QUANTUM DEVICES

Nanowires charge towards integration

Researchers have shown that it is possible to control the coupling between two quantum dots in a semiconducting nanowire, and also to count the charges on these dots with a third quantum dot in a different nanowire.

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Quantum mechanics becomes increasingly important in all semiconductor devices as they shrink in size. These quantum phenomena can degrade the performance of classical devices, so quantum effects are often studied in order to avoid this. Quantum devices flip the situation on its head, however, with researchers going to great lengths to preserve quantum behaviour. On the *Nature Nanotechnology* website today, Charles Marcus and co-workers at Harvard University report an important advance in nanowire-based quantum devices[1]. They fabricate three quantum dots in self-assembled silicon–germanium nanowires, and demonstrate that the dots can form a fully integrated system by using one dot as a sensor to monitor the properties of the other two.

Quantum computation is the driving force behind this work because a quantum computer could, in principle, solve certain important problems that are difficult to address with classical computers[2]. The fundamental unit of a quantum computer is the quantum bit or 'qubit', and researchers are exploring a vast array of physical objects as potential qubits, each with their own challenges and opportunities.

In semiconductors, most prototype qubits have similarities with classical field-effect transistors, and this creates interesting parallels between the design of classical and quantum devices. In both cases, the size and shape of the device and the choice of materials are varied to enhance certain desirable properties of the system. In particular, quantum devices are engineered to minimize uncontrolled disturbances and interactions between the qubit and its environment, both of which can cause the loss of quantum coherence — the ability of the system to retain its quantum nature for a significant period of time.

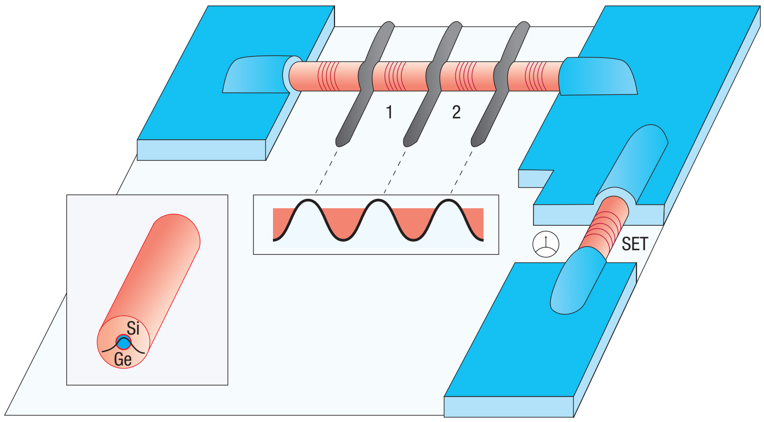

Figure 1 A schematic diagram showing three quantum dots (1, 2, SET) defined in two silicon–germanium nanowires. The overlap between dot 1 and dot 2 can be tuned by changing the voltage applied to the central electrostatic gate (grey) that controls the barrier between the two dots. The third dot functions as a single-electron transistor (SET) that can detect changes in the charge state of either dot 1 or 2. Most importantly, the transistor can detect transfers of charge between the two dots. Left inset: the geometry of the nanowires confines the holes in the central Ge core, separated from the surface of the nanowire by the Si shell. Right inset: for dots 1 and 2, confinement in the third dimension (along the length of the nanowire) is provided by the three gates. Regions where the holes are found are shown in red; the potential confining the holes is shown in black.

Quantum coherence can be enhanced in semiconductor qubits through two main approaches. First, researchers cool their devices to temperatures close to absolute zero — the Harvard team worked at 150 mK — essentially freezing the atoms of the device into fixed positions. However, even at these temperatures, the nuclear spins inside the atoms are still free to rotate. No one has yet found a practical way to cool semiconductor devices to the temperatures needed to lock nuclear spins in place.

To overcome this problem, Marcus and colleagues take a second step and use nanowires made from silicon and germanium — elements in which many of the nuclei have zero-spin. As a result, Si and Ge have been proposed as hosts for candidate qubits[3], and quantum dots made from these materials have shown phenomena not yet observed in other materials[4]. It is an interesting coincidence that these materials, which dominate the semiconductor industry, should also have properties well suited to quantum computers.

The Harvard researchers have made a critical advance in the development of nanowire-based quantum devices by integrating three quantum dots in a pair of SiGe nanowires. The defining feature of quantum dots, which are also known as artificial atoms[5], is that they can confine charge carriers (that is, electrons or holes) in all three dimensions. To form individual quantum dots, the authors exploit the narrow cross-sections of the nanowires to confine holes in two dimensions (see Fig. 1), and electrostatic potentials are applied to nanoscale metal gates to create potential wells that confine the holes in the third dimension (that is, along the wires).

Quantum dots have two features that are advantageous for qubits, and both of these are demonstrated by Marcus and co-workers. The first is a consequence of classical electrostatics: when current flows through a quantum dot, it responds to the motion of nearby charges in a highly nonlinear way, making the quantum dot an excellent charge sensor. The researchers are able to count individual holes in their quantum dots, providing a clear characterization of the devices. Intriguingly, compared with most quantum devices the charge-sensing dot is very far away from the other two dots (more than a micrometre), but the quality of the charge sensing is very good.

The second advantage of quantum dots is their ability to be coupled together, forming a system with richer properties than two uncoupled dots. In a spin-based quantum computer[6], control of the coherent overlap between the charges in neighbouring dots is a fundamental mechanism for two-qubit operations. Marcus and co-workers demonstrate this tunable overlap by measuring the current through the pair of coupled dots as a function of the height of the barrier between them. When the dots are weakly coupled, current only flows through the system when it does not cost any energy to change the number of holes in either dot. When the dots are strongly coupled, they behave like a single larger dot, and the conditions for current to flow are much less stringent.

The Harvard team combines these two advances by coupling their charge-sensing quantum dot to their tunnel-coupled double dots, creating a fully integrated three quantum dot system. In a series of beautiful plots, the team reports measurements of the charge state of the pair of coupled dots, as measured by the charge sensor. In particular, they show that polarization of the pair of dots — the shifting of charge from one dot to the other — is clearly visible in the charge sensor readout.

The next challenge is to measure the spin of individual holes. Spin is the preferred qubit for quantum-dot systems because of its weak coupling to the environment. Although this weak coupling leads to long coherence times, it also makes spin much more difficult to measure than charge. However, a process known as spin-to-charge conversion allows spin to be measured through the measurement of charge, and integrated charge sensing is essential to this approach[7,8].

As Marcus and colleagues have shown, SiGe nanowires offer compelling advantages for quantum devices. Several proposed schemes for semiconductor-based quantum devices are based on a linear architecture, for which long thin nanowires seem ideally suited. At the same time, nanowires present challenges — the authors point out that their dots contain several hundred holes, a number that may need to be dramatically reduced to enable spin measurement. Furthermore, nanowires have a relatively large fraction of atoms at the surface, and the effect of surface and interface states on qubit spin coherence is difficult to predict. Nonetheless, in a rather spectacular way, the Harvard team demonstrate that many of the essential components for quantum devices can be achieved in nanowires.

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