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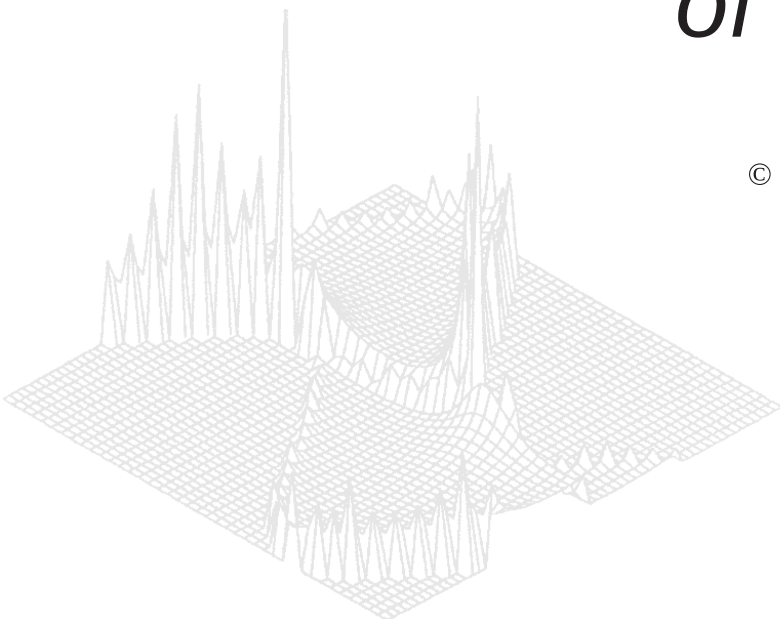

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Experimental Quantum Ratchets based on Solid State Nanostructures*

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Abstract

Ratchets are spatially asymmetric devices in which particles can move on average in one direction in the absence of external net forces or gradients. This is made possible by the rectification of fluctuations, which also provide the energy for the process. Interest in the physics of ratchets was revived in recent years when it emerged that the ratchet principle may be a suitable physical model for 'molecular motors', which are central to many fundamental biological processes, such as intracellular transport or muscle contraction. Most ratchets studied so far have relied on classical effects, but recently 'quantum ratchets', involving quantum effects, have also been studied. In the present article it is pointed out that semiconductor or metal nanostructures are very suitable systems for the realisation of experimental quantum ratchets. Recent experimental studies of a quantum ratchet based on an asymmetric quantum dot are reviewed.

1. Introduction

Many fundamental processes in biological systems are based on so-called 'molecular motors'. These are large protein molecules that use chemical energy to exert forces, for intracellular transport, or to create a concentration gradient by pumping ions through a membrane. A famous example is the motor protein myosin, which can move stepwise along a muscle filament consisting of a periodic protein tubulus, and exerts in this way a force of a few piconewton on another filament (Finer *et al*. 1994). It is the relative motion of the two filaments resulting from the action of many myosin motors that causes muscles to contract. In the process, chemical energy from the hydrolysis of adenosine triphosphate (ATP) molecules into adenosine diphosphate (ADP), and phosphate is consumed. Another example is the enzyme ATPase, which, situated in inner membranes of cells, synthesises ATP by making use of a proton flow generated by a concentration gradient over the membrane. Alternatively, the enzyme can reverse the process and pump protons against the gradient, using energy from ATP hydrolysis. The efficiency of this process has been experimentally measured to be close to 100% (Kinosita *et al*. 1998).

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How do molecular motors work? Due to the Brownian environment within biological tissue, the working principle of molecular motors has to be quite different from that of macroscopic, man-made engines (Astumian 1997). Significant heat gradients, which are crucial for heat engines, for instance, cannot be maintained in a cell. In fact, molecular motors convert chemical energy directly into mechanical energy, without a thermal step. Further, the random collisions with other molecules in the aquatic environment create an extraordinarily noisy environment: a motor protein that attempts to move along a protein tubulus, for instance, is subject to frequent, random collisions with other molecules in the solution, with an energy transfer of order $k_\mathrm{B}T$. This noise level has to be compared to the only 20 $k_\mathrm{B}T$ energy gain available from the hydrolysis of an ATP molecule. A motor protein can therefore not be expected to move deterministically (Magnasco 1993). It is most interesting that, rather than losing efficiency due to this noisy environment, it seems that molecular motors (often also referred to as 'Brownian motors') make use of Brownian noise by rectifying it.

As physical models for these fascinating machines, so-called 'ratchets' are currently being studied (Astumian 1997; Hänggi and Bartussek 1996; Jülicher *et al*. 1997). Generally speaking, a ratchet is a device in which directed particle flow can occur in the absence of any macroscopic net forces or gradients. Two basic requirements have to be met for the operation of a ratchet. First, the potential must be spatially asymmetric. Second, external, non-equilibrium fluctuations must be present to break time-reversal symmetry (this is necessary to satisfy the second law of thermodynamics). These fluctuations then serve also as a source of energy for the process.

