without exhibiting sonoluminescence. On the other hand, a bubble filled with pure argon can only be trapped by sound waves above a certain amplitude and always increases in size as the pressure is increased.

So what is next? Although the bubble-stability problem appears to be solved for water, there are many variables that have not been tested yet, such as the ambient pressure and temperature using different gases and liquids. Active surface agents could also be used to inhibit instabilities and enhance the energy of the collapse.

Other important questions concerning the origin of the light in sonoluminescence emission still remain to be answered. Is a shock wave responsible for the light? Is a plasma created during the collapse? And, ultimately, could sonoluminescence somehow be used to generate energy through nuclear fusion?

Quantum ratchets reroute electrons

From **Peter Hänggi** and **Peter Reimann** in the Department of Physics at the University of Augsburg, Germany

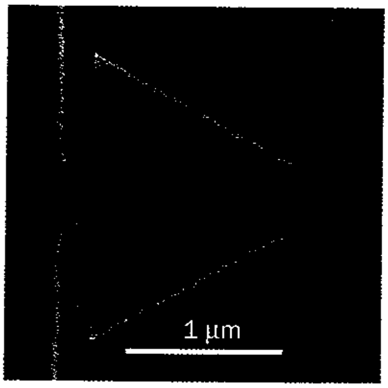
Is it possible to extract energy from random fluctuations and put it to use? This challenging question has provoked discussion ever since the early days of Brownian-motion theory. For large-scale or macroscopic fluctuations, the answer is "yes" – the principle is demonstrated in several mechanical and 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.



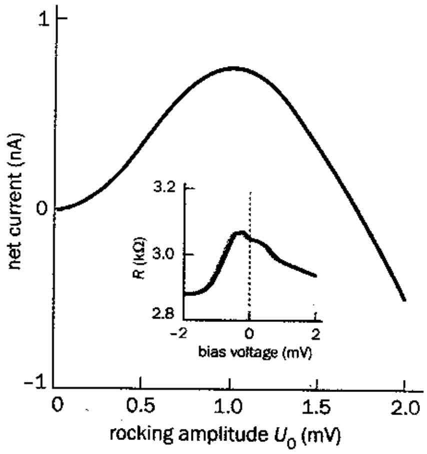
1 An electron microscope image of a triangular-shaped quantum dot etched from a gallium arsenide/aluminium GaAs heterostructure.

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.

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.



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 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.

Spinning electrons could lead electronics revolution

From **Michael Oestreich** and **Wolfgang Rühle**
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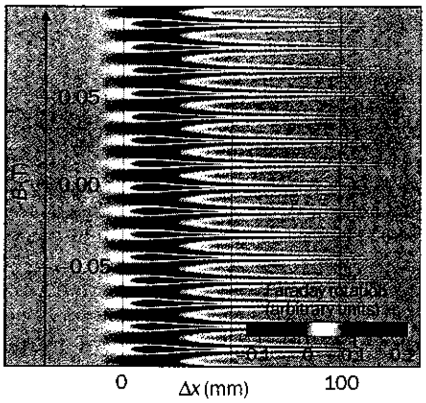
In 1990 Supriyo Data and Biswajit Das of Purdue University in the US proposed a new type of field-effect transistor that works by transporting the spin of electrons, rather than their charge, through a semiconductor. To make such devices work, the electrons must first be polarized, that is all their spins must be made to point in the same direction. Next this polarization must be preserved as the electrons move through the semiconductor; in other words, the number of "spin flips" must be negligible. A significant breakthrough in the second of these challenges was made recently when Jay Kikkawa and David Awschalom of the University of California at Santa Barbara demonstrated that "spin transport" can be accomplished over distances exceeding 100 microns and can last for up to 29 nanoseconds (*Nature* 1999 **397** 139).

The interest in spin-transport phenomena in condensed-matter physics has increased rapidly since the discovery that metallic multilayers show large changes in their electrical resistance when the direction of a small external magnetic field is changed. This effect, known as giant magnetoresistance (GMR), can be as large as 70% at room temperature (see *Physics World* November 1994 pp34–38). The magnetic field changes the spin orientation in the ferromagnetic layers, where the spins all point in the same direction, and this either enhances or prevents the transport of electrons with a specific spin orientation across these layers. The effect is exploited in a variety of applications – for example, GMR read heads in high-density magnetic discs were demonstrated recently, as were magnetic random access memories. However, a more significant development will be when magnetoelectronic effects can be integrated with semiconductor electronics to create "spin electronics".

Last year, our group in Marburg made the first measurements of electron-spin transport in gallium arsenide in a high electric field (*Appl. Phys. Lett.* 1998 **73** 1580). However, the efficient injection of spin-polarized electrons into the semiconductor was a problem, and it remains so. To get round this, spin-oriented electrons were created by the absorption of circularly polarized laser light in a thin layer on the surface of the device. Next the electrons were accelerated by an electric field applied at right angles to the surface, and then passed through 5 microns of gallium arsenide, before they finally recombined with holes in a thin layer of gallium indium arsenide to generate the light. The degree of circular polarization of this light provided a direct measure of the amount of electron-spin orientation that remained. No loss of spin orientation was observed for electric fields up to 6 kV cm^{-1}, and the orientation lasted for several hundreds of picoseconds.



The lateral distance travelled by the electron-spin packets (Δx) was determined by measuring the Faraday rotation of linearly polarized laser light. The *y*-axis shows the magnetic field (*B*) that was applied to align the electron-spin orientation.

Kikkawa and Awschalom have now succeeded in preserving the spin-transport mechanism over much larger distances and for significantly longer times. In contrast to the Marburg experiment, they studied lateral transport (i.e. parallel to the surface rather than into the device), for which much longer drift and diffusion lengths are possible. Again the absorption of circularly polarized light was used to orient the spins, but the Santa Barbara team detected the spin transport in the electric field by measuring what is known as "Faraday rotation". This is the transformation of linearly polarized light into slightly elliptically polarized light by a sample, and it provides a measure of the spin orientation.

The researchers used a "pump–probe" technique whereby a circularly polarized "pump" pulse created the spin orientation and a time-delayed linearly polarized "probe" pulse traced the temporal and spatial evolution of the electron spins. Lateral electric fields moved the electrons as far as several tens of microns away from the point where they were created, while diffusion caused them to spread over distances larger than 100 microns.

Kikkawa and Awschalom greatly increased the sensitivity of their experiment by means of a clever trick that they call "spin amplification". They created spin-oriented electrons with a train of pulses from a titanium sapphire laser that had a stable repetition rate of 76 MHz. A small magnetic-field perpendicular to the spin orientation forced the electrons to precess around the magnetic field direction. The rotation of the electron spin was in phase with the train of laser pulses at certain magnetic fields. When a laser pulse created spin-oriented electrons, the electrons created by the preceding laser pulse had at sharply defined magnetic fields exactly the same spin orientation, even after hundreds of precessions. The total electron-spin orientation therefore accumulated and was amplified, allowing the detection of spin orientation even after several tens of nanoseconds and distances exceeding 100 microns.

The long spin lifetimes and diffusion lengths measured should be sufficient for many electronic devices. Whether spin transport in semiconductors will really lead to commercial electronic devices is not yet clear. Many fundamental problems, for example the spin injection, have yet to be solved. But with spin electronics looking so promising, there is a large international effort to tackle these challenges. Only the future will tell whether these efforts will prove successful.