Aharonov-Bohm Oscillations in the Coulomb Blockade Regime

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We discuss the electronic transmission through lateral dots, featuring both the Aharonov-Bohm-type oscillations observed in high magnetic field sweeps and Coulomb blockade oscillations detected as a function of electron density. We focus on the interplay of these two effects and demonstrate two intrinsic features of submicron dot behavior—the manifestation of the Aharonov-Bohm oscillations in a resonant reflection mode and a novel regime characterized by the simultaneous observation and a commensurate relationship of the two effects.

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In nanoscale semiconductor geometries, modeled as very small capacitors, the charging energy associated with a single electron (e^2/C) can be sufficiently large that "Coulomb blockade" (CB) oscillations appear in the conductance [1]. In contrast to the CB effects observed in metallic systems [2], the energy spacing, ΔE_S, between levels in semiconductor quantum dots [3] or quantum wires [4] can be sufficiently large to play a role in the CB process. Furthermore, in the absence of CB, high magnetic-field sweeps produce oscillations interpreted as resonant tunneling through the discrete single-electron (i.e., E_S) energy levels of an edge state confined by the geometry [5]. Because these oscillations were initially described within an interferometer model similar to the original Aharonov-Bohm (AB) effect [6], they are referred to as AB-type oscillations. Each AB oscillation corresponds to a change of one flux quantum in the area enclosed by the confined edge state. Traditionally the AB and CB processes have been viewed as independent [7], but here we report the first observation of a system in which both processes, AB and CB, are not only simultaneously operative but are also forced by the interaction between them to be commensurate. The phenomena found are intrinsic to dots smaller than 1 μm and are reproducible on thermal cycling.

Quantum dots are formed in AlGaAs/GaAs 2D electron gas systems (2DEG). Two different 2DEGs are used, with electron densities of 3.5 and 5.6×10^{11} cm^{-2} and mobilities of 0.45 and 1.7×10^6 cm^2/Vs. Four gates, patterned on the surface of the sample using *e*-beam lithography, define a circular dot with a lithographic radius of approximately 0.25 μm and with two quantum point contacts (QPCs) as entrance and exit ports [8]. By adjusting the gate potentials it is possible to tune the height of the QPC barriers to control the transmission of the edge states carrying electrons from the "bulk" 2DEG into the dot. For gate settings corresponding to an integer number of fully transmitted edge states in a QPC, the "barrier" conductance G_b is quantized in units of $2e^2/h$ at low magnetic fields, and e^2/h at fields sufficient for spin resolution [9]. Transport through the dot is "reflectionless" when the total conductance, $G_{\rm dot}$, equals G_b. In addition to the top gates a metal plate, positioned 450 μm below the 2DEG, is used to vary the electron density n as a function of back-gate voltage V_g.

Figure 1, curve 1 shows typical CB oscillations in a magnetic field of 9 T. In this magnetic field, the edge states within the QPCs are spin resolved and the top-gate voltages are set so the transmission through each QPC is identical, with partial transmission of a single edge state. When the back-gate voltage is swept, electrons are removed from the dot and the transmission moves periodically through resonances with a periodicity independent of magnetic field. This simple behavior implies a resonance condition determined by the charging energy, which is larger than ΔE_S. The temperature dependence ($T<2$ K) can be modeled in terms of the total capacitance of the dot to the gates and leads [5,10]. Similar CB oscillations have been previously observed in both quantum dots [3] and in disordered quantum wires [4].

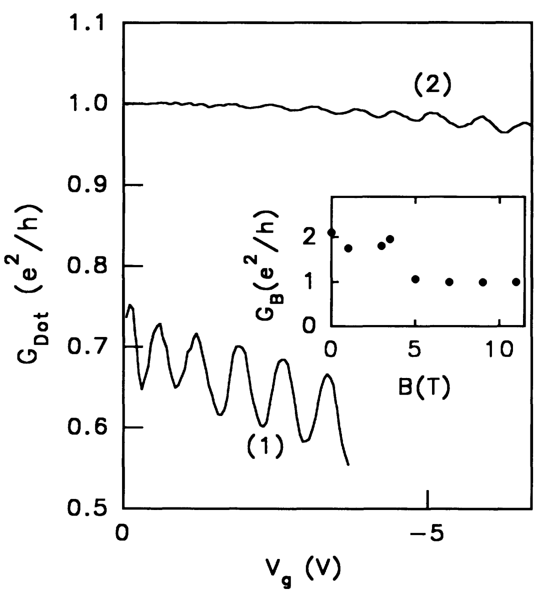

FIG. 1. Conductance of a 0.25-μm dot showing Coulomb blockade oscillations at $B=9$ T and $T=70$ mK for two different top-gate settings. Inset: The magnetic field B dependence of the G_b value at which the onset of the CB oscillations occurs.

