Single-electron switching on chips

The nanoscale circuit has become reality

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Very little distinguishes the first transistor presented by Bell Telephone Labs researchers Bardeen, Shockley, and Brattain in 1947 from the Single Electron Transistor (set) developed by tu delft physicist Pieter Heij. The set, which switches using single electrons, can only be observed with the aid of an electron microscope. Over the past four years, Heij has worked at the Quantum Transport group of professor Dr. Ir. Hans Mooij and Dr. Peter Hadley to develop techniques for joining sets into larger units that can be used for logical operations. This involved the extremely accurate positioning of successive layers of atoms, some of which were only just thick enough to enable electrons to tunnel through. The current models still require extremely low temperatures to work.

Inevitably, the continuing miniaturisation of electronic circuits will grind to a halt at some point. For example,
the oxide layer of the transistors on the latest Pentium chip has a thickness of no more than seven atom layers. Manufacturing a chip's entire surface to the same thickness is immensely difficult - and consequently, very expensive. Making the components on a chip smaller also makes the circuits faster, but increases overall power consumption.

Heij: 'The current generation of transistors - measuring about 180 nanometres - is already running into its natural limits. The Pentium chips become much too hot and require massive fans to cool them. This wouldn't happen with a Single Electron Transistor, which uses much less energy, so they can be arranged much closer together.'

Coulomb blockade
But sets have problems all of their own. The moment you enter the atomic realm, the laws of classical physics start to lose their meaning. Electrons no longer behave the way they ought to in a «classical» electric current. Heij explains: 'The basis of each set is formed by a junction of two conductors separated by a thin insulating layer. We call this a tunnel junction. Normally, the junction is out of bounds to electrons. However, quantum mechanics show us that the electron has a chance of shooting straight through. This is the tunnel effect.'

Under certain conditions, the influx of electrons can even be accurately controlled, thanks to the Coulomb blockade, an effect noted by Leiden physicist C.J. Gorter as long ago as 1951. Once an electron crosses, the blockade prevents other electrons from following the first electron's example. The tunnelling of separate electrons is a bit like a dripping tap. Since the electrons are temporarily prevented from crossing the insulating layer, the electrical charge at the surface of one of the two conductors increases. Once the collected charge reaches a sufficient level, a new electron can shoot across and so reduce the charge, just like a drop of water falls from a tap when the maximum surface tension is reached. In order to release each subsequent drop, the Coulomb blockade must first be overcome, so a new charge must collect.

Absolute zero
A Single Electron Transistor is nothing but a piece of conductive material with a tunnel junction on either side. Each time an electron enters on one side, another electron is removed on the other side. The only way to suppress the Coulomb blockade is by varying the charge applied to the central section. This is done by charging a capacitor connected to it. When the Coulomb blockade disappears, the current suddenly increases dramatically. Heij: 'Even so, in spite of all the exotic effects, a set differs very little from a «normal» transistor: it uses slight variations in the voltage applied to the base electrode to switch a current. This switching effect results in a voltage that is greater than the one applied to the base electrode, and so you end up with an amplifier.'

The first sets, which were made as far back as the late nineteen-eighties, worked at temperatures just above
absolute zero, which meant they were of little use for practical application in computer chips. Major efforts to achieve the same effect at room temperatures have been launched, particularly in Asia.

Heij: 'In order to be able to achieve this, the tunnel junctions must be made as small as possible. They have been scaled down to one square nanometre, but these are very difficult to reproduce. To obtain a single junction that works, you might have to make several thousands that turn out to be too large. That type of research did not appeal to us. It is much more fun to concentrate on designing and manufacturing set-based circuits. After all, you have to be able to tie them all together in the right order before you can use them to actually do things. That was something nobody had been able to do yet.' Working with relatively large components means that any measurements must be conducted at low temperatures - only a few thousandths of a degree above absolute zero - inside a helium cryostat.

Heij: 'The cryostat is part of our standard equipment. The hard bit was actually linking the sets together on a chip, even if they were slightly larger than is actually possible.'

Lithographic techniques were used to create the pattern for the various components and wiring. This is done by exposing a thin layer of photosensitive material, called the photoresist, through a mask and then treating it with a solvent that removes only the sensitised material in the exposed areas. The process is very much like developing photographic prints. The process enables highly complex patterns to be created in an area only micrometres across. In order to achieve the required nanometre resolution, Heij used an electron beam instead of visible light. Since the wavelength of electrons is much smaller than that of light, it can be used to create much finer detail. Heij used an electron beam pattern generator, which is an electron microscope that has been reprogrammed to enable it to be used for writing as well as viewing. The resulting patterns were coated with a thin layer of aluminium using a vapour-deposition process.

Breakthrough
The application of the aluminium layer is done using an installation developed by the department itself.

Heij: 'We start by suspending the silicon wafer at the top end of a vacuum chamber. At the bottom end we vapourise a quantity of aluminium by heating it with an electron gun. The result is that once the aluminium atoms reach the top of the chamber, they are all travelling in the same direction. This enables us to make them hit the substrate at any specific angle."

