Coulomb Blockade in an Open Quantum Dot

S. Amasha,[1,*] I. G. Rau,[2] M. Grobis,[1,†] R. M. Potok,[1,3,‡] H. Shtrikman,[4] and D. Goldhaber-Gordon[1]

[1]Department of Physics, Stanford University, Stanford, California 94305, USA
[2]Department of Applied Physics, Stanford University, Stanford, California 94305, USA
[3]Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
[4]Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot 96100, Israel

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We report the observation of Coulomb blockade in a quantum dot contacted by two quantum point contacts each with a single fully transmitting mode, a system thought to be well described without invoking Coulomb interactions. Below 50 mK we observe a periodic oscillation in the conductance of the dot with gate voltage, corresponding to a residual quantization of charge. From the temperature and magnetic field dependence, we infer the oscillations are mesoscopic Coulomb blockade, a type of Coulomb blockade caused by electron interference in an otherwise open system.

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Mesoscopic systems are conventionally divided into two classes. In closed systems electrons are localized and Coulomb interaction effects determine the transport properties, while in open systems the Coulomb interaction can be neglected at low energies. The class of a system depends on the contacts between the mesoscopic region and the surrounding electrons. If the contacts contain a large number of poorly transmitting channels, such as in metallic nanostructures, then the crossover from closed to open is smooth and occurs when the total conductance of the contacts is on the order of e^2/h [1,2]. If the contacts each have one mode, as can happen in semiconductor nanostructures, then the transition is expected to be sharp: Coulomb blockade (CB) occurs when the mode in each contact is partially transmitting, and in the absence of phase coherence CB disappears when the mode in either contact becomes fully transmitting [3].

This transition from the closed to the open regime has been studied in laterally gated quantum dots [4–9]. Such a dot is contacted via tunable one-dimensional channels called quantum point contacts (QPCs), and $G_{QPC} = 2e^2/h$ corresponds to a single fully transmitting spin-degenerate mode, while $G_{QPC} \ll 2e^2/h$ corresponds to the tunneling regime. A dot is typically contacted by two QPCs. In a one-lead dot (one QPC fully transmitting, while the other is kept $\ll 2e^2/h$) phase coherence influences the transition from closed to open. Electron paths start and end at the transmitting QPC, and these paths interfere and reduce the transmission, trapping electrons on the dot. This leads to a type of CB called mesoscopic Coulomb blockade (MCB) [10,11]. Electron interference, and hence MCB, is strongest at zero magnetic field because a closed path that begins and ends at the same QPC interferes constructively with its time-reversed pair, an effect called weak localization (WL).

In a two-lead dot, where each QPC has one fully transmitting spin-degenerate mode, many paths do not return to the same QPC but rather go from one QPC to the other and allow transport through the dot. This results in different physics from the one-lead case. For example, in the absence of phase coherence, a reflection coefficient in the QPCs causes CB in a one-lead dot, while in a two-lead dot the lowest-order effect is not CB but rather a decrease in the dot conductance [3,12]. While there is no complete theory for phase coherent transport in a two-lead dot that includes interactions, most previous experimental results [13,14] have suggested that accounting for interactions is unnecessary [15]. These prior measurements of a two-lead dot (with $N = 4$ total channels, one for each spin state of the fully transmitting QPC modes) follow the theory for a coherent dot with $N \gg 1$ [16,17], in which CB does not occur. A few experiments, however, have shown weak periodic oscillations of conductance with gate voltage [18–20]. In one case [19], the oscillations were attributed to CB caused by the special one-dimensional dot geometry [21]. The other experiments did not measure CB features such as the renormalized charging energy U^*. Finally, no capacitance measurements have been made on two-lead dots with fully transmitting QPCs to confirm that the oscillations correspond to a quantization of charge, as opposed to other effects such as wave function scarring [22].