When the top-gate voltages are adjusted to set the QPCs (at $V_g = 0$) just on the edge of their conductance plateau (curve 2), the onset of the CB oscillations can be clearly seen as soon as sweeping the back gate moves the QPCs off the plateau by as little as 1%. It is emphasized that it is G_b, the conductance of the individual QPCs, determined in an independent calibration measurement, that is important even though at these fields $G_b \approx G_{\rm dot}$. At lower magnetic fields the edge states in the QPC are not spin resolved so, as shown in the inset, the CB oscillations start as soon as the conductance of the QPCs falls below $2e^2/h$. Further experiments show that for CB to occur *both* QPCs have to be off the plateau. The barrier condition for the onset of the CB effect is therefore surprisingly simple: One partially transmitted edge state must be present in each QPC. CB oscillations for high, identical G_b settings ($> e^2/h$) for the two barriers have also recently been observed in other semiconductor dots [11].

In a blockade-free dot high magnetic-field sweeps can produce Aharonov-Bohm-type oscillations which, in our 0.25-μm dots, are observed up to a characteristic temperature $T_{\rm RR}$ of 600 mK. However, compared with earlier measurements in larger (0.75 μm) dots [6], the transmission in our dots is modulated in a fundamentally different way. In Fig. 2(a) the top-gate voltages have been set for one (spin unresolved) fully transmitted edge state in each QPC and two in the dot itself. The configuration, shown schematically in Fig. 2(e), is then of an outer, fully transmitted edge state and of an inner, confined edge state consisting of discrete zero-dimensional energy levels [6]. The total conductance $G_{\rm dot}$ is slightly less than G_b, suggesting a small amount of coupling between the two edge states within the dot. This is a prerequisite for the appearance of the AB oscillations and we argue their origin is the resonant "reflection" (RR) of the outer fully transmitted edge state through the zero-dimensional levels of the inner confined edge state [12]. This is supported by the disappearance of the oscillations under the following conditions: (a) when the top-gate voltages are tuned for full transmission of the inner edge state through either QPC and (b) at higher magnetic fields (above about 5 T) when there is less overlap of the wave functions associated with the inner and outer edge states. A background of aperiodic structure is also consistent with the interedge state coupling picture [8,13,14]. Resonances in this RR process, corresponding to conductance minima, occur as the discrete energy levels of the inner edge state align with the Fermi energy. Experimentally, this edge state can be depopulated in three ways, each of which causes resonant reflection oscillations. Oscillations have been observed by sweeping the top-gate voltages, which changes the area of the dot, by sweeping the back-gate voltage to change n, and by sweeping the magnetic field.

If pure CB, when the barrier transmission is well below unity, is considered as regime 1 and pure RR oscillations, when there is no CB and there is perfect transmission of one edge state through each QPC, is regime 3, there is also an intermediate regime 2. This is illustrated in Fig. 3, where sweeping the back-gate voltage from −10 V, where there is pure CB, to 0 V moves the system out of

