Seeing the atoms that will shape our future

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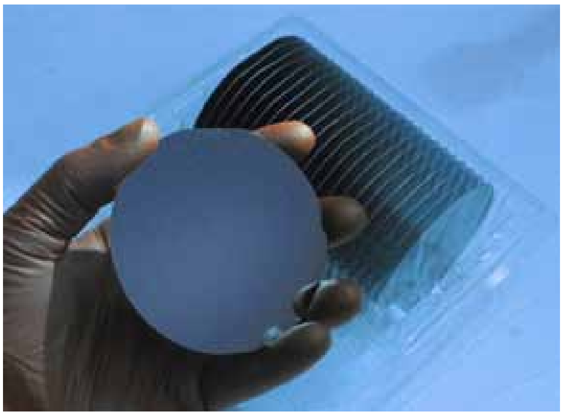
The last few decades are often described as the Information Age. In this time, the way people use and share knowledge has changed faster than at any other time in history. This has been driven largely by the constant improvement of integrated circuits, brought about by shrinking circuit components and packing more of them onto a single silicon chip.

Technologies created in this way have brought us a wide variety of innovations including programmable household appliances that improve our energy efficiency, cars that automatically find the quickest route to any destination to help us save time, and smart phones and the internet to allow us to stay connected to each other.

However, we are reaching a point where components on silicon chips have become so small that soon even a single misplaced atom might change the way a chip behaves. Researchers in the London Centre for Nanotechnology at University College London (UCL) are at the forefront of efforts to study how different arrangements of only a few atoms in silicon could be used to make radically new types of computers.

Silicon, dopants and transistors

One of the most fundamental breakthroughs that enabled the creation of highly scaled integrated circuits was the discovery of how mono-crystalline silicon (see photo) can be produced with unprecedented purity. Silicon is one of the most abundant materials in the universe and is found in common materials such as sand. A crystal made out of silicon atoms is semiconducting: its properties lie between an insulator and a conductor and can easily be tuned into one or the other using electric fields (gating) or impurities (doping).



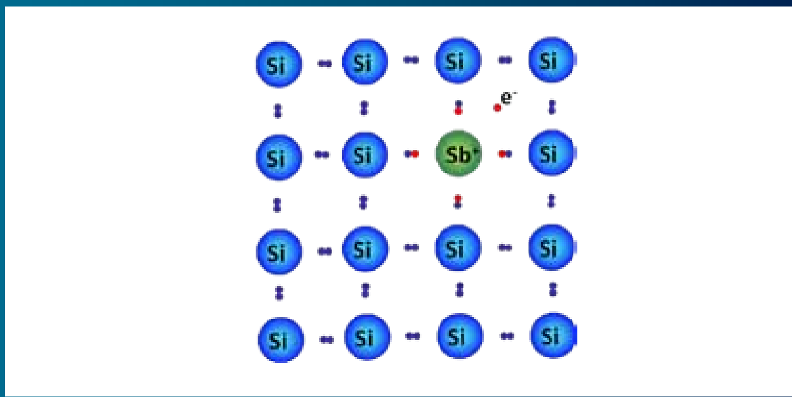
A thin slice cut from a single crystal of high-purity silicon. A wafer like this is used to make hundreds of individual integrated circuits.

The concept of doping is explained in Box 1. It relies on the introduction of non-silicon atoms, called dopants, into the crystal. These dopants either introduce or remove electrons, enabling the engineering of the local charge and conduction characteristics in silicon. Carefully controlling the size and layout of doped areas then allows the fabrication of the fundamental building block of integrated circuits, the transistor.

However, since the next generation of transistors will be less than 100 atoms wide, it will become necessary not only to restrict the area in which the dopants are present but also to control exactly the position of each individual dopant atom. This is a huge challenge, as ways have to be found that allow placing single dopants with atomic scale precision.

Box 1 Doping semiconductors

Silicon has four electrons in its outermost shell. In a crystal, every silicon atom is bonded to four neighbouring atoms. This means that every electron is involved in a covalent bond, leaving no free charges to conduct electrical current.



By introducing impurities with either five or only three electrons in their outermost shell, electrons or holes (i.e. the absence of electrons, which leaves a positive charge) can be introduced into the crystal, enabling the engineering of the electrical properties of the silicon.

Studying dopants

Studying individual dopant atoms and controlling their location is difficult, as the lengths involved are even smaller than the wavelength of light. This means that single donor atoms cannot be looked at, even with the most advanced optical microscope. To overcome this fundamental problem, researchers at UCL use a Scanning Tunnelling Microscope (STM), which is described in Box 2.

