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Coulomb Charging Effects in an Open Quantum Dot Device at Zero Magnetic Field

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We report low-temperature conductance measurements of an open quantum dot device formed in a clean one-dimensional (1D) channel. At zero magnetic field, continuous and periodic oscillations superimposed upon 1D ballistic conductance steps are observed. We ascribe the observed conductance oscillations when the conductance through the dot G exceeds $2e^2/h$, to experimental evidence for Coulomb charging effects in an open dot. This is supported by the evolution of the oscillating features for $G > 2e^2/h$ as a function of both temperature and barrier transparency.

KEYWORDS: quantum dots, charging, one-dimensional, Coulomb blockade, single-electron tunnelling

By using the electrostatic squeezing technique,[1)] it is possible to define a quantum dot which confines electrons in an isolated region within a two-dimensional electron gas (2DEG). Consider a lateral quantum dot[2)] weakly coupled to the source and drain contacts where the tunnelling conductance through the dot G is low, $G \ll 2e^2/h$. If the thermal smearing $k_B T$ and the chemical potentials in the leads are much smaller than the Coulomb charging energy e^2/C which is required for adding an extra electron to the quantum dot, transport through the dot is inhibited. This is the Coulomb blockade (CB) of single electron tunnelling.[3,4)] It has been demonstrated[5)] that transport through small quantum dots is determined by Coulomb charging effects as well as zero-dimensional (0D) quantum confinement effects.

A versatile quantum dot may be defined by two pairs of split-gates which introduce two quantum point contacts acting as the entrance and exit barriers to the dot, and two side-gates which are used to deplete electrons within the dot.[6)] It has been reported[6–8)] that at zero magnetic field Coulomb charging effects only occur when the conductance of the two quantum point contacts, and of the quantum dot as a whole, falls below $2e^2/h$. No oscillations were found when either or both of the quantum point contacts were set to above $G > 2e^2/h$ so that the dot was open to the 2DEG reservoirs.[6–8)] Thus at present, it is widely accepted that at zero magnetic field, the conductance $2e^2/h$ is the upper limit for which Coulomb charging effects can occur.[9)] Nevertheless, there is experimental evidence[10–12)] which appears to contradict this concept. To this end, we have designed a new type of open quantum dot device with tunable barriers.[13,14)] In this paper, we report low-temperature conductance measurements of an open quantum dot device in which impurity scattering is negligible. Due to the unique design of our devices fabricated on an ultra high-quality HEMT, we present clear evidence of Coulomb charging effects in an open quantum dot at zero magnetic field. This is supported by the temperature and barrier transparency dependence of the observed periodic conductance oscillations for $G > 2e^2/h$.

The two-layered Schottky gate pattern shown in the inset to Fig. 1 was defined by electron beam lithography on the surface of a high-mobility $GaAs/Al_{0.33}Ga_{0.67}As$ heterostructure T258, 157 nm above the 2DEG. There is a 30 nm-thick layer of Polymethylmethacrylate (PMMA) which has been highly dosed by an electron beam, to act as a dielectric between the split-gate (SG) and three gate fingers (F1, F2, and F3) so that all gates can be independently controlled. Detailed description of our device fabrication techniques has been published elsewhere.[15)] The carrier concentration of the 2DEG was $1.6 \times 10^{15}\,\mathrm{m}^{-2}$ with a mobility of $250\,\mathrm{m}^2$/Vs after brief illumination by a red light emitting diode (LED). The corresponding transport mean free path is $16.5\,\mu$m, much longer than the effective 1D channel length. Experiments were performed in a top-loading dilution refrigerator at $T = 50$ mK and the two-terminal conductance $G = dI/dV$ was measured with standard phase-sensitive techniques. In all cases, a zero-split-gate-voltage series resistance ($\approx 900\,\Omega$) is subtracted.

Figure 1 shows the conductance measurements $G(V_{SG})$ as a function of split-gate voltage V_{SG} when all finger gate voltages V_{F1}, V_{F2}, and V_{F3} are zero. We observe conductance