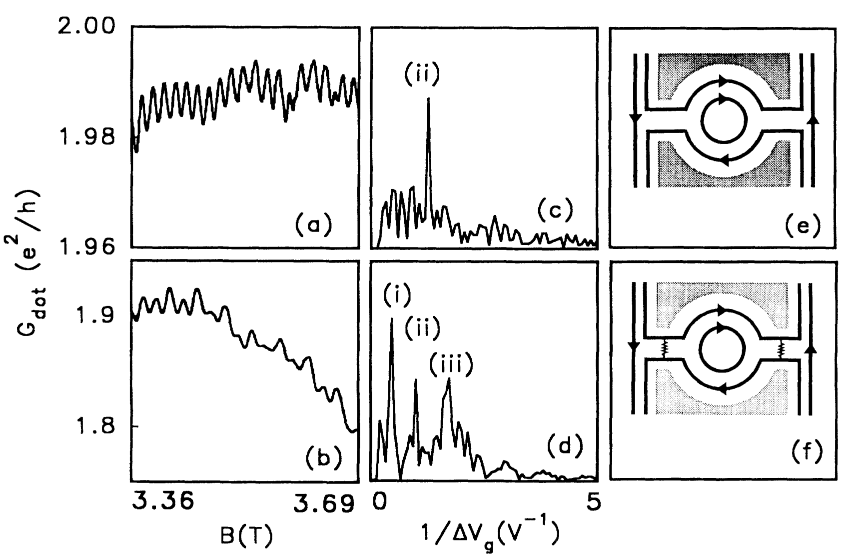

FIG. 2. Magnetic-field sweeps for top-gate settings corresponding to (a) the blockade-free regime 3 and (b) regime 2. Fourier transforms of back-gate sweeps taken at $B = 3.5$ T for top-gate settings corresponding to (c) regime 3 and (d) regime 2. All traces are taken at $T = 70$ mK. *Schematic* representations of the edge states of the dot are shown in (e) for regime 3 and (f) for regime 2. Full transmission of an edge state is drawn as a solid line, while partial transmission is represented by the zigzag pattern. Note that for clarity the interedge state coupling has not been shown.

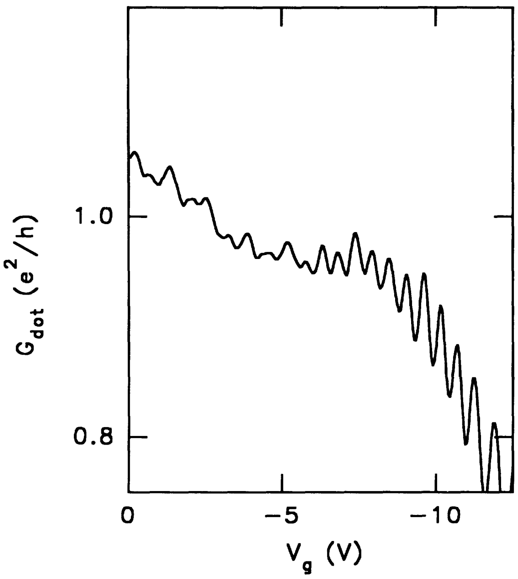

FIG. 3. A typical sweep of back-gate voltage taken at $T=70$ mK and $B=3.5$ T, showing a single CB period in regime 1 (-6 to -10 V) and a doublet structure in regime 2 (0 to -6 V).

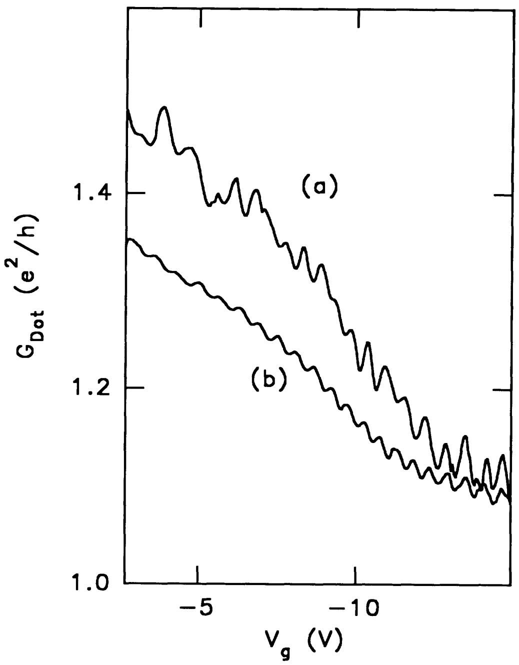

FIG. 4. Back-gate voltage sweeps taken at curve *a*, $T=70$ mK and curve *b*, $T=900$ mK. The top-gate voltage settings and magnetic field (3.5 T) were unchanged.

regime 1 and into regime 2, characterized by a doublet structure. Raising the temperature, so $T > T_{RR}$, restores a single CB oscillation with the same period as oscillations at -10 V. This shows that the doublet structure is related to the RR process. The magnetic-field sweeps produce single period RR oscillations which disappear for $T > T_{RR}$. The data are consistent with simultaneous *commensurate* CB and RR processes. The processes are commensurate because removal of an electron from the inner, totally confined edge state of the dot corresponds to every second CB oscillation but represents one complete cycle of the RR effect. As observed, every second conductance peak is suppressed. In this intermediate regime, where the outer edge state is only partially confined, we observe both its one-dimensional character through the RR behavior and its zero-dimensional character through the CB process, and can use temperature to separate the two properties. In regime 1, by contrast, the outer state can be considered as zero dimensional, preventing the simultaneous observation of RR and CB processes.

