Coulomb Blockade Ratchet

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(March 24, 2022)

Abstract

We investigate the transport properties of a new class of ratchets. The device is constructed by applying an ac voltage to the metallic single electron tunneling transistor, and a net transport current is induced by the time-dependent bias-voltage, although the voltage value is on the average zero. The mechanism underlying this phenomenon is the Coulomb blockade of the single electron tunneling. The directions and the values of the induced net currents can be well controlled by the gate-voltage. A net transport current has also been observed even in the absence of the external bias-voltages, which is attributed to the noise in the circuit.

PACS numbers: 05.40.+j, 73.40.Ei, 73.23.Hk
The principle of mechanical ratchets has been analyzed in the course of the development of modern physics. Recently, the idea of Feynman’s thermal ratchet has been generalized to account for the macroscopic motion of particles in an unbiased asymmetric periodic potential such as material transport in biological systems. A quantum rectifier using the superposition of a sinusoidal oscillation and its second harmonic with a phase shift as bias-voltage applied to a periodic symmetric potential has been predicted to be able to create a net current flow. The prediction has been confirmed by experiments using a 2D-array of triangular-shaped anti-dots. A ballistic rectifier using a single anti-dot as an asymmetric artificial scatterer in a semiconductor microjunction has been demonstrated experimentally to guide carriers in a predetermined spatial direction, thus behaving like a four-diode-bridge rectifier. A geometric quantum ratchet has also been realized by applying an ac voltage bias to a triangular-shaped quantum dot to create a net current. In these two cases, there are no periodic potentials in the system. Instead, the charge carriers move randomly in an asymmetric structure in the direction of the transport current, and can drift out to create a current. In this letter, we present our investigation of a novel class of ratchets. In our device, we do not need external electrostatic potentials to confine the charge carriers, namely electrons, neither do we need specially prepared geometrical confinement. The central part of our ratchet is formed by a metallic grain of arbitrary shape, which is brought within a distance of a couple of Ångstrom from two metallic leads. Electrons can tunnel between the leads and the grain. If the grain is sufficiently small, and coupled properly to voltage sources, such a device is actually the single electron tunneling transistor (SET), where the central grain is called the island, which is coupled to the gate voltage $V_g$ via the gate capacitance $C_g$, and the leads are directly coupled to the transport voltages.

The transport current as a function of dc bias- and gate-voltage has been extensively investigated both theoretically and experimentally in recent years. It becomes clear that in such a device with sufficiently large tunnel resistances at sufficiently low temperatures, tunneling of even a single electron is not allowed for vanishing gate voltage as long as the dc bias-voltage is smaller than the threshold value $V_c = e/2(C_1 + C_2 + C_g)$, where $C_1$ and $C_2$ are the capacitances of the tunnel junctions. As a result, there is a finite bias-voltage, but no current flows. This phenomenon is known as the Coulomb blockade, which can be lifted out by increasing the transport voltage or tuning the gate voltage. Distinct Coulomb staircases in the $I - V$ curves have been observed in our device when the parameters of the two tunnel junctions are made different from each other. For the SET used in our present investigation, the $I - V$ curve is shown in Fig. 1 for $V_g = 0$ and $T = 4.2K$. The corresponding parameters of the device are found to be $C_1 = 7.6 \text{ aF}$, $R_1 = 1.0 \text{ M\Omega}$, $C_2 = 7.6 \text{ aF}$, $R_2 = 105.0 \text{ M\Omega}$, $C_g = 2.0 \text{ aF}$, and $E_c = 4.7 \text{ meV}$.

If the circuit is biased by an ac voltage, the average bias voltage is zero, the average transport current would be, **prima facie**, also zero just as in the case of vanishing transport voltage. This is certainly true for classical tunnel junctions, where the capacitances of the junctions are large, and thus the Coulomb charging energies are negligible compared to the thermal energy even at fairly low temperatures so that the I-V characteristics are Ohmic. For our device with the charging energy of 4.7meV, however, the I-V characteristics at liquid helium temperature are strongly nonlinear due to the Coulomb blockade, and the relation $I(-V) = -I(V)$ is in general not satisfied. Therefore the net current is nonvanishing, even if the average transport voltage is zero. To get a pronounced net current induced by the ac
bias-voltage, the two tunnel junctions should have different parameters so that the I-V curves are strongly asymmetric with respect to the applied voltages. In the experiment reported here, we choose $R_1 \ll R_2$, and indeed we have observed clearly transport currents induced by ac bias-voltages, which have well-defined lineshapes extended periodically for a wide range of the gate-voltage. Moreover, we can control both the direction and the magnitude of the net currents by tuning the gate-voltage. The experimental data are found to agree very well with the theoretical calculations based on the constant charging energy model. Since the only physical reason that we obtain the net current by applying ac bias-voltage is the Coulomb blockade of the single electron tunneling, we call our device a Coulomb blockade ratchet.

