SCANNING PROBE SPECTROSCOPY

Probing dopants at the atomic level

A more comprehensive understanding of coupled quantum systems could soon be in reach with a capacitance-based scanning probe technique that explores the behaviour and interaction of individual dopant atoms in a semiconductor.

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A revolution is occurring in semiconductor fabrication technologies, the ultimate goal of which is to develop devices based on manipulating the charge or spin of individual dopant atoms. Dopants are impurities deliberately added in low concentrations to a semiconductor to alter its electrical or optical properties. As the size of conventional semiconductor devices is reduced to nanometre scales — driven by the desire to maintain the exponential improvement in their performance — these properties become controlled by ever fewer numbers of dopants — the ultimate limit, of course, being that of a single atom. Moreover, controlling the nuclear[1] or bound electron spin[2] associated with individual dopants has been proposed as a potential basis for solid-state quantum computing. Progress in this endeavour relies on the development of techniques to explore the characteristics and behaviour of few-dopant systems[3–5]. To this end, on page 227 of this issue, Kuljanishvili and co-workers describe a capacitance-based scanning probe method to study the charging spectrum of single silicon donors and donor complexes in a GaAs/AlGaAs heterostructure[6]. The technique probes successive charging states of the donor molecules, thereby providing a pathway to determine the correct quantum description for the coupling of isolated donors[7], and a promising platform for testing our understanding of atoms and molecules in the solid state.

The system studied by the authors consists of a thin sheet of Si dopants with a random distribution within a $Al_{0.3}Ga_{0.7}As$ layer (Fig. 1a). This sheet of donors is situated above a high-mobility 2D electron layer, which acts as a base electrode of the capacitor. The other 'plate' of the capacitor is the metallic tip of a scanning tunnelling microscope (STM), which is connected to a highly sensitive charge sensor. The sample and tip are immersed in liquid helium-3, and the tip's charge is monitored in response to applying an a.c. voltage to the underlying base electrode. The distance of the tip above the sample is held fixed, and determines the radius of the area probed (Fig. 1b). The excitation voltage causes charge to oscillate between the silicon donor layer and the 2D electron layer below it, giving rise to an image charge on the scanning probe tip and an enhanced capacitance.

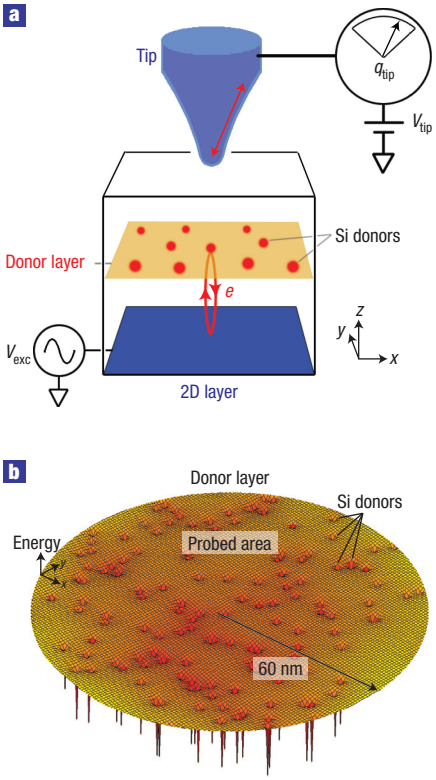

Figure 1 Probing dopants at the atomic scale. **a**, Application of an a.c. voltage to a high-mobility 2D electron layer (bottom), positioned beneath a randomly doped silicon donor sheet, can induce the resonant oscillation of charge from individual dopants in the donor layer to the 2D electron layer, which is monitored by the tip of an STM. **b**, A schematic of the probed area, where the silicon dopants in the donor layer are represented as hydrogenic potentials[6].

By varying the bias on the tip, Kuljanishvili *et al.* observe two effects. First, they see capacitance peaks attributed to single electrons entering individual silicon donors, whose position varies with the location of the probe owing to the random distribution of donors within the plane. Second, and more surprisingly, they observe a series of broader peaks that seem to be independent of probe position, which they attribute to the charging of donor molecules within the plane. The assignment of these peaks is supported by theoretical analysis of the charging spectrum of randomly spaced donors in the probed area. In particular, they attribute three of these broad peaks to the formation of two-donor molecules — donor complexes formed by multiple donor atoms — within the probed area. Several groups have investigated the ground state of isolated dopants in either GaAs- or silicon-based semiconductors using electron-transport studies[3,4], with evidence for two closely spaced donors forming donor molecules[5]. The sensitivity of Kuljanishvili's technique enables the researchers to probe successive electrons entering the molecules, thereby directly measuring the addition spectra of dopant molecules for the first time. As shallow donors are analogous to hydrogen atoms, the results provide a testing ground for fundamental questions of molecular physics, such as the maximum negative ionization of atoms and molecules[8]. The method has the potential to investigate how deliberate changes in the local electronic environment, such as the addition of applied electric fields, can perturb the quantum levels in coupled systems.