In this Letter, we report transport measurements through a two-lead dot, showing conclusive evidence that phase coherence causes CB to emerge in a system thought to be open. With each QPC tuned to allow a single transmitting mode, we observe a characteristic CB oscillation in the conductance when the electron temperature is reduced to 13 mK, lower than previously attained in similar systems. We characterize the oscillation using finite bias conductance and capacitance measurements and determine U^* and the residual charge, respectively. Magnetic field and temperature measurements show that the oscillation amplitude diminishes on scales consistent with breaking of

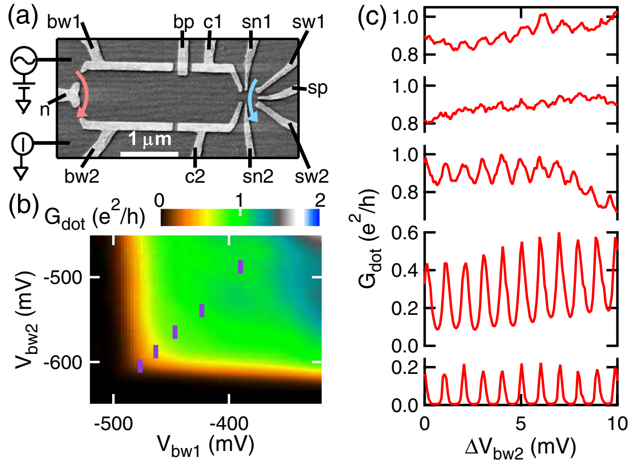

FIG. 1 (color online). (a) Electron micrograph of a device nominally identical to the measured device. (b) $G_{\rm dot}$ vs $V_{\rm bw1}$ and $V_{\rm bw2}$ at $T = 540$ mK and $B = 25$ mT. The vertical lines mark the gate voltages at which the cuts in (c) are taken. (c) $G_{\rm dot}$ as a function of $V_{\rm bw2}$ for different settings of the QPCs at $T = 13$ mK and $B = 25$ mT. The bottom trace is taken at $V_{\rm bw1} = -477$ mV while the top trace is at $V_{\rm bw1} = -390$ mV.

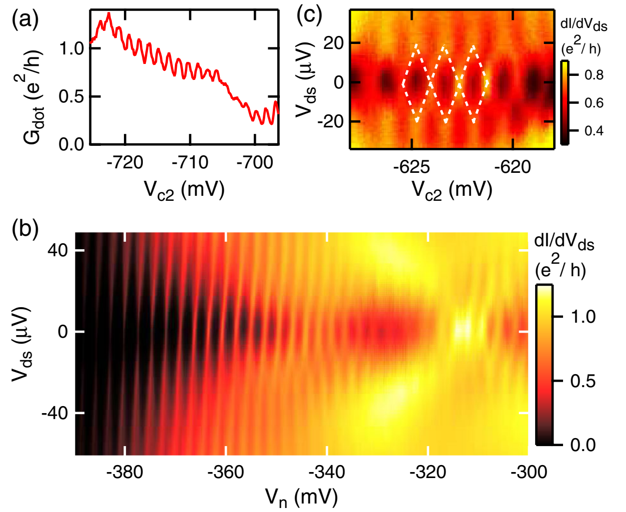

FIG. 2 (color online). (a) $G_{\rm dot}$ measured at $T = 13$ mK (charge sensor not active) and $B = 0$. (b) $dI/dV_{\rm ds}$ as a function of $V_{\rm ds}$ and $V_{\rm n}$ at 13 mK (with the charge sensor active) and $B = 0$. (c) $dI/dV_{\rm ds}$ as a function of $V_{\rm c2}$, when the conductance through each QPC is kept at 2 e^2/h. The data are taken at $T = 13$ mK (charge sensor not active) and $B = 0$. The dashed white lines are guides to the eye.

time-reversal symmetry, demonstrating that phase coherence is responsible for the emergence of MCB in an open two-lead system.