The rectifier effect in a lateral 2D quantum dot SET made in a semiconductor nanostructure has been observed by Weis et al. However, in a semiconductor SET the transport cannot be simply attributed to the Coulomb blockade, but depends on the details of the device such as material, external confinement, and coupling of the energy levels in the quantum dot to the leads. On the contrary, our device is merely characterized by junction resistances, junction capacitances, and gate capacitance, and the induced net current is perfectly periodic in the gate-voltage, and determined explicitly by the above-mentioned parameters of the device. In addition to the case of the ac biased circuit, we have also studied the transport properties of the SET driven by noise sources, which lead to detectable net currents, even in the absence of any applied ac voltages. The transport theory of the SET in the parameter range of our devices biased by dc voltages is well-established. The dc current of the SET can be calculated via

$$I(V) = e \sum_{n=-\infty}^{\infty} \sigma(n, V)[\Gamma_1^+(n, V) - \Gamma_1^-(n, V)]$$

$$= -e \sum_{n=-\infty}^{\infty} \sigma(n, V)[\Gamma_2^+(n, V) - \Gamma_2^-(n, V)].$$

(1)

Here the tunneling rates of an electron tunneling from (-) or onto (+) the central island with n excess electrons via the first (1) or the second (2) junction are labeled by $\Gamma_{1,2}^\pm(n, V)$, and the probability of $n$ excess electrons on the island is denoted by $\sigma(n, V)$. Since the resistances of the tunnel junctions in our experiments are typically of the order of 100 $\text{M}\Omega$, and the capacitances are of the order of 10 $\text{aF}$, the RC time is thus of the order of $10^{-9}$ s, which is much larger than the tunneling time. The latter is of the order of $10^{-15}$ s for metallic tunnel junctions. In the experiments, we have varied the frequencies of the ac voltages $\omega/2\pi$ between 100 Hz and 10 MHz. In this frequency range the period of the bias signal $T = 2\pi/\omega$ is much larger than the intrinsic characteristic time-scales of the SET, such as electron tunneling time or capacitance charging time, so that the SET can follow the variation of the ac signals adiabatically. Hence the induced net current is given by the mean value of the transport voltage, $I_{\text{net}} = \langle I[V(\varphi)] \rangle$, where $I[V(\varphi)]$ is given by Eq. (1) with $V(\varphi) = V_{\text{am}} \cos(\varphi)$ and $\varphi = \omega t$. Since $I[V(\varphi)]$ is a periodic function of time, the mean value of it can be calculated either within a time interval much larger that the period $T$, or within a period of the applied ac voltage. Apparently, the net current expressed in the above formula has no explicit frequency-dependence, which is confirmed by our experiments for various frequencies between 100 Hz and 10 MHz.

The fabrication and operation of our SET has been published elsewhere and will
not be repeated here. The only difference is that the island and the leads in the present device are made of palladium instead of gold. The tunnel gaps were deliberately tuned to be strongly asymmetric in resistance in order to enhance the ratchet effect. To give a comprehensive description of the device, we have investigated the net current as a function of the gate voltage for various amplitudes of the ac bias voltages. For large amplitudes of the bias-voltages, we found that by decreasing the amplitude of the ac bias-voltages, the amplitudes of the induced currents get smaller rapidly, and the lineshapes shrink. Typical curves are shown in Fig. 2 (dots) for large amplitude of the applied ac voltage where the lineshapes are sine-like, and in Fig. 3 (dots) for intermediate amplitude of the applied ac voltage where the variation of the net current is relatively slow in the Coulomb blockade regime. In the figures the corresponding theoretical curves of the net current induced by the applied bias-voltage as a function of the gate-voltage calculated according to Eq. [1] are also shown (dashed lines). By further decreasing amplitude of the applied ac voltage the induced net current is expected to decrease and finally vanish for zero amplitude. However, in the experiments, we observed a fairly pronounced transport current as a periodic function of the gate-voltage, even when our applied ac bias-voltage was vanishing, as shown by the dots in Fig. 4. We explain this by considering that the input terminal of the device picks up the external noise that acts as a background, time-dependent bias-voltage with zero average values. In our experimental setup this is reasonable because there are coaxial cables several meters long between the instruments/filtering at room temperature, and the sample. The presence of noise sets the lower limit for the amplitude of the induced current.

