance, an illustration of current capabilities using top-down microelectronics.

* From the Greek *nano meaning* "very small", which is also used as a prefix meaning a billionth (10^{-9}) of a unit.
In fact, the **nanometre** (1 nm = 10^{-9} metres , or a billionth of a metre), is the master unit for nanosciences and nanotechnologies.

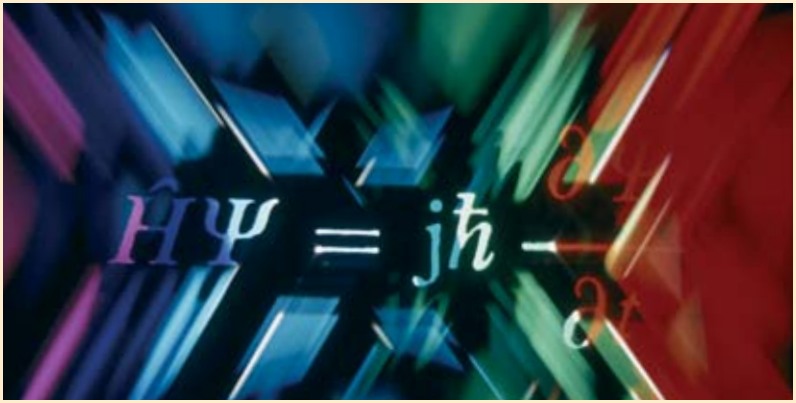
A (next)


natural world
bottom-up
molecule a few Å
CEA
DNA , 3.4 nm
M. Freeman/Photolink
virus, 0.1 µm
Geostock
red blood cell, 5 µm
D. R.
a hair, 50 µm (diameter)
IBM Research
pollen grain, 10 µm to 20 µm
E. Pollard/Photolink
flea, 1 mm
E. Pollard/Photolink
ant, 1 cm
Frédéric Ballenegger
butterfly, 5 cm
Pat Powers and Cherryl Schafer
man, 2 m
S. Wanke/Photolink
0.1 nm
1 nm
10 nm
100 nm
1 µm
10 µm
100 µm
1 mm
1 cm
10 cm
1 m
nanoworld
10^{-10} m
10^{-9} m
10^{-8} m
10^{-7} m
10^{-6} m
10^{-5} m
10^{-4} m
10^{-3} m
10^{-2} m
10^{-1} m
top-down
artificial world
atome, 0.1-1 nm
Yuvanoe
quantum dot, 5 nm
A. Ponchet, CNRS/CEMES
nanoparticle, 10 nm
CEA/DRFMC/J.-M. Pénisson
nanotransistor, 20 nm
CEA-Leti
"Cooper" transistor, 1 µm
CEA-Leti
integrated circuit interconnects, 1 to 10 µm
CEA-Leti
microsystem, 10 to 100 µm
Tronics
card chip, 1 cm
Artechnique/CEA
mobile phone, 10 cm
D. Michon-Artechnique/CEA
private vehicle, 2 m
PSA-Peugeot Citroën

B A guide to quantum physics

Quantum physics (historically known as quantum mechanics) covers a set of physical laws that apply at microscopic scale. While fundamentally different from the majority of laws that appear to apply at our own scale, the laws of quantum physics nevertheless underpin the general basis of physics at all scales. That said, on the macroscopic scale, quantum physics in action appears to behave particularly strangely, except for a certain number of phenomena that were already curious, such as superconductivity or superfluidity, which in fact can only explained by the laws of quantum physics. Furthermore, the transition from the validating the paradoxes of quantum physics to the laws of classical physics, which we find easier to comprehend, can be explained in a very general way, as will be mentioned later.

Quantum physics gets its name from the fundamental characteristics of quantum objects: characteristics such as the angular momentum (spin) of discrete or discontinuous particles called quanta, which can only take values multiplied by an elementary *quantum*. There is also a quantum of action (product of a unit of energy multiplied by time) called Planck's constant (symbolized as h) which has a value of 6.626×10^{-34} joule·second.



D. Sarraute/CEA

An "artist's impression" of the Schrödinger equation.

While classical physics separates *waves* from *particles*, quantum physics somehow covers both these concepts in a third group, which goes beyond the simple wave-particle duality that Louis de Broglie imagined. When we attempt to comprehend it, it sometimes seems closer to waves, and sometimes to particles. A quantum object cannot be separated from how it is observed, and has no fixed attributes. This applies equally to a particle - which in no way can be likened to a tiny little bead following some kind of trajectory - of light (photon) or matter (electron, proton, neutron, atom, etc.).

