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Coulomb blockade in an open small ring with strong backscattering

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Abstract

A comparative study of Coulomb blockade oscillations in a small quantum ring with effective radius 100 nm in ordinary tunnelling and anomalous open regimes is performed. We demonstrate that even though there is no tunnelling barrier between the ring and 2D electron sea in this ring, gigantic Coulomb blockade-like oscillations can be observed. Gate voltage, DC bias and temperature dependences of the ring conductance were experimentally studied at temperatures $0.24-1.4$ K and magnetic fields up to 1.5 T. These studies show the principal differences between Coulomb blockade oscillations in the tunnelling regime and in the open state. The fundamental single-electron period of the oscillations is found to be the same in both regimes. The role of backscattering processes is concluded to be the reason for the existence of strong Coulomb blockade effects in the open state of the ring.

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Keywords: Ballistic transport; Coulomb blockade; Tunnelling

1. Introduction

It is well know that single-electron Coulomb blockade oscillations of the conductance in lateral quantum dots (QDs) have a large amplitude if the dots are separated from the 2D electron gas by tunnel barriers [1]. The question whether these oscillations remain when the tunnel barriers are removed (open state) has been widely studied for the last 15 years both theoretically and experimentally. It was shown that the Coulomb blockade effect perseveres if there exists a backscattering process in the system such that the phenomenon of 'mesoscopic charge quantization' arises [2,3]. However, the amplitude of single-electron oscillations in this regime proves to be small, being ~10% of that in the tunnelling regime [4–7].

Recently, small (effective radius ~100 nm) semiconductor rings formed on the basis of a high mobility 2DEG in an AlGaAs/GaAs heterostructure have shown large amplitude, short-period oscillations in the open state of this ring [8]. In this work we report results of a study of these oscillations, which appear together with ordinary Coulomb blockade (OCB) oscillations realized in the same device.

2. Results and discussion

The studied device is a small quantum ring with effective radius $100-120$ nm (found from Aharonov–Bohm oscillations). The ring is fabricated by means of local oxidation by an atomic force microscope on the basis of an AlGaAs/GaAs structure with 2DEG of mobility about $10^5\,\mathrm{cm^2/V\,s}$ at an electron density of $5\times10^{11}\,\mathrm{cm^{-2}}$. The 2DEG is formed 25 nm below the surface on which a Ti/Au gate is placed. A SEM image of the ring is shown in Fig. 1(b). Aharonov–Bohm oscillations of the conductance of this ring at a fixed gate voltage are shown in the same figure. The period of these oscillations, 0.103 T, gives the effective radius of the ring $r = 113$ nm. The ring is therefore small compared to the mean free path (~1 μm).

Gate voltage, DC bias and temperature dependences of the ring conductance were experimentally studied at

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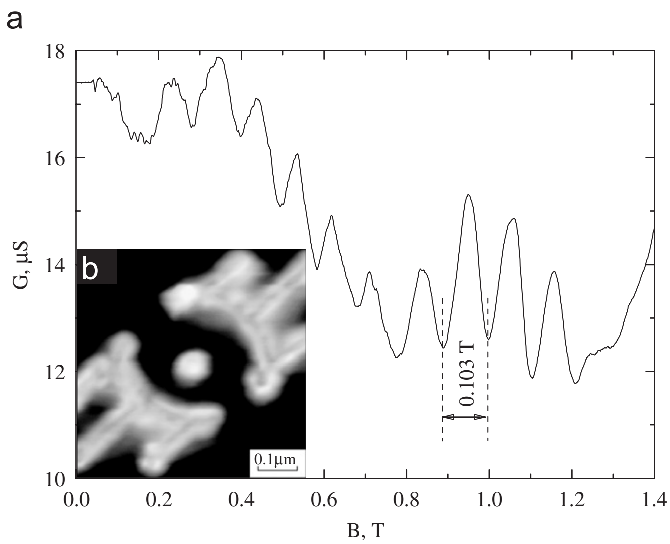

Fig. 1. (a) Conductance as a function of magnetic field at a fixed gate voltage of 280 mV (the temperature is 0.25 K), (b) SEM image of the open ring fabricated by local anodic oxidation technique.