In the case of molecular motors, the required asymmetry is inherent in the structure of the molecules involved, for example, in the case of the myosin/actin system, an asymmetry of the periodic actin filament. The role of the fluctuations is played by the ATP molecules that serve as energy source (Astumian 1997). Each time an ATP molecule attaches to the motor protein, when chemical energy in the ATP/ADP+P reaction is released, and when the products of this reaction detach from the motor, the molecular conformations of the proteins involved change, thus also changing the effective potential felt by the motor protein. While much is still unknown about how molecular motors work in detail, the basic principles of ratchet effects can be studied in much simpler systems.

An illustrative example of a ratchet is the 'flashing ratchet' sketched in Fig. 1. Diffusive particles are subject to a time-dependent sawtooth potential. When the potential is 'off', the particles diffuse isotropically. When the potential is 'on', however, the particles will move from their present, random position towards the nearest local potential minimum. Due to the asymmetry of the sawtooth potential, the nearest minimum is on average to the left of the particle. Periodic switching of the potential will therefore result in a net particle flow towards the left, although no net force acts on the particles (Rousselet *et al*. 1994). When the parameters are well chosen, the current can even flow against an external force, in which case the ratchet extracts usable work from the switching potential [see Astumian (1997); see also Elmer *et al*. (1998), who have made available on the Internet an illustrative description and simulation of a sawtooth ratchet with fluctuating barriers]. Interestingly, while excess thermal noise will render the ratchet process inefficient, the ratchet needs the thermal particle motion to operate. Another well known ratchet system is Feynman's ratchet-and-pawl machine (Feynman *et al.* 1963; Parrondo and Espanol 1996), but one can find much earlier machines that extract work from fluctuations (Parrondo and Espanol 1996). A particularly picturesque example is Cox's clock, a *perpetuum mobile* built in the 18th century that extracted work from variations of the atmospheric pressure (Dircks 1968, p. 122).

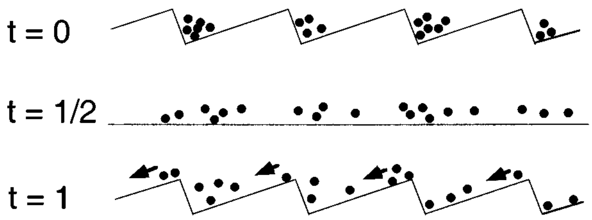

Fig. 1. Illustration of a ratchet device consisting of classical particles in a time-dependent, periodic sawtooth potential. The thermal energy of the particles is assumed to be non-zero, but less than the height of the potential barriers. In the beginning of the cycle, at $t = 0$, the particles are localised around the potential minima. When the potential is switched off ($t = \frac{1}{2}$), the particles diffuse isotropically in both directions. When the potential is switched on again, the particles slide down the slope they are caught on, which results in an average motion to the left. Periodic switching of the potential thus creates a directed motion to the left although the net force is zero.

So far, most work on ratchets has been concerned with fully *classical* ratchet systems. Experimentally, the directed motion of Brownian particles has been demonstrated in spatially periodic, asymmetric, time-dependent potentials that were created electrically (Rousselet *et al.* 1994) and optically (Faucheux *et al.* 1995). Mercury drops have also been used in demonstrations of classical ratchet effects (Gorre *et al.* 1996). From a fundamental point of view it is, however, very interesting to also study ratchet devices under conditions where *quantum* effects are important, such as interference effects, tunnelling or effects of reduced dimensionality due to energy quantisation (Reimann *et al.* 1997; Zapata *et al.* 1996).

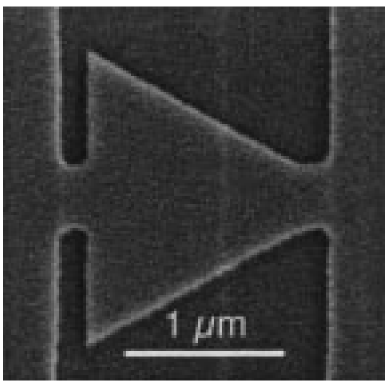

Fig. 2. Scanning electron microscope image of a triangular electron cavity that can be used as a quantum dot ratchet. About 70 nm under the surface is a conducting layer of two-dimensional electrons. In the darker regions this conducting layer is interrupted by wet etching, thus confining electrons in a triangular cavity connected to the surrounding two-dimensional electron gas via point contacts. At low temperatures, electron transport through the triangular cavity is determined by the coupling of electron wave modes in the point contacts to the quantised electron states inside the cavity.