This is the underlying feature behind the Heisenberg uncertainty principle, which is another cornerstone of quantum physics. According to this principle (which is more *indeterminacy* than *uncertainty*), the position and the velocity of a particle cannot be measured *simultaneously* at a given point in time. Measurement remains possible, but can never be more accurate than *h*, Planck's constant. Given that these approximations have no intrinsically real value outside the observation process, this simultaneous determination of both position and velocity becomes simply impossible.

B (next)

At any moment in time, the quantum object presents the characteristic of *superposing* several states, in the same way that one wave can be the *sum* of several others. In quantum theory, the amplitude of a wave (like the peak, for example) is equal to a **probability amplitude** (or probability wave), a complex number-valued function associated with each of the possible sates of a system thus described as quantum. Mathematically speaking, a physical state in this kind of system is represented by a **state vector**, a function that can be added to others *via* superposition. In other words, the sum of two possible state vectors of a system is *also* a possible state vector of that system. Also, the product of two vector spaces is also the sum of the vector products, which indicates **entanglement**: as a state vector is generally spread through space, the notion of local objects no longer holds true. For a pair of entangled particles, *i.e.* particles created together or having already interacted, that is, described by the *product* and not the *sum* of the two individual state vectors, the fate of each particle is linked - entangled - with the other, regardless of the distance between the two. This characteristic, also called *quantum state entanglement*, has staggering consequences, even before considering the potential applications, such as quantum cryptography or - why not? - teleportation. From this point on, the ability to predict the behaviour of a quantum system is reduced to probabilistic or statistical predictability. It is as if the quantum object is some kind of "juxtaposition of possibilities". Until it has been measured, the measurable size that supposedly quantifies the physical property under study is not strictly defined. Yet as soon as this measurement process is launched, it destroys the **quantum superposition** through the "collapse of the wave-packet" described by Werner Heisenberg in 1927. All the properties of a quantum system can be deduced from the equation that Erwin Schrödinger put forward the previous year. Solving the **Schrödinger equation** made it possible to determine the energy of a system as well as the **wave function**, a notion that tends to be replaced by the probability amplitude.

According to another cornerstone principle of quantum physics, the **Pauli exclusion principle**, two identical half-spin ions (**fermions**, particularly electrons) cannot simultaneously share the same position, spin and velocity (within the limits imposed by the uncertainty principle), *i.e.* share the same *quantum state*. **Bosons** (especially photons) do not follow this principle, and can exist in the same quantum state.

The coexistence of **superposition states** is what lends **coherence** to a quantum system. This means that the theory of **quantum decoherence** is able to explain why macroscopic objects, atoms and other particles, present "classical" behaviour whereas microscopic objects show quantum behaviour. Far more influence is exerted by the "environment" (air, background radiation, etc.) than an advanced measurement device, as the environment radically removes all *superposition of states* at this scale. The larger the system considered, the more it is coupled to a large number of degrees of freedom in the environment, which means the less "chance" (to stick with a probabilistic logic) it has of maintaining any degree of quantum coherence.

TO FIND OUT MORE:

Étienne Klein, *Petit voyage dans le monde des quanta*, Champs, Flammarion, 2004.

C Molecular beam epitaxy

Quantum wells are grown using Molecular Beam Epitaxy (from the Greek *taxi*, meaning order, and *epi*, meaning over), or MBE. The principle of this physical deposition technique, which was first developed for growing III-V semiconductor crystals, is based on the evaporation of ultra-pure elements of the component to be grown, in a furnace under ultra-high vacuum (where the pressure can be as low as $5 \cdot 10^{-11}$ mbar) in order to create a pure, pollution-free surface. One or more thermal beams of atoms or molecules react on the surface of a single-crystal wafer placed on a substrate kept at high temperature (several hundred °C), which serves as a lattice for the formation of a film called epitaxial film. It thus becomes possible to stack ultra-thin layers that measure a millionth of a millimetre each, *i.e.* composed of only a few atom planes.

The elements are evaporated or sublimated from an ultra-pure source placed in an effusion cell (or Knudsen cell; an enclosure where a molecular flux moves from a region with a given pressure to another region of lower pressure) heated by the Joule effect. A range of structural and analytical probes can monitor film growth *in situ* in real time, particularly using surface quality analysis and grazing angle phase transitions by LEED (*Low energy electron diffraction*) or RHEED (*Reflection high-energy electron diffraction*). Various spectroscopic methods are also used, including Auger electron spectroscopy, secondary ion mass spectrometry (SIMS), X-ray photoelectron spectrometry (XPS) or ultraviolet photoelectron spectrometry (UPS).