Although it has become commonplace to use STMs to manipulate and control individual atoms and to perform detailed spectroscopy studies of the electronic structure of semiconducting surfaces, the present

study represents a technically challenging development. Issues of mechanical and thermal stability present particular difficulties for detecting the movement of charge between atoms buried deep within a semiconducting layer — doing so requires an STM that can operate at milliKelvin temperatures with 0.01 e $Hz^{-½}$ charge sensitivity. Such a capability is currently available only to a limited number of research groups worldwide.

Arguably, the authors could be criticized for not presenting data from more than one sample. However, the measured sample is a randomly doped delta-layer, which essentially represents an infinite number of samples of differing dopant distribution depending on tip location. The authors present similar-looking molecular data from one location of the sample, and also averaged over three locations of the sample. As such, the experimental data reported seems convincing. But a test of their approach will be to apply it to a system that has been fabricated with true atomic precision, to study the interaction between dopants whose position and therefore coupling is well defined. Such atomic precision of dopant placement is being pursued by several groups in which individual atoms are manipulated using STMs[9–11]. The next step for experiment is the realization of engineered single-dopant-atom devices and the ability to couple these in a controlled manner.

The importance of the results presented by Kuljanishvili *et al.* span many different emerging fields. There is a growing interest in single-dopant-atom architectures and their coupling for future quantum information technologies, quantum cellular automata and precise single-electron transistors. In addition, as commercial transistors scale down below the 32 nm node, where only tens of dopant atoms exist in each device, the role of individual dopants in transistor operation is becoming paramount[12]. Most important of all, though, the ability to probe the energy levels of single dopant atoms and their coupling paves the way to the development of a fundamental understanding of few-body quantum mechanical systems — particularly in the realm of *ab initio* computational techniques. Despite significant improvements in computing power, the ability to simulate the quantum mechanical behaviour of large systems from first principles is still limited. But by enabling experimental access to such behaviour at the level of individual atoms, techniques such as those demonstrated by Kuljanishvili *et al.* are bringing us to the point where experiments and simulations will soon converge. With this ongoing development, we will begin to see an exciting transformation in the way theorists and experimentalists work together in developing future semiconductor technologies, and in understanding the quantum world.

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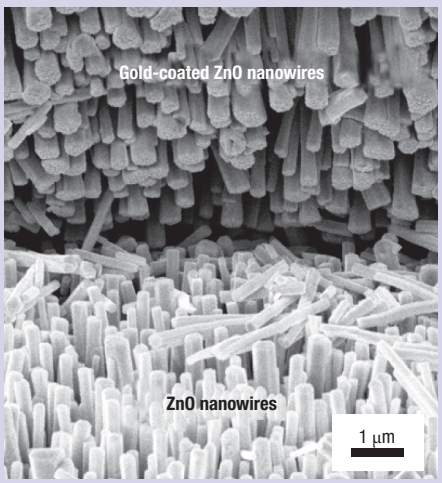
ENERGY HARVESTING

Rubbed the right way

Anyone who has received an electric shock from a colleague after walking across a synthetic carpet knows that even the most mundane of activities can generate energy. But is there any way that this energy can be harnessed? Yong Qin and colleagues suggest it could (*Nature* **451,** 809–813; 2008), using fabrics made of specially coated fibres that produce electricity through the piezoelectric effect.

The authors' fibres consist of two intertwined strands of Kevlar. On one of the strands they grow a forest of radially aligned bare zinc-oxide nanowires, and on the other a similar coverage but of gold-coated nanowires (pictured). Stretching one of the strands back and forth along the length of the second strand causes the nanowires to rub against each other. This rubbing causes the bare zinc-oxide nanowires to bend, which, owing to the piezoelectric characteristics of the oxide, causes a separation of charge to develop across the diameter of each wire. As this happens, the rectifying metal–semiconductor junctions that form at the points of contact between the opposing sets of nanowires allow only negative charge to pass from the bare nanowires to the gold-coated nanowires. This, in turn, generates a voltage across the two strands.



From a single double-stranded fibre, the authors generate peak closed-circuit currents of around 5 pA. By entangling multiple strands together — which increases the area of contact between opposing nanowires — this current can be increased by a factor of up to 50, to an average output current of 200 pA for a six-stranded bundle. And by reducing the core resistance of the strands by depositing a conducting layer before the nanowires, they improve the output of their double-stranded fibres by three orders of magnitude.

One of the advantages of Qin and colleagues' fibre-based generators — compared with previously reported schemes for generating electricity with piezoelectric nanowires — is that they operate at low frequency, which means they can produce power from a wider range of sources of mechanical vibration, such as that generated by someone's physical movement. The flexibility and low-temperature growth conditions of the system are other advantages. By weaving these fibres into a 'power shirt', the authors estimate that up to 20–80 mW of power could be generated by one square metre of fabric — comparable to the power used by a personal music player.

Ed Gerstner