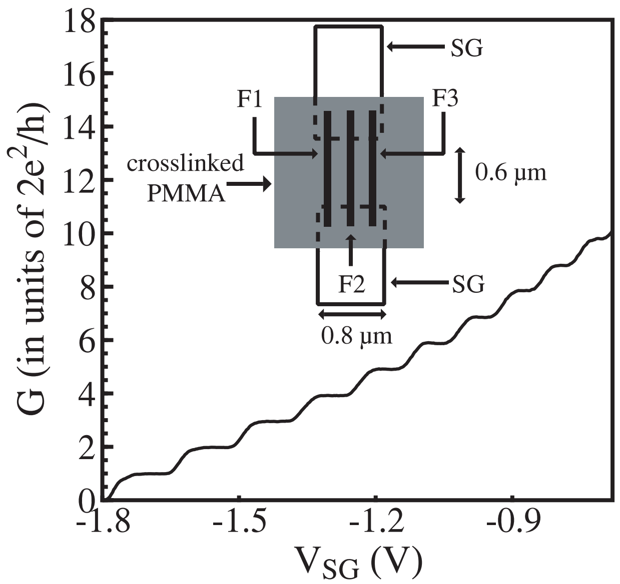

Fig. 1. $G(V_{SG})$ for all finger gates at 0 V. The inset shows a schematic device diagram. Three are three finger gates labelled as F1, F2, and F3 lying above the split-gate (labelled as SG), with an insulating layer of crosslinked PMMA in between.

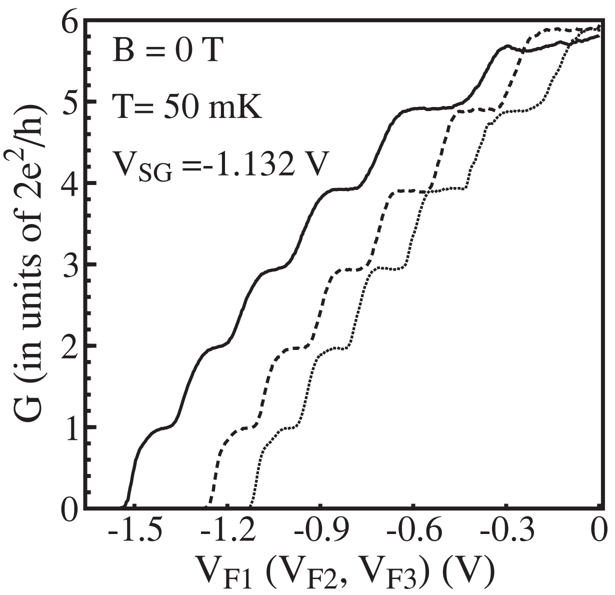

Fig. 2. $G(V_{F1})$ (in solid line), $G(V_{F3})$ (in dashed line) and $G(V_{F2})$ (in dotted line) for $V_{SG} = -1.132$ V when each one of the finger gates is swept while the others are grounded to the 2DEG.

plateaux at multiples of $2e^2/h$, with no resonant feature superimposed on top, as expected for a clean 1D channel. When the channel is defined at $V_{SG} = -1.132$ V, five quantised conductance steps are observed when each one of the finger gates is swept while the others are grounded to the 2DEG, as shown in Fig. 2. These experimental results demonstrate that we have a clean 1D channel in which impurity scattering is negligible. Periodic resonant features, as shown later, are only observed when large negative voltages are applied to both F1 and F3.

We can define a lateral quantum dot by applying voltages on SG, F1 and F3 while keeping F2 grounded to the 2DEG. Trace 1 in Fig. 3 shows the gate characteristics $G(V_{SG})$ for $V_{F1} = -1.941$ V and $V_{F3} = -1.776$ V at $T = 50$ mK. Periodic and continuous conductance oscillations superimposed on ballistic conductance steps are observed. We ascribe the observed conductance oscillations for $G < 2e^2/h$ to Coulomb charging effects.[6–8] The observed periodic conductance oscillations for $G > 2e^2/h$ are unexpected and are the main subject of this paper. Unlike lateral quantum dots whose tunnel barriers are defined by two pairs of split-gates, in our system, the tunnel barriers arise from depletion from overlying finger gates. This causes a large barrier thickness so that we do not observe well-isolated single electron tunnelling beyond pinch-off in our case. In contrast to the well-quantised conductance plateaux shown in Fig. 1, applying voltages to F1 and F3 results in conductance steps that are not as flat or well quantised. With the finger gates grounded to the 2DEG, the channel pinches-off at $V_{SG} = -1.8$ V compared with $V_{SG} = -0.7$ V when $V_{F1} = -1.941$ V and $V_{F3} = -1.776$ V. Thus as voltages are applied to F1 and F3, the lateral confinement weakens and the conductance steps become less pronounced. The conductance steps also deviate from their quantised values. The most likely reason for this effect is due to the introduction of two tunnel barriers which enhances backscattering in the channel, thereby reducing the transmission probability of 1D channels[16] to be less than 1. However, as

