

Figure 2 Sisyphus cooling of amplification of mesoscopic circuits⁴. The two energy levels of a quantum two-level system (a qubit) are shown versus the current of the circuit, which drives the qubit. The cycle $1 \rightarrow 2 \rightarrow 3 \rightarrow 4$ on the right side mimics Sisyphus cooling in atomic physics, and Sisyphus' fate in Greek mythology. The current plays the role of Sisyphus and the qubit plays the role of the rock. Initially, Sisyphus pushes the rock uphill (blue uphill arrows 1 and 3), but the rock eventually falls down to the bottom of the valley (blue downwards arrow 4). Sisyphus then starts the process all over again by pushing the rock uphill. The cycle $1' \rightarrow 2' \rightarrow 3' \rightarrow 4'$ on the left side represents 'Sisyphus amplification', where the rock always rolls downhill. Animations illustrating these cycles are available online at <http://dml.riken.jp/cool>.

The same idea can be also used for 'Sisyphus heating', and, more significantly, for signal amplification akin to lasing (see the cycle $1' \rightarrow 2' \rightarrow 3' \rightarrow 4'$ in Fig. 2). This cycle could be described as that of a 'happy

Sisyphus' because the rock is always rolling downhill, and eventually it is lifted up by the applied microwave photons — the rock is now pushing Sisyphus downhill, instead of Sisyphus pushing the rock

uphill. The qubit now amplifies the circuit current (and this amplification is related to lasing) by pushing the current downhill until it reaches the resonance, where the microwave photon is absorbed, promoting the qubit to its higher-energy state, where the qubit again pushes the circuit current. The qubit energy eventually decays to its lower-energy state emitting a low-energy photon. The energy loss, due to this emitted photon, is lower than the energy gain from the microwave, and therefore the microwave energy is now used to slowly amplify the current of the circuit.

The mechanisms demonstrated by Grajcar *et al.*⁴ can be used for cooling and lasing, both of which are subjects of great interest in the field of superconducting qubit circuits^{9–12}. A particularly intriguing perspective is to apply these techniques to cooling mechanical resonators at the nanoscale; this might provide opportunities to observe the transition between classical and quantum resonant behaviour.

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QUANTUM ELECTRONICS

Hybrid electron control

The ability to change the degree of hybridization of a donor electron between the coulombic potential of its donor atom and that of a nearby quantum well in a silicon transistor has now been achieved. This is a promising step in the development of atomic-scale quantum control.

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Doping is a crucial process in semiconductor electronics. The introduction of even a few parts per billion of dopant atoms into a semiconducting material can significantly

change its electrical and optical properties. In conventional electronics, the key effect that dopants have is to contribute free charge and thereby to modify a semiconductor's conductivity. But as semiconductor devices become smaller, and ever more functionality is demanded of them, other properties, such as spin and even the precise nature of the quantum wavefunctions of dopants, can become important. Exploiting such properties not

only promises to improve the speed and performance of future electronic devices, but could enable the development of solid-state quantum computing. Achieving the latter, however, requires the ability to exert full quantum control over the wavefunctions of donor electrons, and ideally over those of individual electrons. On page 656 of this issue, Lansbergen and colleagues demonstrate the ability to identify and manipulate the state of an individual

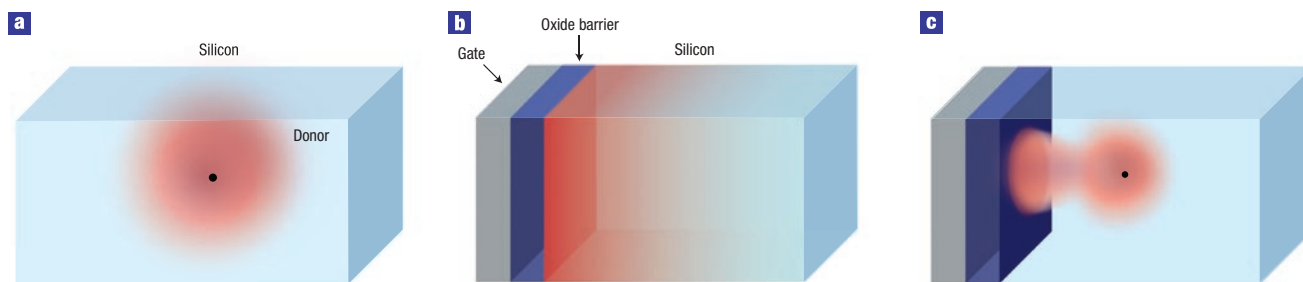


Figure 1 Manipulating the hybridization of a single donor electron in silicon. **a**, At zero gate voltage and low temperature, the charge density associated with a donor electron's wavefunction is localized around its corresponding donor atom. **b**, When sufficient bias is applied to a nearby gate, the electron can be drawn to and confined within the potential well that forms at the interface between the silicon and the oxide that insulates it from the gate. The effect of the donor potential is not included in this illustration. **c**, At intermediate gate voltages, the electron's wavefunction is best described as a hybrid of both donor and well-confined states. Note that the electron remains laterally bound to the donor potential, even at the interface.

electron bound to a single dopant atom in a silicon device¹, thus providing an important step towards the realization of silicon-based quantum electronics.

