NANOELECTRONICS

# Transistors arrive at the atomic limit

A single-atom transistor has been made by positioning a phosphorus atom between metallic electrodes, also made of phosphorus, on a silicon surface.

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One cannot make a sample of material that is smaller than an atom: this sets a lower limit on the size of any part of a solid-state device. Even before this atomic limit is reached, however, the properties of devices containing tens or hundreds of atoms differ significantly from their large-scale counterparts, which presents an increasingly difficult challenge for the semiconductor industry. Nevertheless, silicon transistors have been relentlessly scaled down in size over recent decades, resulting in devices with gate oxides that are only several atomic layers thick and channels that are just tens of nanometres long. One of the main challenges now is caused by natural variations in the number and position of the dopant atoms in the channel, which leads to device-to-device fluctuations that are detrimental to operation[1].

But as top-down approaches to device fabrication run into these problems, opportunities open for bottom-up approaches that build devices atom by atom, including single-atom transistors[2] and quantum-information-processing devices[3]. However, creating single-atom devices in silicon — and controlling the position of every atom — is a daunting experimental task[4]. Now, writing in *Nature Nanotechnology*, Michelle Simmons and co-workers report that they have reached an important milestone in atomic-scale device fabrication by building the first silicon-based single-atom transistor from the bottom-up[5].

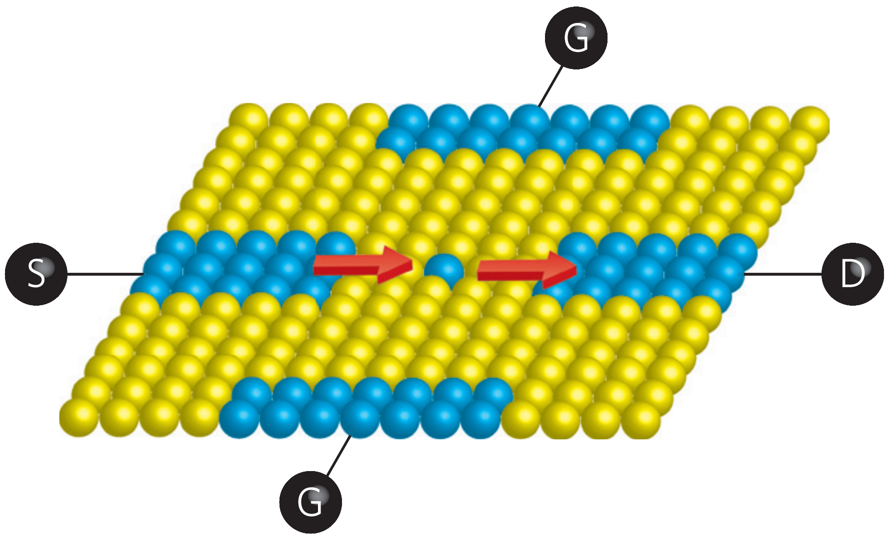


**Figure 1 |** Schematic of the single-atom transistor made by Simmons and co-workers[5]. A single phosphorus atom (blue sphere) is placed with atomic precision on the surface of a silicon crystal (yellow spheres) between the metallic source (S) and drain (D) electrodes, which are formed by phosphorus wires that are multiple atoms wide. Electric charge flows (red arrows) from the source to the drain through the phosphorus atom when an appropriate voltage is applied across the gate electrodes (G). This schematic is not to scale: there are several tens of rows of silicon atoms between the phosphorus atom and the source and drain electrodes, and more than 100 rows of silicon atoms between the phosphorus atom and the gate electrodes.

The device is fabricated using a combination of scanning tunnelling microscopy (STM) and hydrogen-resist lithography. This involves covering the surface of a clean silicon wafer with a layer of hydrogen, and then using the tip of an STM (with a suitable voltage applied) to remove the hydrogen from specific regions of the surface. When the wafer is subsequently exposed to phosphine ($PH_3$), the remaining hydrogen acts as a mask, so that the phosphorus can only bind to the surface in those regions from where the hydrogen has been removed. As such, Simmons and co-workers — who are based at the University of New South Wales (UNSW), the Korea Institute of Science and Technology Information, Purdue University and the universities of Sydney and Melbourne — are able to 'write' a nanostructure made of phosphorus atoms onto the silicon wafer. Finally, the nanostructure is encapsulated by growing a fresh layer of silicon on top of it, which keeps the phosphorus atoms fixed at their positions and also protects them from the environment.

Previous work at UNSW has demonstrated that the combination of STM and hydrogen-resist lithography can be used to make a wide range of device elements. For example, back in 2004, the UNSW team showed that (metallic) structures with a variety of different shapes could be fabricated with this approach[6]. As is well known, phosphorus is a group V atom that acts as a donor atom in silicon — it adds a single electronic charge to the host lattice. Because the structures in their initial experiments were many phosphorus atoms wide, the overlap of so many donor-electron wave-functions created a metallic system. And in subsequent work, Simmons and co-workers at UNSW and the University of Wisconsin-Madison showed that this approach could also be used to fabricate quantum-dot devices[7]. This involved defining two metallic leads (and two gate electrodes) with a region of phosphorus atoms between them that was small enough for the electron charging energy to be higher than the thermal energy: the electric current through this device displayed Coulomb blockade effect, which is a classic hallmark of a quantum dot. And recently, the UNSW–Purdue–Melbourne collaboration reported that Ohm's law remains valid in phosphorus wires just four atoms wide[8].

The central achievement of the latest work is to use the STM–hydrogen-resist lithography approach to position a single phosphorus atom between source and drain contacts and two (more distant) gate electrodes (Fig. 1). The electrical characteristics of the resulting single-atom transistor are, in a way, similar to those of a conventional transistor in that the current between the source and drain can be controlled by applying a voltage to the gate electrodes. However, when the gate voltage is just below the threshold for transistor operation, the single-atom transistor behaves as a small quantum dot.

In this quantum-dot regime the source–drain current shows Coulomb blockade effects that reflect the three possible charge states of the phosphorus atom: the zero-electron state ($D^+$), the one-electron state ($D^0$) and the two-electron state ($D^-$) (ref. 9). Simmons and co-workers carefully measured the current characteristics and the energies associated with these different charge states, and compared these values with the results of large-scale tight-binding calculations of their entire device structure. The strong agreement between experiment and simulation, without the use of any fitting parameters, unequivocally demonstrates that a single-atom transistor was fabricated. Furthermore, they found that the energy levels associated with the three charge states were close to their 'bulk' values, which is a strong sign that the nearby electrodes did not influence the donor atom significantly.

Single-atom transistors represent the ultimate limit in solid-state device miniaturization, but they are also interesting for another reason. Deterministically positioned single-dopant atoms in silicon, electrically addressable by metallic leads, are at the heart of a number of promising proposals for quantum-information-processing devices[3]. The long coherence and relaxation times associated with single dopants make them very attractive candidates for quantum-device architectures.

The atom-by-atom fabrication technique developed by Simmons and co-workers therefore fulfils a long-standing need for a method that is capable of atomic-scale device fabrication in silicon. And although the technique is not directly applicable on an industrial scale, it does bring the development of truly atomistic electronics — and the possibilities they offer — into the experimental realm. ❐

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