The purpose of the present paper is to point out that metal or semiconductor nanostructures are particularly suitable as experimental systems for studies of quantum ratchet effects. As an example, properties of the first experimental quantum ratchet (Linke *et al*. 1998*b*, 1999), an asymmetric quantum dot (Fig. 2), will be reviewed (see also Hänggi and Reimann 1999).

2. Experimental Quantum Ratchets

Experimental studies of quantum ratchet effects need the following basic prerequisites: First, quantum particles must be exposed to a potential of controlled (a-)symmetry on length-scales and under experimental conditions where quantum effects are important. Second, external fluctuations must be imposed on this system and the net current of quantum particles must be measured as a function of external fluctuations. As will be discussed in the following, it turns out that these requirements can be ideally fulfilled in semiconductor and metal nanostructures.

For the realisation of an *asymmetric potential* in solid state material, state-of-the-art nanotechnology offers many options: periodic or non-periodic, one-, two- and three-dimensional potentials can today be fabricated with high accuracy. For instance, the quantum dot ratchet (Fig. 2) that will be discussed below was defined laterally using electron-beam lithography and wet etching in GaAs/AlGaAs heterostructure material. Similarly, surface gates could be used instead of the wet etching (Beenakker and Houten 1991). To create a periodic, asymmetric potential similar to the sawtooth potential in Fig. 1, one can think of a variety of vertical arrangements, for instance an asymmetric superlattice created using epitaxy techniques. Other examples of semiconductor-based quantum ratchet potentials have been proposed recently (Sordan and Nikolic 1996; Wagner and Sols 1998). The most obvious choice of *particles* to be subjected to the potential are electrons, whose current can be measured with extremely high accuracy, but one could also think of using phonons or other quasiparticles. The *length-scale* of the potential will then have to be chosen in such a way that quantum effects, such as electron tunnelling through a barrier, energy quantisation in a low-dimensional potential, or electron wave interference effects, are important for the electron transport. This requirement is also straightforward to fulfill. The case of electron interference will be discussed below in connection with the quantum dot ratchet. The last requirement is the need to impose *fluctuations* on the ratchet system. Here also the possibilities are many: surface gates controlling barriers, magnetic or electric fields, time-dependent light excitation, or the variation of temperature are examples. Also, the frequencies of the fluctuations may be varied from very low, changing the system quasi-statically, to very high (that is, fast compared to relevant relaxation times) such that the system is in the highly dynamical response regime.

3. A Quantum Dot Ratchet

As an example of an experimental semiconductor quantum ratchet device, we review here the properties of a quantum dot ratchet (Linke *et al*. 1998*b*, 1999). It consists of an asymmetric (triangular), ballistic, phase-coherent electron cavity with one point contact at the tip and one in the centre of the base of the triangle (Fig. 2). The device had a side length of typically 2 μm and was defined by wet etching in high-mobility GaAs/AlGaAs two-dimensional electron gas material. An additional top-gate (not shown in Fig. 2) allowed the Fermi energy of the electron gas to vary. The two-dimensional electron gas areas to the left and the right of the triangular dot can be contacted such that the electric resistance of the cavity can be measured directly. At low enough temperatures ($T < 1$ K), when the electron–electron interaction is sufficiently suppressed and where the Fermi edge is sharp, electron transport through the dot is determined by the coupling of the wave modes in the point contacts to the quantised electron states inside the cavity (Christensson *et al.* 1998). In this regime, where quantum effects are important for electron transport through such ballistic electron cavities, the latter are also referred to as quantum dots.

The spatial asymmetry required for a ratchet effect is provided in these devices by the shape of the cavity. An external perturbation (or fluctuation) can be imposed on the system by applying an electric field along the symmetry axis. This electric field has the effect of changing the potential formed by the dot in a self-consistent way, such that the electron states inside the dot depend on the applied field. Consequently, the transport properties of the dot also change as a function of the field, that is, the dot is studied in the nonlinear regime. Due to the broken spatial symmetry of the dot, the nonlinear dot resistance depends on the direction of the field, such that a sinusoidally time-varying (but on average disappearing) electric field will result in a directed current, that is, the asymmetric dot acts as a ratchet.