We measure a dot fabricated from an AlGaAs/GaAs heterostructure with a two-dimensional electron gas (2DEG) with density 2×10^{11} cm^{-2} and mobility 2×10^6 cm^2/V s. Figure 1(a) shows an electron micrograph of the metallic surface gates. We apply negative voltages to the gates to form a large dot of area ≈ 2.6 μm^2 (calculated spin-degenerate level spacing $\Delta = 2.7$ μeV) that we study, as well as an adjacent small dot that we use as a charge sensor [23,24]. The gates bw1, n, and bw2 define the QPCs of the dot, while c1, c2, and bp change the shape of the dot [13,25]. We compensate for the small effect gates c1, c2, and bp have on the QPCs. The voltages on gates sn1 and sn2 are set so there is no measurable conductance through the channel between them.

Figure 1(b) shows the zero-bias conductance $G_{\rm dot}$ of the large dot as a function of the QPC gates. These data are taken at $T = 540$ mK to suppress universal conductance fluctuations (UCFs) [13] and at $B > 5$ mT to avoid WL. In this regime $G_{\rm dot}$ is the series conductance of the two QPCs and there is a plateau at $G_{\rm dot} = 1e^2/h$, corresponding to the 2 e^2/h plateau in the conductance of each QPC. Figure 1(c) shows data taken at 13 mK at different values of ($V_{\rm bw1}$, $V_{\rm bw2}$). When the QPCs are in the tunneling regime, CB peaks are observed (bottom trace). Even when both QPCs are set to 2 e^2/h (top two traces), we observe an oscillation with period $\Delta V_{\rm bw2} = 1$ mV, the same as the CB peaks. The corresponding periodicities suggest the oscillation is CB.

Figure 2(a) shows this oscillation with voltage settings that correspond to the middle of the dot's $1e^2/h$ plateau and at $B = 0$. We note the oscillation is larger in amplitude than in the top two traces in Fig. 1(c); this B dependence will be discussed in conjunction with Fig. 4. The periodicity $\Delta V_{\rm c2} = 1.5$ mV is consistent with the CB peak spacing in $V_{\rm c2}$ measured with the QPCs in the tunneling regime, and the larger value of $\Delta V_{\rm c2}$ as compared to $\Delta V_{\rm bw2}$ reflects the smaller capacitance of gate c2 to the dot compared to bw2. The large variations in $G_{\rm dot}$ on the scale of tens of millivolts in gate voltage are caused by the UCFs, and are easily distinguishable from the periodic oscillations.

To find the charging energy we measure differential conductance $dI/dV_{\rm ds}$ as a function of the bias voltage $V_{\rm ds}$ [Fig. 2(b)]. For $V_{\rm n} \lesssim -370$ mV neither QPC is fully transmitting and we see clear Coulomb diamonds with a charging energy of $U \approx 115$ μeV. As $V_{\rm n}$ is made less negative, the conductance of the QPCs increases. This causes U to be renormalized [6,7] and as a consequence the vertical size of the diamonds shrinks. At $V_{\rm n} \approx -315$ mV the QPCs are fully transmitting, and we see diamond features with a renormalized $U^* \approx 16$ μeV (details in Ref. [26]). These diamonds are superimposed on larger UCFs which form a Fabry-Perot pattern in gate voltage and bias [27]. The diamonds associated with the oscillations are shown in more detail in Fig. 2(c), where the gates are set to the middle of the dot's $1e^2/h$ plateau. The diamonds are consistent with CB and the shape can be qualitatively described with a simple model of a dot strongly coupled to its leads (see details in [26]).