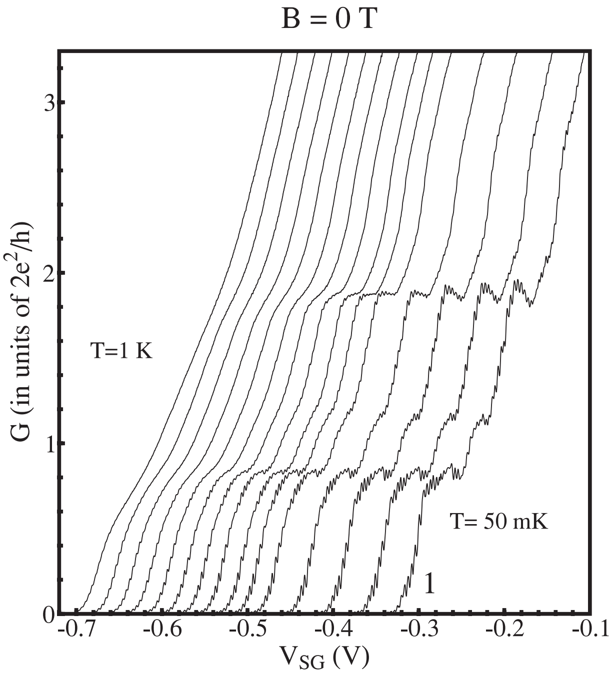

Fig. 3. $G(V_{SG})$ for $V_{F1} = -1.941$ V, $V_{F2} = 0$ V, and $V_{F3} = -1.776$ V at various temperatures T. From left to right: $T = 1$, 0.5, 0.45, 0.41, 0.35, 0.3, 0.26, 0.2, 0.18, 0.17, 0.15, 0.11, 0.09, 0.065 and 0.05 K. Curves are successively displaced by a horizontal offset of 0.02 V for clarity.

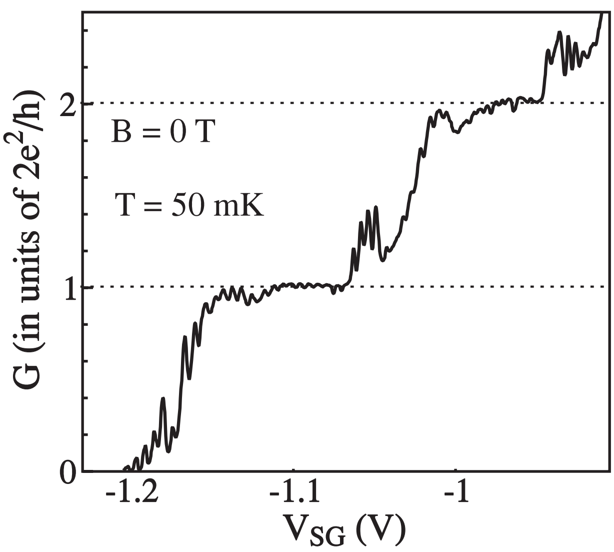

Fig. 4. $G(V_{SG})$ for $V_{F1} = -1.1$ V, $V_{F2} = 0$ V, and $V_{F3} = -1.0$ V.

shown in Fig. 4, continuous and periodic conductance oscillations are also observed when well-quantised 1D ballistic conductance steps co-exist. Thus we suggest that the slight deviation from perfect transmission only varies the background conductance in our system and has little effects on the observed continuous and periodic conductance oscillations in V_{SG} shown in both Figs. 3 and 4.

Previously in a lateral quantum dot[6–8] it has been observed that Coulomb oscillations increase in height and decrease in width as the conductance decreases. This increase in height arises from accumulation of electron wavefunction in the dot, giving rise to resonant coherent effects, as the dot becomes isolated from the source and drain contacts. From Fig. 3 we can see that no such increase in height is observed in our system as the conductance is decreased. We believe that the thicker tunnel barriers in our system make it more difficult for the electrons to tunnel out such that the electron lifetime within the dot becomes so long it exceeds the inelastic scattering time. In such a situation resonant coherent effects decrease with the result that the Coulomb blockade peaks do not increase in height close to pinch-off. We also find that the peak widths do not decrease as G decreases. Generally for $G > 2e^2/h$, it is expected that the presence of a fully transmitted 1D channel might cause mode mixing between 1D channels in the quantum dot which smears out Coulomb charging effects. However since our samples are fabricated on an ultra high-quality HEMT it is likely that there is little 1D mode mixing such that the level broadening for Coulomb oscillations is similar for both cases when $G < 2e^2/h$ and $2e^2/h < G < 4e^2/h$. Thus as G decreases, the oscillations observed in our system do not appear to decrease in width.