As anyone who has done an introductory solid-state physics course will know, when a group-V donor atom (such as phosphorous or arsenic) is substituted for a silicon atom (group IV) in a silicon crystal matrix, it behaves as a solid-state analogue of a simple hydrogen atom², but for two important differences. The first is that the binding energy of a donor atom's excess valence electron is much lower than in a normal hydrogen atom, of the order of few tens of millielectron volts, requiring operation at a temperature of just a few kelvin. And the second is that it has a much larger Bohr radius, of the order of several nanometres. It is this second fact, combined with recent technological progress³, that introduces the possibility of manipulating the ground-state wavefunction of an individual donor's electron within the nanoscale device structure. And it is exactly this possibility that Landsbergen and colleagues pursue, manipulating a single dopant atom within the silicon channel of a device known as a FinFET.

A FinFET is similar to a conventional field-effect transistor (FET) in that it consists of a semiconducting channel formed between a source and drain electrode. The conductivity of the channel is modulated by a field applied through a nearby gate electrode that is electrically isolated from the semiconductor by an insulating oxide. But unlike the simple planar arrangement of a conventional FET, the channel of a FinFET is narrower — less than 200 nm wide — and enveloped on three of its sides by gates. Such a structure enabled the identification, through combined experimental and theoretical effort, of a single donor atom embedded

within the channel in close proximity to the insulating oxide.

When an appropriate voltage is applied to the gate of a FinFET (or indeed any FET), an attractive potential well is formed at the interface between the gate oxide and the silicon channel. It has been predicted that when a single donor is positioned close enough to this interface, the electron may be pulled away from the donor towards it. What the donor electron sees is a double-well potential due to a superposition between the attractive well potentials of the donor and barrier interface. Such a situation has been studied theoretically and it was found that the amount of 'talk' between the donor and the interface depends mainly on two parameters — the gate voltage, or the corresponding electric field applied in the direction perpendicular to the interface with the barrier oxide, and the distance between the donor atom and the barrier oxide. At low fields, the electronic ground state is expected to remain localized around the donor (Fig. 1a), whereas for strong enough fields the donor is fully ionized, and the electron is confined near the interface (Fig. 1b). Two regimes were identified for such a donor-ionization process: If its distance from the interface is comparable to the effective Bohr radius, a hybrid superposition state, delocalized between the two wells, may form for a range of characteristic fields (Fig. 1c), and adiabatic passage may be driven by the gate potential. In contrast, for large distances, tunnelling occurs and the electron will only be observed within one of the quantum wells.

Although this may sound conceptually straightforward, it is a daunting task to realize experimentally. Landsbergen *et al.* set out to perform transport measurements on a number of such devices, in the hope that in some of them an isolated dopant atom would be suitably located in the

proximity of the oxide barrier such that signatures of its existence would emerge in the source–drain current characteristics. This was indeed found to be the case for six out of the 100 samples that were studied. For these few samples they found typical current peaks that are associated with transport through single-donor ground states. From the measurements they could infer whether the donors were neutral or charged, as well as determine the energy cost of binding a second electron to the donor — the charging energy. From a simple model for the charging energy the distance between the donor and the interface was shown to vary from 3 to 5 nm, on the order of the donor's Bohr radius. This corresponds to a regime where partially ionized superposition states such as illustrated in Fig. 1c may be observed, a scenario that was validated by extensive atomistic tight-binding simulations. From the experiments and theory, it was suggested that the FinFET's gate potential may be used as a control knob for the degree of hybridization depicted in Fig. 1c, thus opening up the possibility for single-donor manipulation in silicon nanodevices.

Single-donor manipulation in silicon has been sought after for more than a decade following the original proposal for a donor-based quantum computer in silicon⁴. It is only with the presented experiments that convincing gate-control of single donors has been demonstrated. However, as also shown by the experiments, serious challenges in device fabrication lie ahead before any realistic development of donor-based qubits in silicon can be attempted.

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