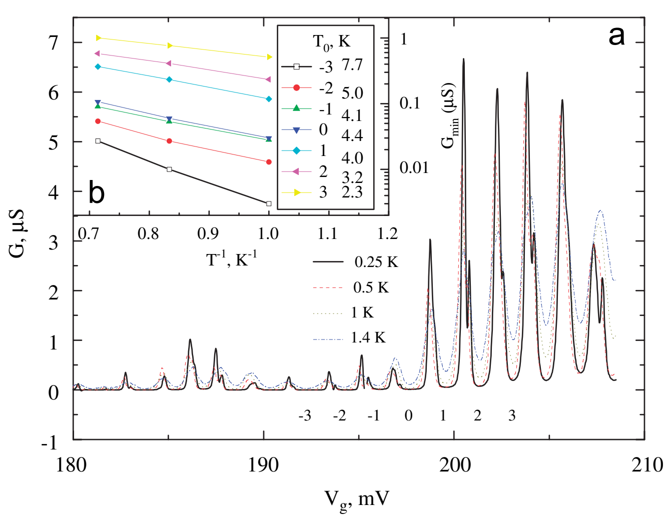

Fig. 2. (a) Conductance as a function of gate voltage in the Coulomb blockade regime at four different temperatures. (b) Temperature dependance of the conductance in the dips (marked by numbers from −3 to 3) between Coulomb blockade peaks. The activation temperature changes from 2.3 to 7.7 K.

temperatures 0.25−1.4 K and magnetic fields up to 1.5 T. Fig. 2 demonstrates that the conductance $G(V_g)$ forms a set of regularly spaced peaks (growing in amplitude as the temperature decreases) with period $\Delta V_g = (1.6-1.7)$ mV. It is reasonable to suppose that these are single-electron Coulomb blockade peaks and we deal with OCB in a closed ring. However, the behavior of the amplitude of these peaks is not consistent with this supposition. It is clearly seen that there are in fact two sets of peaks. The first set (at $V_g < 198$ mV) is characterized by an average peak amplitude of about 0.3 μS and the second set (at 198 mV < $V_g < 210$ mV) consists of peaks with much (about 10 times) higher amplitude, and the transition between these two sets is very sharp (within one period). These two sets of single-electron peaks have previously been observed in Ref. [9] but they were not clearly separated and a detailed analysis of them was not performed.

Let us start by considering the properties of the first set corresponding to the smaller voltage region $V_g < 198$ mV. The results of DC bias (V_{sd}) experiments for this region for several gate voltages corresponding to minima and maxima of the peaks are shown in Fig. 3(a). Fig. 3(b) shows the results in grayscale format for the whole range of V_{dc} and V_g. One can see the diamond-like structure which is typical of Coulomb blockade effects [1]. We conclude from this that the first region is that in which there are OCB effects. The results for the second region corresponding to 198 mV < V_g < 210 mV are presented in Fig. 3(c). At first glance a similar behavior of the conductance is observed in this region. However, more careful analysis demonstrates that there are significant differences. While in the OCB region the width of the zero conductance region around $V_{sd} = 0$ is 1.6−1.8 mV and is approximately equal to the period of the gate voltage oscillations ($\Delta V_g = 1.65$ mV), this width in the second region is narrower ($\Delta V_{sd} =$ 0.9−1.1 mV) and less than the period $\Delta V_g = 1.7$ mV. The diamond-like pictures of both regions (compare Fig. 3(b) and (d)) support this distinction. The slope of $V_{sd}(V_g)$ function is close to 1 in Fig. 3(b) while the same slope in Fig. 3(d) is close to 0.5. Moreover this latter slope depends on the fluctuational potential realization because it has a different value (about 0.25) for another cooling cycle. So in the second region we have the realization of an unusual Coulomb blockade (UCB) regime.

Temperature measurements show differences in the conductance behavior of the peak minima for the OCB and UCB regimes. The qualitative behavior of $G_{min}(T)$ dependences is similar (see Fig. 2(a)): at $T > 0.5$ K activation behavior is observed and at $T < 0.5$ K a saturation arises. A more detailed analysis shows a different behavior of $G_{min}(T)$ in the OCB and UCB regimes (see Fig. 2(b)): in $G_{min}(T)$ OCB is characterized by activation temperature $T_0 = (4-8)$ K while in UCB it is significantly less $T_0 = (2-4)$ K, which decreases as V_g increases.