This highly advanced microscope was invented by G. Binning and H. Rohrer in 1981, for which they were awarded the Physics Nobel Prize five years later. To create an image of the surface, an STM uses an atomically sharp tip that is computer controlled and "feels" the surface corrugation. This

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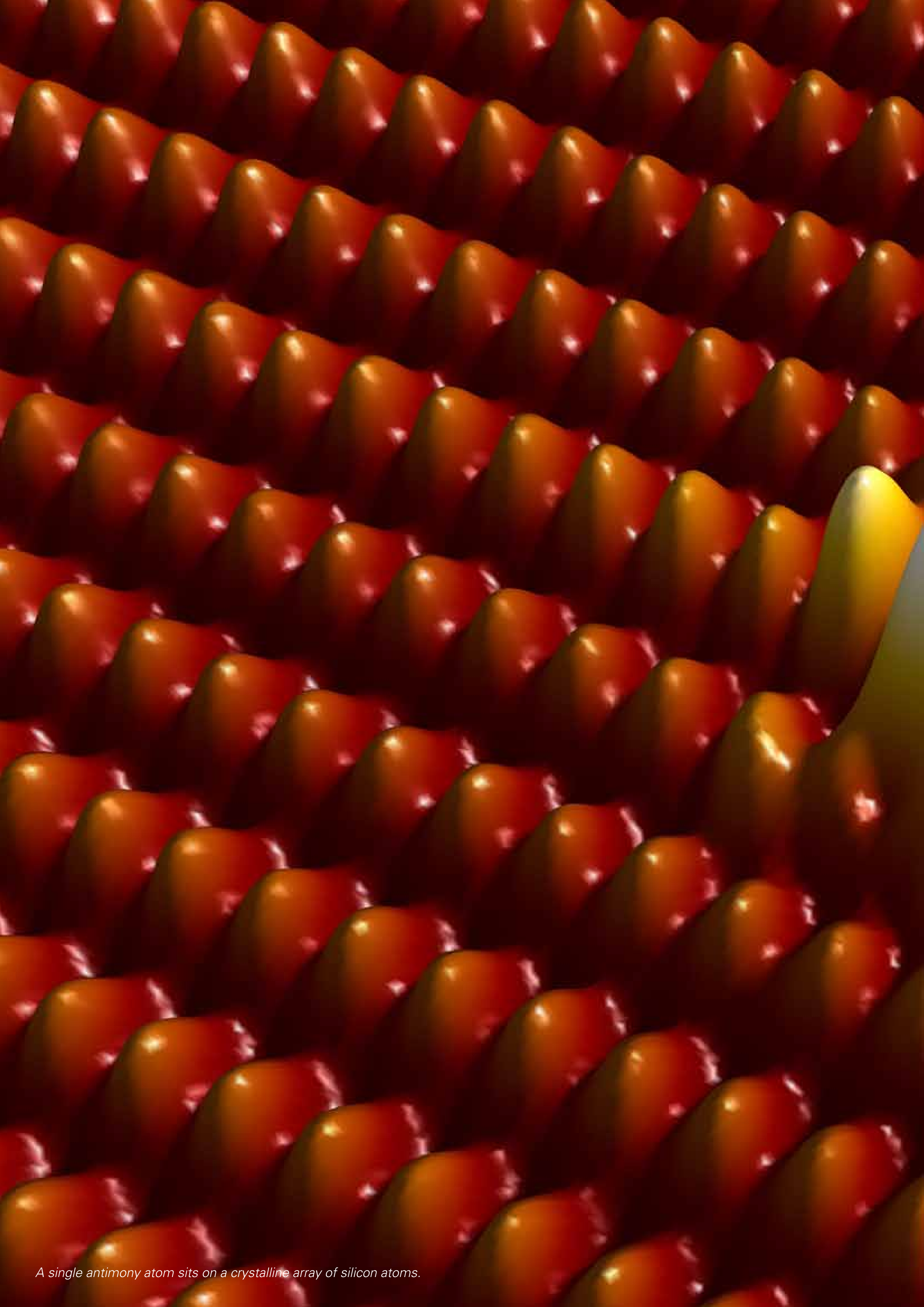

A single antimony atom sits on a crystalline array of silicon atoms.