As *ultra-high-vacuum* technology has progressed, molecular beam epitaxy has branched out to be applied beyond III-V semiconductors to embrace metals and insulators. In fact, the vacuum in the growth chamber, whose design changes depending on the properties of the matter intended to be deposited, has to be better than 10^{-11} mbar in order to grow an ultra-pure film of exceptional crystal quality at relatively low substrate temperatures. This value corresponds to the vacuum quality when the growth chamber is at rest. Arsenides, for example, grow at a residual vacuum of around 10^{-8} mbar as soon as the arsenic cell has reached its set growth temperature.

The pumping necessary to achieve these performance levels draws on several techniques using ion pumps, cryopumping, titanium sublimation pumping, diffusion pumps or turbomolecular pumps. The main impurities (H_2, H_2O, CO and CO_2) can present partial pressures of lower than 10^{-13} mbar.

D The transistor, fundamental component of integrated circuits

The first transistor was made in germanium by John Bardeen and Walter H. Brattain, in December 1947. The year after, along with William B. Shockley at Bell Laboratories, they developed the bipolar transistor and the associated theory. During the 1950s, transistors were made with silicon (Si), which to this day remains the most widely-used semiconductor due to the exceptional quality of the interface created by silicon and silicon oxide (SiO_2), which serves as an insulator. In 1958, Jack Kilby invented the integrated circuit by manufacturing 5 components on the same substrate. The 1970s saw the advent of the first microprocessor, produced by Intel and incorporating 2,250 transistors, and the first memory. The complexity of integrated circuits has grown exponentially (doubling every 2 to 3 years according to "Moore's law") as transistors continue to become increasingly miniaturized.

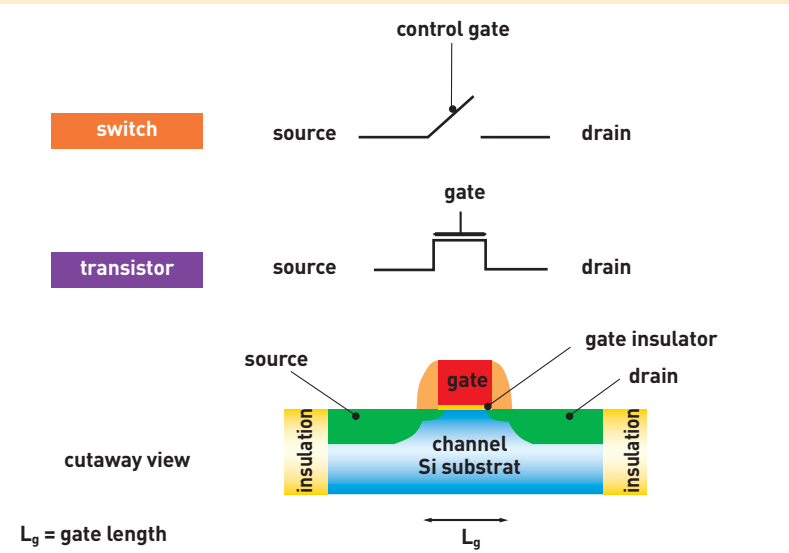


Figure.
A MOS transistor is a switching device for controlling the passage of an electric current from the source (S) to the drain (D) via a gate (G) that is electrically insulated from the conducting channel. The silicon substrate is marked B for Bulk.

The transistor, a name derived from *trans*fer and res*istor*, is a fundamental component of microelectronic integrated circuits, and is set to remain so with the necessary changes at the nanoelectronics scale: also well-suited to amplification, among other functions, it performs one essential basic function which is to open or close a current as required, like a switching device (Figure). Its basic working principle therefore applies directly to processing binary code (0, the current is blocked, 1 it goes through) in logic circuits (inverters, gates, adders, and memory cells).

The transistor, which is based on the transport of electrons in a solid and not in a vacuum, as in the electron tubes of the old triodes, comprises three electrodes (*anode, cathode* and *gate*), two of which serve as an electron *reservoir*: the source, which acts as the emitter filament of an electron tube, the drain, which acts as the collector plate, with the gate as "controller". These elements work differently in the two main types of transistor used today: *bipolar junction transistors*, which came first, and *field effect transistors* (FET).

