at low gate voltages, at room temperature. This lowers the threshold voltage at which the transistor switches 'on', with serious implications for circuit performance. Peaks in the conductance as a function of gate voltage at low temperature confirm that only a small number of dopant atoms are determining the behaviour of the transistor. The main impact of the CEA work derives from this link between severe threshold-voltage fluctuations at room temperature caused by a single dopant atom, and the understanding of transport through individual dopant atoms gained from low-temperature tunnelling spectroscopy.

The CEA team also show that the ionization energy of the single dopant in the channel of their transistor can be as high as twice the bulk value. The ionization energy is the energy required to excite a charge carrier that is bound to the dopant so that it can move freely through the semiconductor, and its value directly influences device functionality. Sanquer and colleagues observe that this energy rises as the dopant moves closer to the oxide layer that separates the gate and the channel in their devices, consistent with previous studies that showed the ionization energy of a donor increasing in the vicinity of a dielectric interface[2–4]. The CEA data show the impact of a single donor on transistor function at room temperature, and demonstrate that dopant position, as well as number, contributes to variability, compounding this difficult problem.

The relevance of this work extends beyond industrial device optimization, to new applications that use the unique quantum properties of single dopants. In quantum computation, for example, a gated
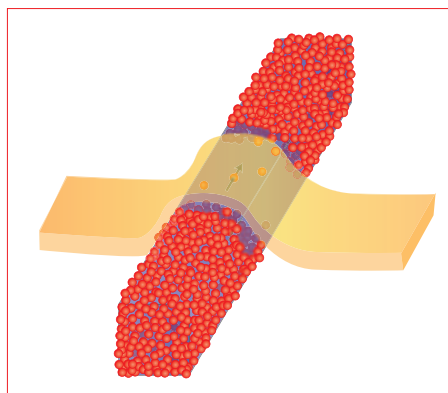
Figure 1 | The transistors made by Sanquer and co-workers[1] contain a short silicon channel between source (bottom left) and drain (top right) contacts that contain a high concentration of arsenic dopant atoms (red balls). A gate electrode (beige) is used to control the flow of charge through the channel. During the fabrication process some of the dopant atoms are unintentionally placed in the channel, resulting in higher currents through the channel at low gate voltages.

donor is used to address and link quantum bits, and this approach has received detailed theoretical and experimental attention[5–8]. As single donors become more important to devices, it will become increasingly important to control position and ionization energies, for the reasons made clear by Sanquer and colleagues.

In the longer term, the ultimate challenge for nanoscale devices will be deterministic doping. In this fast-developing field, researchers are using both top-down and

bottom-up techniques to overcome the random placement of dopants. Although single-ion implantation has been achieved with an accuracy of about 10 nm using conventional top-down techniques[9,10], fluctuations in the performance of devices made using this method persist. Subnanometre precision may be required to remove variability, and has in fact already been achieved using atomic hydrogen as a resist layer on scanning-tunnelling-microscope-patterned silicon, followed by chemical vapour deposition of dopants[11,12]. Transistors fabricated by this technique have been measured *ex situ* and show Coulomb blockade, a tell-tale sign of transport through a nanostructure. We therefore expect significant progress towards functional quantum devices and field-effect transistor structures with atomic precision in the near future. ❑

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PROBE MICROSCOPY

Images from below the surface

An atomic force microscope can reveal a range of subsurface information about a sample through mechanical excitation of both the sample and the tip.

Ricardo Garcia

Imaging beneath the surface of a sample has always been a challenge in microscopy. Typically, high-resolution images of a subsurface structure are obtained by slicing the material and observing the newly created surface, but this approach can also damage the sample. Atomic force microscopy (AFM) has been used to study the morphology of a wide variety of surfaces at the

nanoscale, but subsurface imaging has usually been considered beyond the scope of these instruments. Writing in *Nature Nanotechnology*, Laurene Tetard, Ali Passian and Thomas Thundat of the Oak Ridge National Laboratory and the University of Tennessee now report that an AFM can be used to image subsurface structures with nanoscale resolution without damaging them[1].