We directly observe the residual charge quantization with capacitive measurements. Making the voltage on a dot gate less negative increases the charge on the dot and

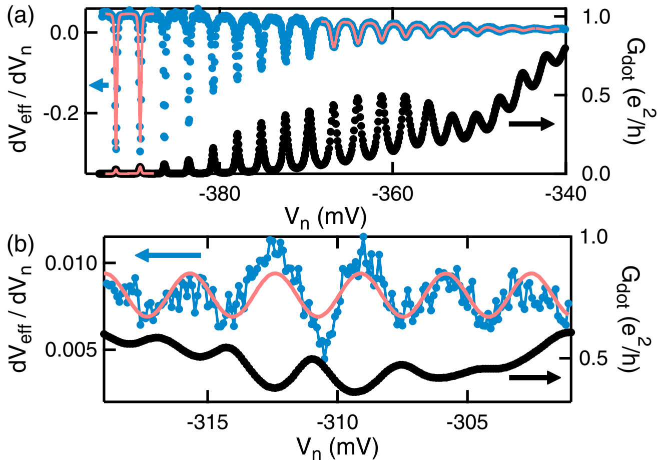

FIG. 3 (color online). (a) Simultaneous measurement of $dV_{\rm eff}/dV_{\rm n}$ (blue dots, left axis) and transport (black dots, right axis). The solid lines show fits discussed in the text. (b) Charge-sensing data (left axis) and transport (right axis) at the values of $V_{\rm n}$ for which the QPCs are open to $2e^2/h$ conductance. The solid red line is a fit described in the text.

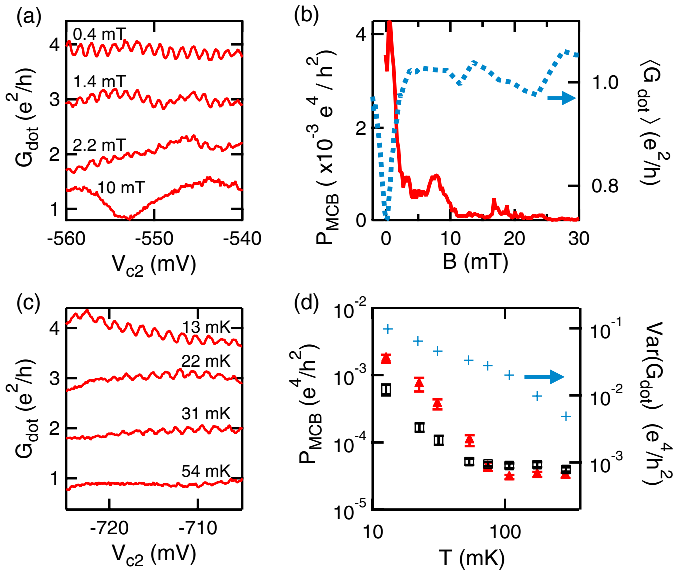

FIG. 4 (color online). (a) $G_{\rm dot}$ vs $V_{\rm c2}$ at several magnetic fields at 13 mK. Traces are spaced by $1e^2/h$. (b) $P_{\rm MCB}$ (solid line, left axis) obtained by Fourier transforming data like those in (a). The dotted line shows the ensemble-averaged $G_{\rm dot}$ vs B. All data are taken at 13 mK. (c) $G_{\rm dot}$ vs $V_{\rm c2}$ at $B = 0$ and several temperatures. Traces are spaced by $1e^2/h$. (d) $P_{\rm MCB}$ averaged for data taken over a wider range of $V_{\rm c2}$ than in (c) at several values of $V_{\rm c1}$. The data are taken at $B = 0$ (filled triangles, left axis) and $B = 30$ mT (open squares, left axis). For comparison we show measurements of $\mathrm{Var}(G_{\rm dot})$ (crosses, right axis) at $B = 0$.