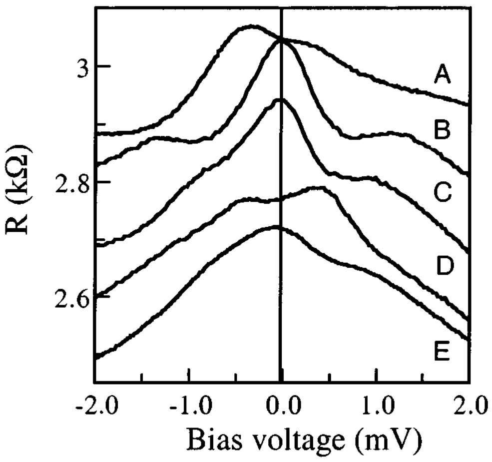

Fig. 3. Measurements of the differential resistance as function of the applied bias voltage. The different lines correspond to different values of the Fermi energy, which was varied with a top-gate in the experiment. Because of the broken symmetry of the triangular dot, the resistance depends in general on the sign of the voltage [from Linke *et al.* (1998*b*)].

In Fig. 3 the two-terminal differential resistance of a triangular quantum dot is shown as a function of an applied DC bias voltage. The different curves in this figure were obtained at different Fermi energies and a temperature of $0{\cdot}3$ K. Clearly, the signals are not symmetric with respect to zero voltage. The details of the signal (and the direction of the asymmetry) depend on the Fermi energy, because at different Fermi energies different states inside the dot are sampled. These will then also react differently to changes of the external field. In a similar way, the asymmetry of the nonlinear resistance depends also on small magnetic fields that change the states inside the dot (Linke *et al.* 1998*a*).

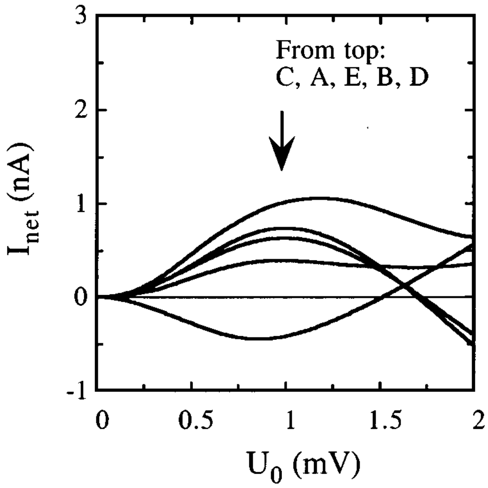

Fig. 4. Calculated net (time-averaged) current as a function of the amplitude of an applied AC voltage, based on the experimental data from Fig. 3. The direction of the net current depends on the Fermi energy and on the amplitude at which the dot ratchet is rocked [from Linke *et al.* (1998*b*)].

Clearly, the conductance of the dot depends on the direction of the field. Consequently, when an AC voltage is applied to the quantum dot, a net current in one direction will be induced, that is, the dot acts as a rectifier or ratchet. The net current (calculated on the basis of raw experimental data on the nonlinear resistance shown in Fig. 3) is shown as a function of an applied AC amplitude in Fig. 4. Most interestingly, the direction of the current induced by this quantum dot ratchet depends on the Fermi energy, on the excitation amplitude and on the magnetic field (this latter dependence is not shown here).

The intuitive interpretation of the experimental results presented here has been theoretically confirmed by fully quantum-mechanical calculations of electron wave propagation through a triangular cavity in the nonlinear regime (Linke *et al.* 1998*b*). In these calculations the experimentally observed asymmetric nonlinear resistance and the dependence on the Fermi energy, as well as the scale and behaviour of the rectified current, were qualitatively reproduced. It was also shown that the asymmetric *shape* of the triangular cavity alone is enough to cause rectifying quantum effects, while no such effects are found in a rectangular (symmetric) cavity, as is required by the symmetry of the potential (Linke *et al.* 1998*a*). Further, the rectifying effects were found theoretically to be larger when not only the shape of the cavity but also the distribution of an external electric field was assumed to be not symmetric.

4. Conclusion and Outlook

It was the aim of the present article to show that solid state nanostructures offer a large variety of possibilities for the realisation of quantum ratchet devices. As an example, the properties of a quantum dot ratchet were reviewed. These first experiments were carried out with a single quantum dot in the quasi-static regime. Different behaviour, and possibly new physics, can be expected if instead a periodic ratchet consisting of many quantum dots in series is studied (Linke 1997). Also, the frequency at which the quantum dot ratchet is 'rocked' by an applied AC voltage could be chosen to be higher than the typical relaxation time of the electrons, such that the system would be driven out of the adiabatic regime.

Ratchet devices based on solid state nanostructures clearly have the potential to make significant contributions to the understanding of ratchet effects, and to uncover new and fascinating basic physics. In the long run, it may then be possible to create devices that more closely model the biological systems that provide much of the driving force for this field of research, and to understand whether ratchets are indeed useful models for molecular motors. The potential importance of such insights for our understanding of fundamental processes in biological cells, and even a vague prospect of at some point being able to design and use artificial molecular motors, make this effort more than worthwhile.

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