NANOTECHNOLOGY

Reversible diodes for moving quanta

Nanoscale engineering can now take advantage of a new ratchet device: it acts as a diode for superconducting vortices, but its directionality can be controlled and repeatedly reversed to become an effective 'two-way street'.

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SimCity is a popular computer simulation game that allows players to develop a virtual city by laying down roads, bridges, tunnels, car parks and mass-transit lines — all the infrastructure of a thriving metropolis. Nanoscale science and technology has a similar goal: to lay down, at the nanoscale, components that are the equivalents of roads, tunnels and lines of mass-transit, and to use them to move cargo between regions in a device. The 'cargo' might be colloidal particles in suspensions, fluids inside microfluidic pipes, quanta of electricity (electrons), or quanta of magnetic flux (superconducting vortices). A classic example is an electrical capacitor — effectively a 'car park' to temporarily store electrons, which can be eventually moved elsewhere.

Such devices are becoming smaller and smaller, and the necessary nanoroads between them can take more exotic forms than the conventional wires in circuits, depending on what type of cargo needs to be transported. Ratchet devices[1], for example, offer novel ways to control the motion of tiny particles, such as colloidal particles[2,3] or binary mixtures[4]. Now, writing in *Nature*, de Souza Silva and colleagues[5] describe a multiply reversible ratchet effect for quanta of magnetic flux — effectively a 'two-way street' for a quantum micropolis.

Ratchet devices are based on spatially asymmetric substrates (Fig. 1a) that rectify an applied, oscillating or fluctuating, driving force. Because particles can move more easily in one direction than the other, the applied oscillating force produces a net drift in that direction. However, the fixed substrate asymmetry only allows motion in that direction — it's a one-way street. It would be desirable to be able to reverse this direction of motion by changing some external parameter. Villegas *et al.*[6] have produced a magnetic superconducting hybrid device that allows a reversal of the rectified motion, by changing the amplitude of the applied oscillating drive; and my group has also investigated this reversal of diode polarity for quanta of magnetic flux[7,8]. But in the device built by de Souza Silva *et al.*[5], multiple current reversals are achieved by increasing an applied magnetic field.

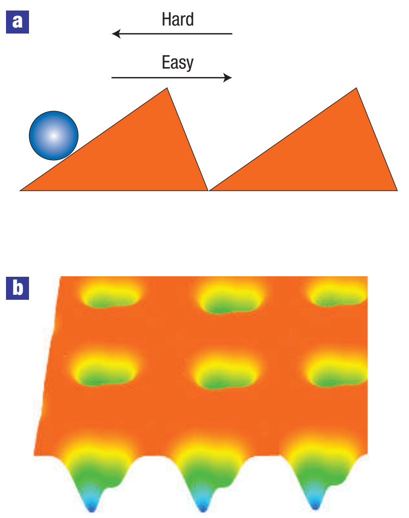

Figure 1 The asymmetric landscape of a ratchet. **a**, When a particle is pushed towards the left, it encounters a steep slope and cannot move easily. When the driving force is towards the right, it encounters a gentler slope and moves more easily. **b**, Such a landscape can be realized in nanoscale devices by creating an array of double-well potentials in a substrate, with one potential-well deeper than the other.

They use a substrate design that has a periodic array of double-well potentials (Fig. 1b), which directs the net motion of superconducting vortices in a spatially asymmetric nanofabricated superconductor. To picture the process in our nanocity landscape (albeit as an over-simplified cartoon), imagine a small subway carriage with two seats: a large one and a slightly smaller one. Now let's slowly increase the number of passengers entering the carriage, which does not allow standing passengers — all must sit. The large seat attracts the first passenger. The second passenger would take the other (smaller) seat, because it is empty. The third passenger, given the choice of sharing a large seat or a small one, would obviously choose the larger of the two. The fourth passenger would sit in the small one, as it is at that instant less crowded. And so on. Thus, each incoming passenger can reverse the role of the 'preferred seat' — and the process is similar for repelling particles entering a double-well potential.