Bipolar transistors use two types of charge carriers, electrons (negative charge) and holes (positive charge), and are comprised of identically doped (p or n) semiconductor substrate parts

D (next)

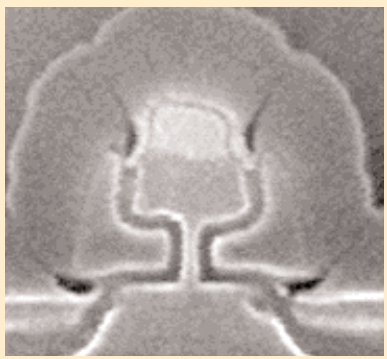
separated by a thin layer of inversely-doped semiconductor. By assembling two semiconductors of opposite types (a p-n junction), the current can be made to pass through in only one direction. Bipolar transistors, whether n-p-n type or p-n-p type, are all basically current amplifier controlled by a gate current[1]: thus, in an n-p-n transistor, the voltage applied to the p part controls the flow of current between the two n regions. Logic circuits that use bipolar transistors, which are called TTL (for transistor-transistor logic), consume more energy than field effect transistors which present a zero gate current in off-state and are voltage-controlled.

Field effect transistors, most commonly of **MOS** (metal oxide semiconductor) type, are used in the majority of today's **CMOS** (C for complementary) logic circuits[2]. Two n-type regions are created on a p-type silicon crystal by doping the surface. These two regions, also called drain and source, are thus separated by a very narrow p-type space called the **channel**. The effect of a positive current on the control electrode, naturally called the **gate**, positioned over the semiconductor forces the holes to the surface, where they attract the few mobile electrons of the semiconductor. This forms a conducting channel between source and drain (Figure). When a negative voltage is applied to the gate, which is electrically insulated by an oxide layer, the electrons are forced out of the channel. As the positive voltage increases, the channel resistance decreases, letting progressively more current through.

In an integrated circuit, transistors together with the other components (**diodes**, condensers, resistances) are initially incorporated into a "chip" with more or less complex functions. The circuit is built by "sandwiching" layer upon layer of conducting materials and insulators formed by **lithography** (Box E, ***Lithography, the key to miniaturization***). By far the most classic application of this is the microprocessor at the heart of our computers, which contains several hundred million transistors (whose size has been reduced 10,000-fold since the 1960s), soon a billion. This has led to industrial manufacturers splitting the core of the processors into several subunits working in parallel!

Lucent Technologies Inc./Bell Labs

The very first transistor.



STMicroelectronics

8 nanometre transistor developed by the Crolles2 Alliance bringing together STMicroelectronics, Philips and Freescale Semiconductor.

(1) This category includes **Schottky transistors** or **Schottky barrier transistors** which are field effect transistors with a metal/semiconductor control gate that, while more complex, gives improved charge-carrier mobility and response times.

(2) Giving **MOSFET** transistor (for Metal Oxide Semiconductor Field Effect Transistor).

E Lithography, the key to miniaturization

Optical lithography (photolithography) is a major application in the particle-matter interaction, and constitutes the classical process for fabricating integrated circuits. It is a key step in defining circuit patterns, and remains a barrier to any future development. Since resolution, at the outset, appears to be directly proportional to wavelength, feature-size first progressed by a step-wise shortening of the wavelength λ of the radiation used.

Artechnique

Photolithography section in ultra-clean facilities at the STMicroelectronics unit in Crolles (Isère).

The operation works via a reduction lens system, by the *exposure* of a photoresist film to energy particles, from the ultraviolet (UV) photons currently used through to X photons, ions, and finally electrons, all through a mask template carrying a pattern of the desired circuit. The aim of all this is to transfer this pattern onto a stack of insulating or conducting layers that make up the mask. These layers will have been deposited previously (the *layering* stage) on a wafer of semiconductor material, generally silicon. After this process, the resin dissolves under exposure to the air (*development*). The exposed parts of the initial layer can then be etched selectively, then the resin is lifted away chemically before deposition of the following layer. This lithography step can take place over twenty times during the fabrication of an integrated circuit (Figure).

In the 1980s, the microelectronics industry used mercury lamps delivering near-UV (g, h and i lines) through quartz optics, with an emission line of 436 nanometres (nm). This system was able to etch structures to a feature-size of 3 microns (μm). This system was used through to the mid-90s, when it was replaced by excimer lasers emitting far-UV light (KrF, krypton fluoride at 248 nm, then ArF, argon fluoride at 193 nm, with the photons thus created generating several electronvolts) that were able to reach a resolution of 110 nm, pushed to under 90 nm with new processes.

In the 1980s, the CEA's Electronics and Information Technology Laboratory (Leti) pioneered the application of lasers in lithography and the fabrication of integrated circuits using excimer lasers, and even the most advanced integrated circuit production still uses these sources.

The next step for high-volume production was expected to be the F_2 laser (λ = 157 nm), but this lithography technology has to all intents and purposes been abandoned due to complications involved in producing optics in CaF_2, which is transparent at this wavelength. While the shortening of wavelengths in exposure tools has been the driving factor behind the strong resolution gain already achieved, two other factors have nevertheless played key roles. The first was the development of polymer-lattice photoresists with low absorbance at the wavelengths used, implementing progressively more innovative input energy reflection/emission systems. The second was enhanced optics reducing diffraction interference (better surface quality, increase in numerical aperture).