To confirm that regime 2 is intrinsic to dots of this size, the dots were thermally cycled and illuminated several times. Although the two kinds of oscillations were always present, on most occasions this process revealed RR oscillations containing an additional feature. This behavior is shown in Fig. 4 where curve *a* shows a structure more complicated than the doublet discussed above. In curve *b*, the temperature has been raised to 900 mK to suppress the RR contribution and only a simple CB term remains. To help clarify this extra structure, Figs. 2(b) and 2(d) show a magnetic-field sweep and the Fourier transform of a V_g sweep for a similar situation. In the Fourier transform, peak (iii) is identified as the CB contribution because it also appears in regime 1 (pure CB) and persists up to $T=2$ K. However, in contrast to the data shown in Fig. 3, there are two rather than one low-frequency RR peaks, both of which disappear by 900 mK when the temperature is raised. The three peaks (i), (ii), and (iii) occur at ratios 1:2:4 in frequency (within measurement resolution) and are identified with every fourth, second, and single electron depopulating the dot. In Fig. 2(c), which shows the Fourier transform of the back-gate sweep for regime 3, i.e., when the dot is blockade free, there is only one (RR) peak present and this is at a higher frequency than both peaks (i) and (ii) in Fig. 2(d). The frequency shift of peak (ii) is too large to be explained by a simple change in dot area induced by changes in top-gate voltage and, in fact, on some cooldowns the shift was of the opposite sign. Equivalent behavior is seen in the *B* field sweeps; in Fig. 2(a) the single period AB oscillations of regime 3 are clearly visible, but in Fig. 2(b) every second oscillation is suppressed. A frequency shift is also clearly seen in the magnetic-field sweeps, corresponding to the shift observed in the V_g sweeps.

We speculate that the frequency shift reflects the commensurability that must be induced in the CB and RR processes when they are simultaneously present and that this is the first observation of a realignment of the RR period by interaction with the CB effect. The opposite sign of this shift on different cooldowns reflects the sensitivity of the RR period in regime 3 to changes in electrostatic potential due to different impurity configurations. The mechanism by which every second RR oscillation in regime 2 is suppressed, both as a function of magnetic field and back-gate voltage, remains to be understood. The conventional Aharonov-Bohm description cannot explain it and it is not an artifact of spin effects alone: Intuitively, since spin is expected to be conserved in the RR process, and a calculation of the energy-level spectrum for our edge state configuration shows every second electron in the RR process to be of opposite spin, the amplitude variation might be attributed to a spin effect. However, allowing for spin, this same energy spectrum cannot account for the equally spaced oscillations of regimes 2 and 3. Further, as the sample orientation is tilted from $\theta=0°$ to 70°, the period of the AB oscillations simply varies as $1/\cos\theta$, which is inconsistent with spin splitting. We believe that consideration of electron-electron interactions within the RR process will be needed to understand this effect.

In conclusion, the interplay between RR and CB effects has been studied in small quantum dots. The AB effect arises because a fully transmitted edge state is modulated by resonant reflection. We have shown that barrier conditions can be set up for the coincidence of RR and CB related oscillations and, in this regime, we have observed a suppression of every second RR oscillation, as well as a frequency shift imposed on the RR mechanism by the Coulomb blockade.

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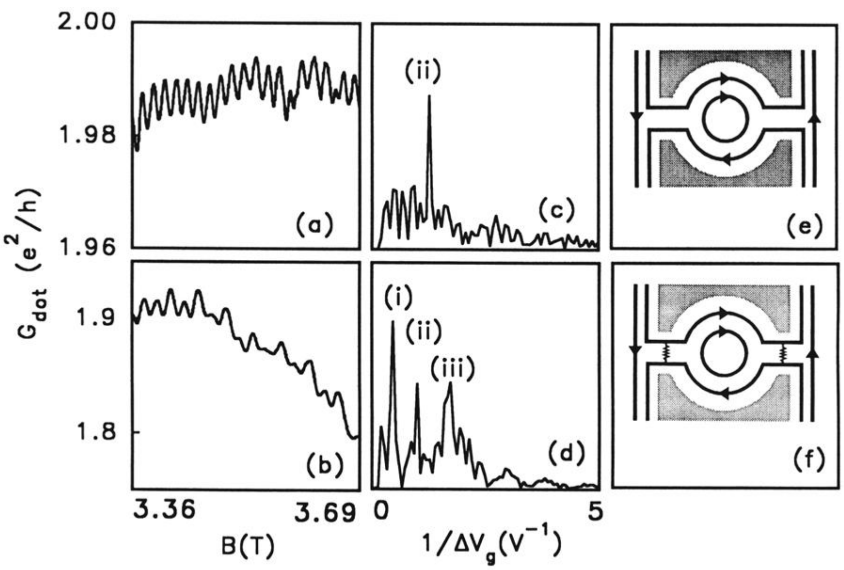

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