In an array of double-well potentials such as shown in Fig. 1b, the asymmetry of the wells acts like a ratchet,

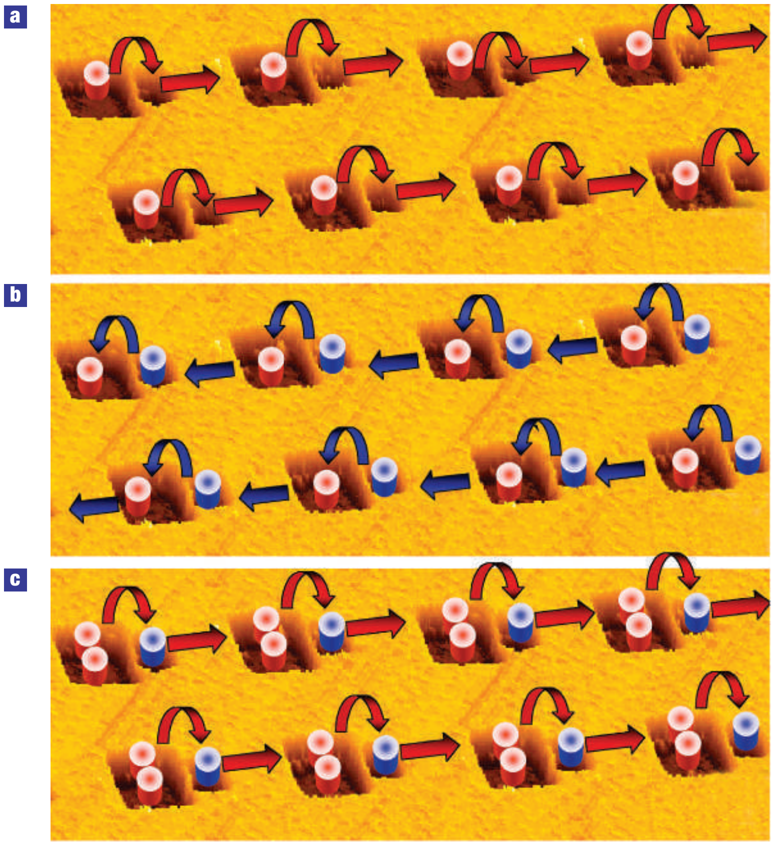

Figure 2 The vortex diode, in which the direction of the net motion depends on the density of magnetic-flux quanta (vortices), as shown by de Souza Silva and colleagues[5]. **a**, When the applied magnetic field corresponds to one vortex per double-well pinning site, it is easier for the vortices to jump first to the weaker potential well and then out of the double-well, than to jump directly out of a deep well. This produces a diode effect: vortices experience a net motion to the right when an oscillating a.c. electrical current is applied. **b**, When the magnetic field is increased such that there are now two vortices per double-well pinning site, the deep well is already occupied by a strongly pinned vortex (red). This vortex repels the other (blue) one inside the shallow well, which (through vortex–vortex interaction) becomes the new low-energy minimum. Thus the polarity of the ratchet has changed: now the blue vortices can easily jump into the left well, pushing out the red vortex. **c**, The situation again reverses when the number of vortices is increased.

rectifying the motion of particles pushed back and forth on this energy landscape. Figure 2 shows what happens when the density of repelling particles being forced to oscillate on this substrate is slowly raised. When one of these particles — in this case, a magnetic-flux quantum, or superconducting vortex — falls to the bottom of the deeper well, it will remain there and will repel additional particles, effectively changing the asymmetry of the double-well potential. The repelled particles now experience a ratchet-shaped landscape with a reversed polarity. The process is repeated as more particles are added, occupying this time the previously unoccupied well — thus, the ratchet-shaped landscape once more reverses its polarity. It's the interaction between particles that makes this reversal of polarity possible.

De Souza Silva and colleagues[5] exploit this process to achieve a remarkable number of reversals of the orientation of the ratchet 'teeth', tuning the directionality through an external magnetic field. Such controllability of the direction of the diode puts a useful new tool at the disposal of the nanocity planners. For instance, vortex motion can create noise in sensitive superconducting devices, so it is desirable to find ways of moving them away from the most noise-sensitive areas of a device. In a broader context, the standard means of transporting cargo at the nanoscale become less feasible as the size of devices shrinks, and although asymmetric devices are already being studied as nanoscale diodes[6], they are not easily multiply-reversible. But the multiple reversals of the d.c. output of an a.c.-driven device achieved by de Souza Silva *et al.* point a clear way forward in developing an effective transport network for a quantum micropolis.

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