Over the years, the increasing complexity of the optical systems has led to resolutions actually *below* the source wavelength. This development could not continue without a major technological breakthrough, a huge step forward in wavelength. For generations of integrated circuits with a lowest resolution of between 80 and 50 nm (the next "node" being at 65 nm), various different approaches are competing to offer particle projection at ever-shorter wavelengths. They use either "soft" X-rays at extreme ultraviolet wavelength (around 10 nm), "hard" X-rays at wavelengths below 1 nm, ions or electrons.

The step crossing below the 50 nm barrier will lead towards low-electron-energy (10 eV)-enabled nanolithography with technology solutions such as the scanning tunnelling microscope and molecular beam epitaxy (Box C) for producing "superlattices".

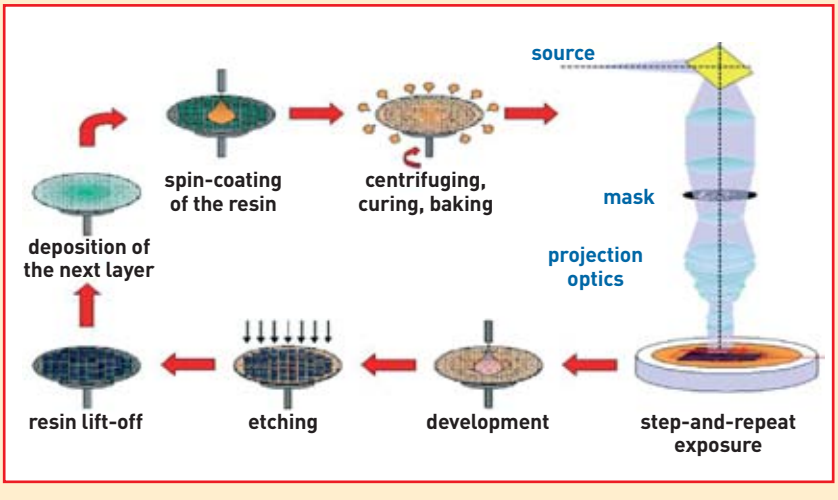


Figure. The various phases in the lithography process are designed to carve features out of the layers of conducting or insulating materials making up an integrated circuit. The sequences of the operation are laying of a photoresist, then projecting the pattern on a mask using a reduction optics system, which is followed by dissolution of the resin that is exposed to the light beam (development). The exposed parts of the initial layer can then be etched selectively, then the resin is lifted away before deposition of the following layer.

G The tunnel effect, a quantum phenomenon

Quantum physics predicts unexpected behaviour that defies ordinary intuition. The tunnel effect is an example. Take the case of a marble that rolls over a bump. Classical physics predicts that unless the marble has enough kinetic energy it will not reach the top of the bump, and will roll back towards its starting point. In quantum physics, a particle (proton, electron) can get past the bump even if its initial energy is insufficient, by "tunnelling" through. The tunnel effect makes it possible for two protons to overcome their mutual electrical repulsion at lower relative velocities than those predicted by classical calculations.

Tunnel effect microscopy is based on the fact that there is a finite probability that a particle with energy lower than the height of a potential barrier (the bump) can still jump over it. The particles are electrons travelling through the space between two electrodes. These electrodes are a fine metal tip terminating in a single atom, and the metal or semiconductor surface of the sample. In classical physics a solid surface is considered as a well-defined boundary with electrons confined inside the solid. By contrast, in quantum physics each electron has wave properties that make its location uncertain. It can be visualized as an electron cloud located close to the surface. The density of this cloud falls off exponentially with increasing distance from the solid surface. There is thus a certain probability that an electron will be located "outside" the solid at a given time. When the fine metal tip is brought near the surface at a distance of less than a nanometre, the wave function associated with the electron is non-null on the other side of the potential barrier and so electrons can travel from the surface to the tip, and *vice versa*, by the tunnel effect. The potential barrier crossed by the electron is called the tunnel barrier. When a low potential is applied between the tip and the surface, a tunnel current can be detected. The tip and the surface being studied together form a local tunnel junction. The tunnel effect is also at work in Josephson junctions where a direct current can flow through a narrow discontinuity between two superconductors.

In a transistor, an unwanted tunnel effect can appear when the insulator or grid is very thin (nanometre scale). Conversely, the effect is put to use in novel devices such as Schottky barrier tunnel transistors and carbon nanotube assemblies.