By using a mask and suspending the wafer at various different angles, Heij obtained a shadow effect, which enabled him to determine the exact amount of overlap between successive layers. The overlap is the bit that forms the tunnel junction.

Heij: 'After applying the first layer, we allow a tiny amount of oxygen into the vacuum chamber. This creates an oxide layer, the thickness of which we can control to within very precise limits - down to a few
tenths of a nanometre. This is important, since the oxide layer forms the core of the junction. It is the spot where the electrons tunnel through."

The same trick was used to create the link between two different sets. In this case the layer had to be slightly thicker in order to prevent the tunnelling effect. Under no circumstances should the sets contact each other directly, but they must be able to sense each other. Heij tried without success to achieve this using thin layers of silicon oxide, but the result proved too «leaky».

Heij: "Our great breakthrough came when we thought of using oxygen to create an insulating layer. To obtain sufficient insulation, the new layer had to be thicker than the one in the tunnel junction. So we created a high-energy plasma at the surface of the aluminium by applying a considerable voltage. The idea seems simple, but nobody had thought of it before. Until then, the oxygen was used only to create the layers for tunnel junctions."

Memory cell
Once the manufacturing methods had been developed, the testing could start. Heij was the first to create a memory cell that could be read by means of a small current using a number of sets connected together. Scientists all over the world are engaged in research to create Single Electron Memories (sems) this way, but the Delft version is the most elegant by far, requiring only two instead of four or six sets. Heij then focused on making an inverter, which is a component that converts a positive voltage into a negative voltage and vice versa. Heij: 'Again, a pair of connected sets will do the job. The basic principle is in fact fairly simple: using a control electrode, each set can be driven to block the current independently of the other. The beauty of our inverter lies in the fact that its output voltage is higher than the input voltage. This kind of amplification is essential for building complex chips, for otherwise you would end up with no voltage at all after a couple of components.' Basically, the path has been cleared for manufacturing a chip containing large numbers of these components.

Heij: 'The only problem is how to drive each one of them separately, but that is something the boys in the chips industry will know how to do. The technology we have developed for connecting sets can also be used for the ultra-small tunnel junctions that operate at room temperature. It's going to take a lot of manpower, so my guess is that the Asian countries will be the first to tackle it.'

The Delft technology has not been patented.

Heij: 'With the exception of the plasma oxidisation technique, much of the individual steps involved in the process was prior art. The only thing we did was to take them and to combine and use them in a slightly different way.'

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Schematic diagram showing the quantummechanical tunnel effect. (a) Initially, the plane separating the conductor and the insulator is practically charge-neutral. (b) As the electrons flow into the electrode, a charge builds up at the conductor's surface. (c) Once a sufficient charge has built up, an electron tunnels through the insulator, reducing the surface charge, so the whole process can repeat itself.
Test results of the Coulomb blockade in a Single Electron Transistor (SET). At a switching voltage of 0 V and the current is blocked up to a supply voltage of approximately 100 mV. This is caused by the Coulomb blockade: as the size of the transistor decreases, more energy is required to overcome the blockade. If the control voltage is increased to 30 mV, a current starts to flow.
Schematic diagram showing the shadow deposition process. (a) Top view of the mask used to create a tunnel junction in the electron-sensitive resist layer. (b) A section through the dotted line in (a). The first aluminium film is deposited at an angle under high-vacuum conditions. (c) After oxidisation with oxygen, the second aluminium film is deposited at a different angle. (d) Electrom Microscope image of the cross-section through a completed tunnel junction.
Pieter Heij wanted to stop electrons from tunnelling though in certain locations. This required a much thicker layer of aluminium oxide than was possible using standard oxidisation techniques. By using oxidisation in an oxygen plasma while heating the sample to 200 °C, oxide layers up to 10 nm thick could be made that provided perfect insulation. (a) The first layer of aluminium has a natural oxide skin about 3 nm thick. (b) The layer is further oxidised by exposing it to an oxygen plasma. (c) The second layer of aluminium overlaps the first layer to form a capacitor. (d) Top view of two SETs connected together. The dumbbell shape was created first by means of oxidisation in an oxygen plasma, after which the overlapping SETs were created using the shadow evaporation technique.

Close-up view of part of a silicon wafer containing the electronic circuitry and the (visible) contact points for the SETs. The wafer on the left still carries its green electron-sensitive resist-layer, while the wafer on the right has had a metal film vapour-deposited on it, after which the resist was removed with a solvent.

Inside the air lock of the evaporation installation, the aluminium is oxidised in contact with an oxygen plasma (a cloud of ionised oxygen gas), which shows as a green luminescence. The light-coloured area at the centre is the location of the silicon wafer during the oxidisation process.
Zooming in on the SETs, from 1 mm to 1 µm.
A wire bonder is used to connect the chip to the outside world using ultrathin bonding wires. These wires are bonded to the terminals by means of friction. At the end of the arm, a minute bit vibrating at a high frequency holds the wire against the terminal to bond the two together.

Close-up view of the connecting wire and the bit.
Heij's chip is ready to undergo a series of cryostat tests at temperatures close to absolute zero (−273 °C). Each series of tests takes a few weeks, several days of which are spent gradually cooling the test object to the desired temperature.