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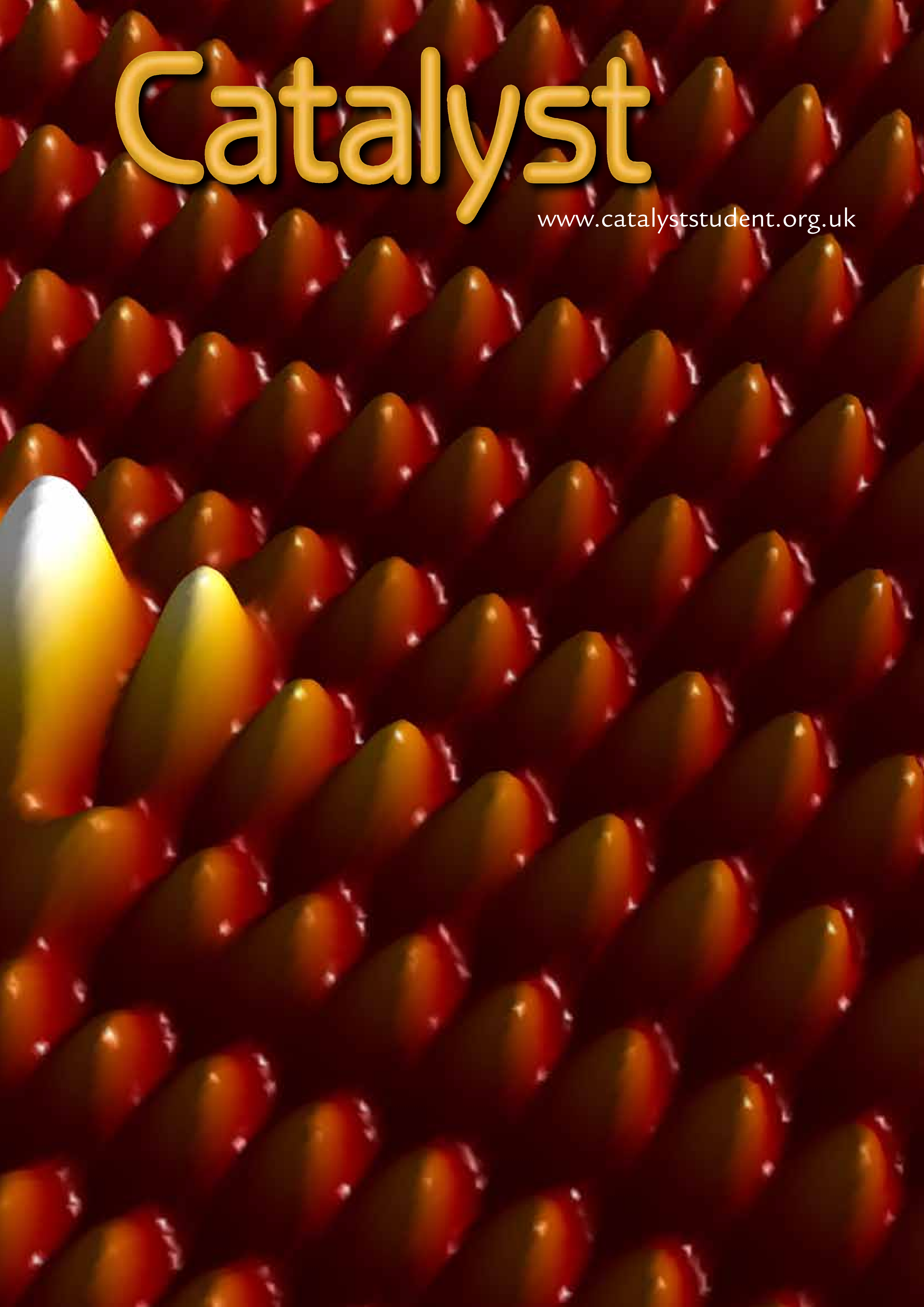
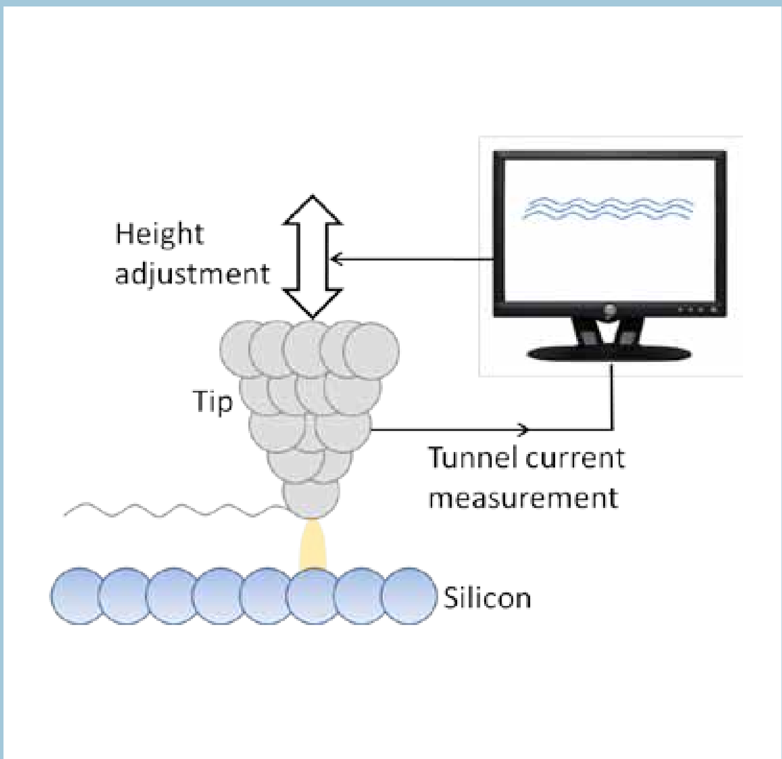