changes the conductance of the charge sensor by $\Delta G_{\rm CS}$. To increase sensitivity, we average repeated measurements over the same range in $V_{\rm n}$ using the simultaneously measured transport data to correct for small shifts caused by background charge fluctuations. We convert $\Delta G_{\rm CS}$ into an effective voltage change $V_{\rm eff}$, which if applied to the gate sp would produce the same $\Delta G_{\rm CS}$. For $V_{\rm n} < -375$ mV the conductances of both QPCs are less than $2e^2/h$ and we have well-defined CB in $G_{\rm dot}$ as shown in Fig. 3(a). The charge sensor shows steplike decreases in $V_{\rm eff}$ when electrons are added to the dot. We plot the derivative $D = dV_{\rm eff}/dV_{\rm n}$ in Fig. 3(a) and for $V_{\rm n} < -375$ mV the CB peaks correspond to large dips in D. As $V_{\rm n}$ is increased, the dips remain aligned to peaks in $G_{\rm dot}$. Figure 3(b) shows measurements with the QPC conductances at $2e^2/h$. We see a periodic variation in D, with the dips corresponding to peaks in $G_{\rm dot}$. This confirms that the conductance oscillation corresponds to a residual quantization of charge on the dot.

In the absence of theory for a phase coherent two-lead dot, we extract the quantized charge by fitting the data to the available theory for a one-lead dot. D is determined by the capacitances of the dot d and the charge sensor CS [8]: $D = R_{\rm n} + R_d(C_{{\rm n},d} - e dN_d/dV_{\rm n})/C^*_{d,{\rm tot}}$. Here $R_{\rm n} = C_{\rm n,CS}/C_{\rm sp,CS}$ and $R_d = C_{d,{\rm CS}}/C_{\rm sp,CS}$, where $C_{x,{\rm CS}}$ and $C_{x,d}$ are the capacitances between a gate x and the dot and CS, respectively. $C_{d,{\rm CS}}$ is the capacitance between the dot and the CS, N_d is the number of electrons on the dot, and $C^*_{d,{\rm tot}}$ is the renormalized total capacitance of the dot with $U^* = e^2/C^*_{d,{\rm tot}}$. For $V_{\rm n} < -385$ mV the line shapes are well described by theoretical predictions for $dN_d/dV_{\rm n}$ [28]. The solid red lines in Fig. 3(a) show the results of simultaneously fitting the $G_{\rm dot}$ and D data using values of $R_{\rm n}$, $C_{{\rm n},d}$, and $C^*_{d,{\rm tot}}$ estimated from other measurements (see Ref. [26] for details). This fit gives $R_d = 0.93$ (we estimate an error of ± 0.21), and we use this value to analyze the data in other gate voltage regions. For $-370 < V_{\rm n} < -340$ mV the solid line in Fig. 3(a) shows a fit to the prediction for a one-lead dot without phase coherence, with the adjustable QPC near $2e^2/h$ [3,8]. In the limit of a perfectly transmitting contact, this theory predicts there should not be a periodic variation in the charge-sensing signal, so we fit the data in Fig. 3(b) to a model for MCB in a one-lead dot [10]: $e\ dN_d/dV_{\rm n} = C_{{\rm n},d}[1 + (A/e) \times \cos(2\pi C_{{\rm n},d} V_{\rm n}/e)]$ where A gives the residual charge quantization. We find that $A/e = 0.27^{+0.21}_{-0.08}$, indicating that a significant amount of charge is still quantized.

If the conductance oscillation is MCB, then it should be sensitive to an applied magnetic field which disrupts the constructive interference between time-reversed paths that causes WL. Figure 4(a) shows $G_{\rm dot}$ at several fields. We follow Cronenwett *et al.* [11], Fourier transforming the data and integrating the power spectral density around the frequency of the oscillation to find the power $P_{\rm MCB}$. The results are shown as the solid line in Fig. 4(b). The dotted line in Fig. 4(b) shows $G_{\rm dot}$ averaged over an ensemble of dot shapes obtained by changing the voltages on gates c1, bp, and c2 [25,29]. The dip around $B = 0$ is caused by WL, and its width is the field scale necessary to break time-reversal symmetry. The fact that the amplitude of the oscillation decreases over the same field scale is strong evidence that the oscillation is MCB. We note that in a two-lead dot, any trajectory containing a loop contributes to WL, including trajectories that go from one QPC to the other [30]. These trajectories should contribute to MCB. For $B > 5$ mT $P_{\rm MCB}$ is small but nonzero: weak oscillations are still present at some gate voltages and magnetic fields, e.g., the top two traces in Fig. 1(c). These oscillations occur because, even at finite field, electron paths can still constructively interfere; however, without the reliably constructive interference of time-reversed paths, the oscillations are weaker and less frequent.