By measuring the input noise to the SET in the frequency range of $10 \text{Hz}$ to $100 \text{kHz}$, we found that the dominating noise source has a broad spectrum with almost constant intensity smaller than $10^{-4} \text{mV/} \sqrt{\text{Hz}}$. However this broad band noise is unlikely to induce the measured net current, because the induced net current depends strongly on the amplitude of the ac bias-voltage. For the parameters of our device, the net current induced by the applied ac bias-voltage becomes smaller in the order of magnitude if the amplitude of the ac bias-voltage decreases from a few $\text{mV}$ to a value smaller than $1 \text{mV}$. This is at least one order of magnitude larger than the rms value of the broad band noise voltage in our circuit. Even if the rms value of the broad band noise is larger than $1 \text{mV}$, the amplitude of the signal in each small frequency interval is still very small, while the bandwidth of the noise spectra remains large. As a consequence, the contribution of the broad band noise to the induced net current is negligible. To consolidate this argument, we have deliberately applied a broad band noise source with the rms value of input voltage as large as $8.5 \text{mV}$ to the device. As shown by the crosses in Fig. 4, this additional noise source has indeed little effect on both the amplitude and the lineshape of the net current as compared to the one of the unbiased device.

We attribute the net current in the unbiased device to the noise source with large amplitudes in the high frequency range. The measured data can be fitted reasonably well by the standard sequential tunneling theory [2] if one chooses the amplitude of the fitting ac bias-voltage to be $2.3 \text{mV}$, as shown by the dashed line in Fig. 4. Furthermore, we have calculated the induced net current as a function of the gate-voltage in the presence of both the applied ac voltage and the circuit noise voltage. The circuit noise is modeled by the ac voltage with the amplitude obtained from Fig. 4, and with the frequency much higher than that of the applied voltage. Then the current for a given point of the applied voltage is...
calculated as the mean value with respect to the circuit noise in a time interval much smaller than the period of the applied voltage, but much larger than the period of the modeled ac voltage of the circuit noise, i.e. \( \bar{I}[V(\varphi)] = \langle I[V_{am}\cos(\varphi) + \tilde{V}_{am}\cos(\tilde{\varphi})] \rangle \), and the observed current is thereafter calculated as the mean value with respect to the applied ac signal, \( \bar{I}_{\text{net}} = \langle \bar{I}[V(\varphi)] \rangle \). The results are shown by the solid lines in Fig. 2 and Fig. 3. For a fairly large amplitude of the ac bias-voltage, the influence of the circuit noise is weak, as shown in Fig. 2, while for an intermediate amplitude of the ac bias-voltage, the influence is significant. As shown in Fig. 3, the result of the ac plus noise bias-voltage agrees very well with the experimental data for the whole curve, while the one of the pure ac bias-voltage gives the correct amplitude and the lineshape near to the resonance at \( C_gV_g = e/2 \) module e, yet a somewhat smaller value near to the Coulomb blockade at \( C_gV_g = 0 \) module e. From the above analysis, it seems that the measured unbiased net current is very likely to be induced by the circuit noise with large amplitudes in the high frequency range.

In summary, we have investigated the Coulomb blockade ratchet using the metallic single electron tunneling transistor. We have observed fairly long periods of the net currents induced by the ac bias-voltages, which agree very well with the sequential tunneling theory. In the absence of applied voltages, we also observed pronounced, periodic net currents, which are probably induced by the circuit noise. We have hence shown how the background noise is, in a ratchet-like fashion, transformed by the single electron device into a net current of electrons.

The authors would like to thank H. Linke for valuable comments on our manuscript, and A. Löfgren, P. Omling, and H. Xu for stimulating discussions.
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FIGURES

FIG. 1. I-V curve of the SET at 4.2K and \( V_g = 0 \) with the device parameters \( C_1 = 7.6aF \), \( R_1 = 1.0M\Omega \), \( C_2 = 7.6aF \), \( R_2 = 105.0M\Omega \) and \( C_g = 2.0aF \).

FIG. 2. Induced current as a function of the gate voltage for a large applied ac voltage with the rms value of 6mV. The dots are the experimental data, while the solid and dashed lines correspond to the theoretical results with or without the circuit noise contributions, respectively.

FIG. 3. Induced current as a function of the gate voltage for an intermediate applied ac voltage with the rms value of 3mV. The dots are the experimental data, while the solid and dashed lines correspond to the theoretical results with or without the circuit noise contributions, respectively. Note the dashed line is less smooth near the Coulomb blockade, which is smeared out by the circuit noise to become the solid line. The latter agree very well with the experimental data.

FIG. 4. Induced current as a function of the gate voltage in the absence of the applied ac voltage. The dots are the experimental data without additional broad band noise, the dashed curve is the theoretical fitting with an amplitude of the ac bias-voltage of 2.3mV. The crosses are the experimental data when the device is biased by a broad band noise voltage with the rms value of 8.5mV.