avoids the use of light and enables the visualization of individual atoms, as shown on pages 10-11.

The image shows a silicon crystal surface where every protrusion represents a single silicon atom. The central disturbance is caused by a single antimony (Sb) dopant and it can be seen how it has a huge influence on its surroundings. Using images such as this, researchers can investigate structural and electronic properties of individual donor atoms and furthermore determine the dopant position with atomic scale precision.

Box 2 Scanning tunnelling microscopy



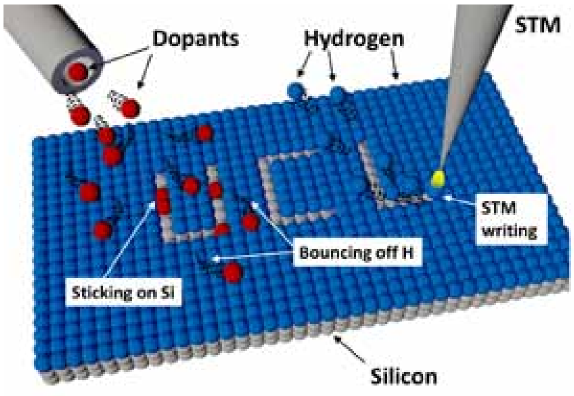
Scanning tunnelling microscopes use a sharp metal tip that is brought very close to the surface. A voltage is applied between the tip and the sample and the quantum mechanical tunnel effect allows electrons to cross the gap between tip and sample. The current created by these tunnelling electrons is so incredibly sensitive to the distance between the tip and the sample that it allows the microscope to "feel" whether the tip is on top of or in between two atoms. By recording the height profile of a complete area, a topography image of the surface is made.

Manipulating atoms

The truly amazing advantage of an STM is however not just the visualization of dopant atoms, but the fact that it also has the unique capability to manipulate individual atoms, one at a time. This is achieved by using the tip of the microscope to influence individual atomic bonds on the surface, enabling the creation of electronic devices with unprecedented length scales and accuracy.

The process for making such atomic scale devices is shown in the diagram (above right). In a first step, the silicon crystal surface is covered with a one atom thick layer of hydrogen, changing the chemical reactivity of the surface and preventing any other atoms from sticking. As shown in the image, electrons with a high energy, ejected from the STM tip, can then be used to selectively remove individual hydrogen atoms. This allows the creation of precisely controlled holes in the hydrogen layer, exposing the underlying silicon atoms.

To fabricate devices, dopants are then filled into these holes by evaporating them onto the whole area. The dopants only stick to the exposed silicon atoms where the hydrogen layer was removed; they simply bounce off the rest of the surface. This enables the placement of dopants with atomic scale precision and can be used to make prototype devices for the next generation of integrated circuits.



Using a scanning tunnelling microscope to write with individual atoms on a silicon surface

Future devices

Besides pushing conventional circuit components to their smallest possible size, this fabrication process can also be used to create more exotic devices. The current rate of miniaturization will reach a level where a device consists of only a few atoms in less than a decade, so it seems the trend in miniaturization cannot continue forever. Researchers are therefore already trying to find alternative ways to implement more powerful computing concepts.

By using dopant atoms to fabricate quantum bits (qubits), exotic quantum properties such as entanglement and superposition could be harnessed to solve complicated calculations significantly faster than with conventional computers. The ability to place and characterize dopants at the atomic scale offers the exciting opportunity to build prototypes of such devices and study their characteristics, hopefully enabling the breakthrough for the next generation of computational concepts such as spintronics or quantum information processing.

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