Passian and co-workers have built an instrument that combines elements of ultrasonic[2–5] and dynamic force[6–8] microscopies to generate images of structures that lie below the surface of biological and synthetic materials. In dynamic AFM, a mechanical excitation causes the ultrasharp tip of the microscope to oscillate, and nonlinear tip–surface forces modify the amplitude and phase of these
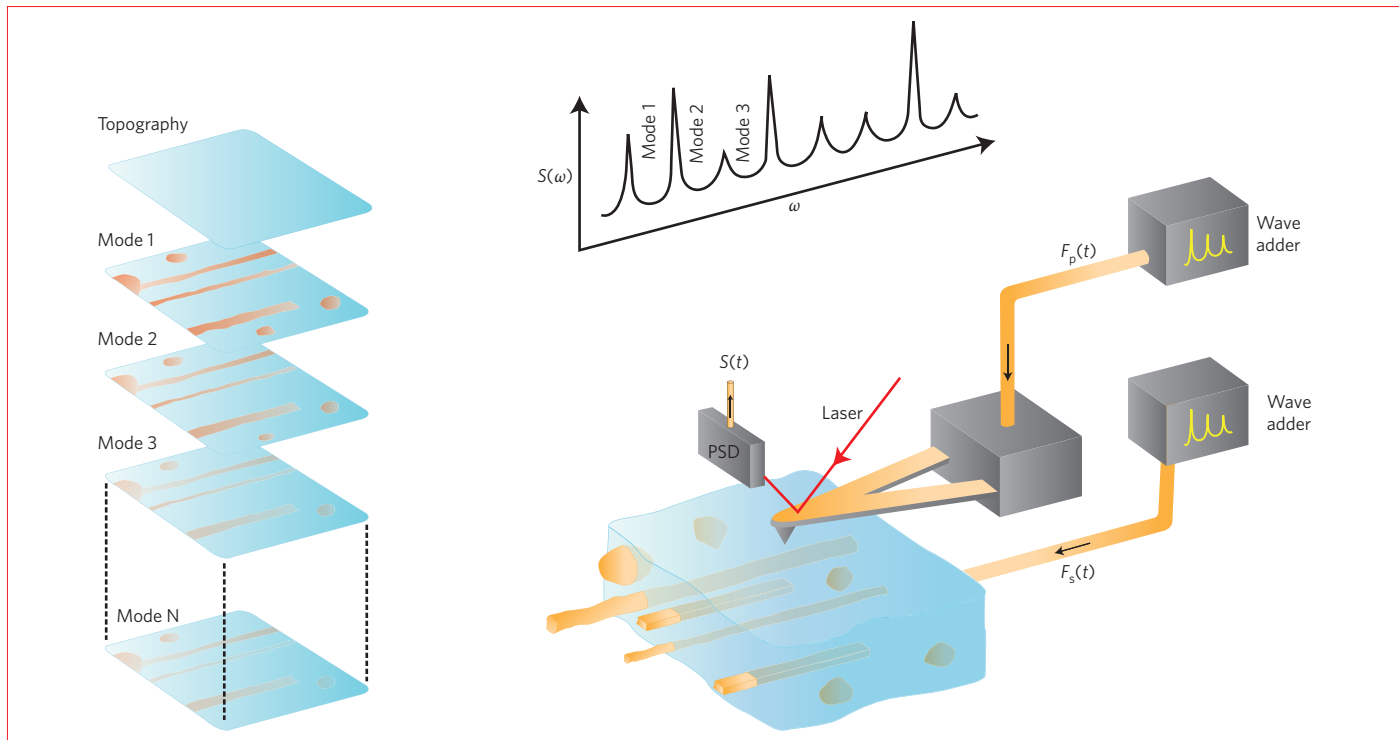
Figure 1 | In mode-synthesized AFM both the tip (probe) and the sample are mechanically excited by signals that contain a number of known frequency components (modes). $F_s(t)$ and $F_p(t)$ are, respectively, the sample and the probe excitation forces. From these modes the tip–sample interaction synthesizes a myriad of new modes, which can be seen in the plot of signal S versus frequency ω (top); S is measured as a function of time with a laser and a position-sensitive detector (PSD), and then Fourier-transformed to obtain the plot of S versus ω. The frequency of a given synthesized mode is a linear combination of the frequencies used to excite the tip and the sample. An image can be acquired from the phase or amplitude of S by using a lock-in amplifier that is referenced to one of the synthesized modes. Each image will reveal a different texture of the embedded and/or surface features of the sample.

oscillations, while also generating harmonic components at multiples of the excitation frequency[9]. By controlling the amplitude of the oscillations with a feedback mechanism, an image of the topography is generated. Measuring shifts in the phase also provides information on the properties of the sample.

The method of Passian and colleagues is based on exciting the sample as well as the tip. The mechanical excitation of the sample generates waves that propagate through the sample, which are scattered by the internal structure of the material being studied. As a consequence the amplitude and phase of the waves are modified in a way that depends on the surface structure of the sample. Eventually the scattered waves emerge at the surface, where they can influence the tip–surface coupling.

In this approach, the AFM tip has a dual role. On the one hand, it collects the mechanical waves coming from below to generate an image of the subsurface. On the other hand, it mixes these waves with its own frequency components to generate a new set of frequencies. Those newly created frequency components reflect the nanomechanical coupling between the tip and the sample. At the core of this coupling is the nonlinear

character of the tip–surface interaction force. Passian and colleagues call this process mode-synthesizing AFM (Fig. 1).

The Oak Ridge team has illustrated the capabilities of this approach by imaging poplar wood cells. The images provide a wealth of information about the subsurface mechanical properties and morphology, which is codified in the frequency space. Unsurprisingly, the use of delocalized mechanical waves to generate images of the subsurface structure leaves several interpretation challenges. For example, it is not straightforward to transform frequency or phase shifts into specific information about the inner structure of the cell. Another unresolved issue is how to separate topography from mechanical property effects in the frequency signal. Although AFM is affected by some of these issues, they are more prominent in this new approach.

By combining nanomechanics and nonlinear interactions, the AFM can generate sub-50-nm images of buried and embedded structures. Thus, force microscopy could fill the void that exists between the high-resolution images provided by cross-sectional electron microscopy, which require modification of

the material, and the micrometre-resolution images provided by non-destructive optical or acoustic techniques. The next logical step in the development of mode-synthesizing force microscopy is to transform the myriad of frequency components into knowledge about the mechanical and structural properties of the subsurface world. This is likely to be a significant challenge, but the rewards will greatly outweigh any anticipated hardships. ❑

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