MCB should also depend on temperature T. The dephasing time τ_ϕ, which is the time scale on which electrons in the dot lose phase coherence, decreases with increasing T [29]. This decrease in τ_ϕ weakens the MCB in two ways: first by reducing the electron interference and second by broadening the states in the dot [31]. Increased T also broadens the Fermi distribution in the leads. If we consider just the reduction of interference with increasing T, MCB should be weaker once τ_ϕ is on the scale of the dwell time $\tau_d = \pi\hbar/\Delta \approx 0.8$ ns, which is the characteristic time the electron spends in the dot. Figure 4(c) shows measurements of $G_{\rm dot}$ at different T, and MCB is suppressed for $T \gtrsim 54$ mK. From measurements of τ_ϕ vs T extracted from WL [25] we find $\tau_\phi = \tau_d$ at $T \approx 80$ mK, and this temperature scale is consistent with our observations. Figure 4(d) shows the results of extracting $P_{\rm MCB}$ from data at $B = 0$ (filled circles) and $B = 30$ mT (open squares). The oscillation decreases rapidly with increasing T (the saturation at $P_{\rm MCB} = 2 \times 10^{-5} e^4/h^2$ is from the noise floor). We compare our data to measurements of $\mathrm{Var}(G_{\rm dot})$ [25], a quantity that characterizes the size of the UCFs and hence also depends on phase coherence. Although we do not expect $P_{\rm MCB}$ and $\mathrm{Var}(G_{\rm dot})$ to have the same T dependence, we see that $P_{\rm MCB}$ is at least as sensitive to T as is $\mathrm{Var}(G_{\rm dot})$, supporting the conclusion that the oscillations depend on phase coherence.

For completeness, consider the effect of a small reflection coefficient r^2 of the QPCs [defined by $G_{\rm QPC} = (2e^2/h) \times (1 - r^2)$]. Such an r^2 can be caused if the QPCs are not perfectly transmitting, or by a closed orbit where an electron enters the dot and reflects off a wall back into the same QPC. Without phase coherence this r^2 cannot account for the observed oscillations. (1) The field scale over which $P_{\rm MCB}$ decreases in Fig. 4(b) is that necessary to introduce several flux quanta in the dot. The area of the QPC and a single-bounce closed orbit are much smaller than the dot. Were they the cause of the oscillation then the magnetic field scale would be much larger than we observe. We induce reflections in both QPCs by making $V_{\rm n}$ more negative and confirm this expectation [26]. (2) In the absence of phase coherence, the lowest-order effect of finite r^2 is to decrease $G_{\rm dot}$, whereas any oscillations are order r^4 or higher [12] and hence highly suppressed. Thus the oscillations we observe require phase coherence in the dot.

In conclusion, in a two-lead dot we observe an oscillation in $G_{\rm dot}$ that we identify as MCB, a type of CB that depends on electron interference. This type of dot was thought to be well described without explicit Coulomb interactions. Our results demonstrate that the understanding of this system, and more generally two-terminal mesoscopic systems with several transmitting modes and long coherence times at low temperatures, is incomplete and that theoretical work is necessary to explain the interplay of coherence and Coulomb interactions.

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*samasha@stanford.edu
†Present address: Hitachi GST, San Jose, CA 95135, USA.
‡Present address: Solum, Mountain View, CA 94043, USA.

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