The results clearly show that in our ring, as the gate voltage is increased, at certain gate voltage ordinary single-electron oscillations transform into unconventional oscillations which have another origin. We suggest that this transformation is caused by removing the tunnel barriers between the ring and the 2D regions which it connects. This would infer that the UCB regime is realized in the open ring. In contradiction to earlier studies [4–7] the gigantic Coulomb blockade-like oscillations can be observed in open state [9] (the ratio of peak conductance value to minimum conductance one exceeds 10^2, see Fig. 2).

One of the important properties of the small ring studied is the existence of strong backscattering [9] caused by QDs situated in the input and output points of the ring [10]. Most probably this backscattering alone results in the UCB regime. Its existence in the UCB regime is supported by the

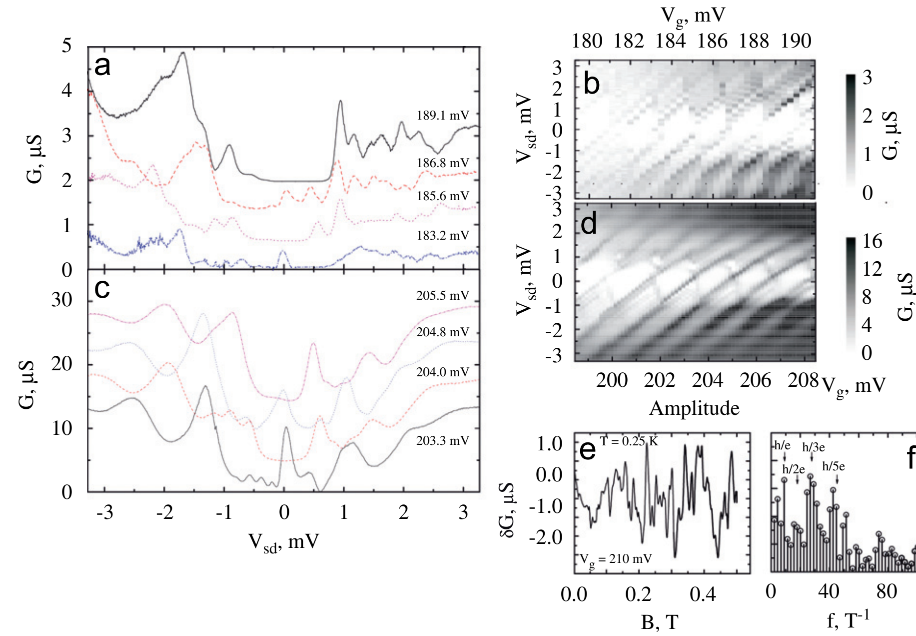

Fig. 3. (a) Conductance as a function of source drain voltage V_{sd} at several gate voltages is shown for the OCB region. (b) Conductance in grayscale format for the whole range of V_g and V_{sd}. In (c) and (d) conductance in the UCB region is shown. (e) Oscillations of the conductance as a function of magnetic field at gate voltage, 210 mV, with monotonic background subtracted. The FFT spectrum of the oscillations is shown in (f) where several odd subharmonics of h/e are indicated by arrows.

observation of high Aharonov–Bohm oscillation (Fig. 3(e)) subharmonics ($h/3e$, $h/5e$) observed in this regime (see Fig. 3(f)). A more certain conclusion requires the development of the Coulomb blockade theory in an open mesoscopic system with strong backscattering processes.

3. Summary

The results of our comparative study of OCB and UCB regimes show principal differences between Coulomb blockade oscillations in tunnelling regime and these oscillations in the open state except the fundamental single-electron period of the oscillations which is very similar in the both regimes. Our experiments demonstrate that in a small semiconductor quantum ring gigantic Coulomb blockade single-electron oscillations are possible to realize in the open state of the device. We propose that this is caused by strong backscattering processes in the ring. This is supported by the observation of high frequency Aharonov–Bohm oscillations.

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