Quantum ratchets reroute electrons

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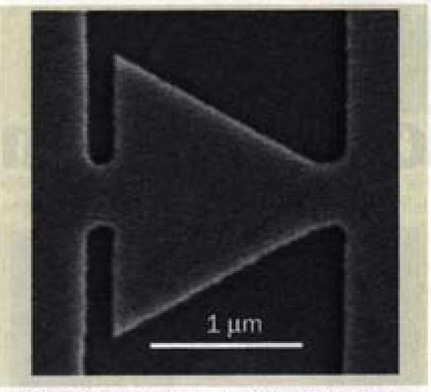
Is it possible to extract energy from random fluctuations and put it to use? This challenging question has provoked discussion ever since the early days of Brownian-motion theory. For large-scale or macroscopic fluctuations, the answer is "yes" – the principle is demonstrated in several mechanical and electrical devices in everyday use, such as the self-winding wristwatch. In this case, the slightest movement of the wearer's wrist causes a metal weight attached to the winding mechanism to pivot freely, winding the spring that powers the mechanical watch.

Much subtler is the issue of whether microscopic random fluctuations, such as thermal Brownian motion or even the haphazard motion of quantum particles, acting as a random energy source can cause the particles to flow in one direction only.

In recent years this field has been the scene of remarkable activity, motivated by the prospect of potentially high-profile technological and biological applications, such as molecular motors. In particular the directed transport of particles in an asymmetric potential known as a ratchet has received a lot of attention. This research, however, has focused on "thermal ratchets" in which the particles undergo thermal Brownian motion: the next challenge is to move from the classical world and account for quantum mechanical effects.

Recently a collaboration between physicists at Lund University in Sweden and the Niels Bohr Institute in Copenhagen has taken a significant step forward and built a quantum ratchet (H Linke *et al.* 1998 *Europhys. Lett.* **44** 341 and **45** 406). The device is based on an aluminium-doped gallium arsenide (GaAs/AlGaAs) quantum dot with a ratchet-like, triangular-shaped cavity. The device was fabricated by electron nanolithography techniques and incorporated two point contacts (figure 1). The results support the idea that the ratchet is indeed exhibiting quantum mechanical properties.

Experiments have confirmed that particles moving randomly in an asymmetric potential can drift in one direction even when the average of all the macroscopic forces applied is zero. On the face of it, this result seems to contradict the intriguing balance that exists when a system is in thermal equilibrium and prohibits the emergence of directed motion. But the picture is drastically different for systems that are far from thermal equilibrium. Then the detailed balance symmetry can break down and there is nothing to prevent particles on a ratchet moving in one direction.

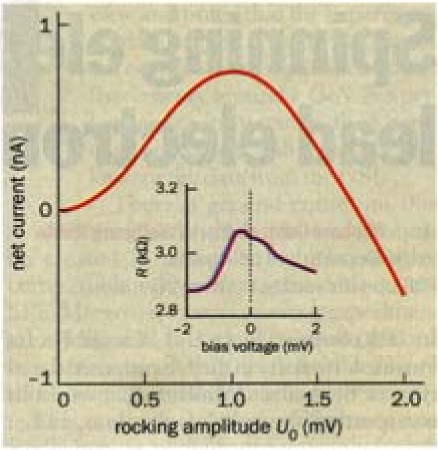


1 An electron microscope image of a triangular-shaped quantum dot etched from a gallium arsenide/aluminium GaAs heterostructure.

Ratchets have also attracted a great deal of theoretical interest. Many of the models that have been developed to describe classical, thermal ratchets predict that the particle motion will change direction depending on the properties of the system, for example the mass of the Brownian particle.

The current authors developed the first theory of quantum ratchets in 1997 (*Phys. Rev. Lett.* 1997 **79** 10). It describes a so-called "rocking quantum ratchet" – a quantum Brownian particle, such as an electron at low temperature, moving in a periodic ratchet potential under the influence of quantum noise. The potential is tilted alternately to the right and left by a slowly varying "rocking force". This force can either be periodic or random in time.

In contrast to the behaviour predicted by classical theories, the full quantum mechanical treatment predicts that the electron in the ratchet will produce a finite, net particle current even as the temperature is cooled towards absolute zero. Basically, this finding is due to quantum tunnelling. Another striking prediction of the quantum theory is that at low, finite temperatures the particle current can change direction.



2 The variation of the time-averaged current when a slowly "rocking" AC voltage is applied to a triangular dot at 0.3 K. The inset shows the differential resistance measured as a function of the applied DC bias voltage.

The measurements on the Scandinavian-built quantum ratchet were made at 0.3 K, where the electron transport through the cavity occurs within the realm of quantum mechanics. The genuine quantum nature of the transport mechanism has been corroborated by a series of measurements of the differential resistance – the ratio of the DC bias voltage, U, to the bias current. The team found that there was a pronounced asymmetry around $U = 0$ (see inset in figure 2). The temperature dependence of this asymmetric behaviour is related to quantum interference effects inside the ratchet. This conclusion is supported by the dependence of the results on tiny magnetic fields passing through the device. These fields are too small to change the classical path of the electron motion; instead they alter the quantum interference between the electrons by changing their relative phase.

The researchers applied a slowly oscillating sinusoidal "rocking voltage" and deduced the net current from the differential resistance (figure 2). Strikingly, the direction of the net current reversed as the amplitude of the rocking voltage varied. In other words it was possible to control the direction of the net current with the rocking voltage.

Last year one of the authors (PH) and a colleague proposed a whole new class of quantum "rectifiers" that allow the direction of the quantum transport in a periodic symmetric structure to be controlled (I Goychuk and P Hänggi 1998 *Europhys. Lett.* **43** 503). The applied bias voltage is a mix between a sinusoidal oscillation and its second harmonic, with a relative phase difference that can control the direction of the quantum motion in a sensitive way. These quantum ratchets also function at higher temperatures where quantum interference effects begin to fade out and classical electron transport sets in.

This has been beautifully demonstrated by experimentalists from the Ludwig Maximilians University in Munich, Germany, using a 2D periodic array of triangular-shaped antidots (areas where electrons are excluded rather than confined) at a temperature of 4.2 K (A Lorke *et al* 1998 *Physica B* **249–251** 312). The researchers were able to control the directed current by both irradiating the array using a far-infrared source and applying a magnetic field. The periodic system represents a rocking ratchet for electrons that operates in the classical transport regime, in contrast to the device produced by Linke and collaborators.

Using these novel concepts in combination with nanolithography techniques, the results demonstrate that it is possible to construct devices for the quantum rectification of electrons. Apart from providing new insights into nonlinear electron transport, quantum ratchets also enable electrons to be guided along pre-assigned pathways. This feature could well lead to new types of quantum machinery operated by "running" electrons.