Having defined a quantum dot, we now calculate the dot size and the number of electrons it contains following the method described in the work by Field and co-workers.[17) For $V_{SG} = -0.5$ V, $V_{F1} = -1.941$ V, and $V_{F3} = -1.776$ V, we observe Aharonov-Bohm type oscillations as a function of applied perpendicular magnetic field[18) with a period ΔB of 14.7 mT, giving a dot area A of 2.81×10^{-13} m^2. Using the split-gate to change the dot area at a constant magnetic field of 0.8 T, the Aharonov-Bohm period[19) of oscillations ΔV_{SG}^{AB} is measured to be 8.772 mV. Thus $\Delta V_{SG}^{AB}/\Delta A = 1.70 \times 10^{12}$ Vm^{-2}. Each CB oscillation corresponds to removing an electron from the dot so that the reciprocal of the CB period $\Delta N/\Delta V_{SG}^{CB}$ is 263.3 V^{-1}. From the product of these two terms we obtain the local carrier density in the dot to be 4.47×10^{14} m^{-2}. Combining this value with the dot area A gives the number of electrons in the dot $N \approx 126$. From the local Fermi energy E_F^{loc} and the number of electrons within the dot, we estimate the 0D confinement energy E_F^{loc}/N to be at most 12.4 μeV, comparable to the thermal smearing at 50 mK. The reason for this is due to the large dimensions of our sample. Therefore electron transport through our quantum dot can be described in terms of a classical Coulomb charging picture where the 0D quantum confinement energy is much smaller than the Coulomb charging energy, similar to the case of a metal.

As shown in Fig. 3, for $G < 2e^2/h$, the conductance oscillations persist up to $T = 1$ K. The oscillations for $G > 2e^2/h$ have a strong temperature dependence and become unobservable above $T = 410$ mK. Note that the thermal broadening k_BT at this temperature is still much larger than the estimated 0D quantum confinement energy, excluding an interpretation that conductance oscillations for $G > 2e^2/h$ are due to tunnelling through 0D states in the quantum dot. To determine the total capacitance between the dot and the gates of the sample, we measure the conductance oscillations by varying the voltage on the different gates, while keeping the voltages on the remaining gates fixed. From this we obtain $\Delta V_{F1} = 23.81$ mV, $\Delta V_{F2} = 8.68$ mV, $\Delta V_{F3} = 25.89$ mV, and $\Delta V_{SG} = 3.59$ mV. According to this the total gate-dot capacitance C_g is estimated to be 7.58×10^{-17} F. Since our quantum dot is open to the source and drain contacts, we neglect the capacitance between the dot and the 2DEG reservoirs. In this case, we calculate the Coulomb charging energy e^2/C_g to be 0.211 meV, comparable to the thermal broadening at $T \approx 2$ K, which is consistent with the observation that close to pinch-off Coulomb oscillations persist up to 1 K.

To study the unexpected presence of periodic conductance oscillations for $G > 2e^2/h$ in more detail, we have measured their dependence on barrier transparency. Figure 5(a) shows $G(V_{SG})$ as V_{F1} and V_{F3} are simultaneously decreased, thus increasing barrier height (decreasing barrier transparency) at zero magnetic field. Figure 5(b) is a continuation of Fig. 5(a) at even more negative finger gate voltages. We number peaks in $G(V_{SG})$ counted from pinch-off. Note that at pinch-off, we estimate that there are still ≈ 70 electrons within the dot. Consider the sixth single electron tunnelling peak counted from pinch-off. It is evident that as the barrier heights are raised by making the gate finger voltages more negative, the peak height decreases, and the peak occurs at a less negative V_{SG}, i.e., where the channel is wider. Thus effectively we are keeping the number of electrons within the dot constant while changing the dot shape. We note that the first ten tunnelling peaks counted from pinch-off in Fig. 5(a) gradually disappear as the finger gate voltages are made more negative. This is due to the increasing barrier thickness such that tunnelling conductance becomes immeasurably small.[17) Over the whole measurement range, we can follow up to 48 conductance tunnelling peaks at various $V_{F1}(V_{F3})$ and are thus able to study their barrier transparency dependence. Note that the observed conductance oscillations for $G > 2e^2/h$ have the same period as that of the oscillating features for $G < 2e^2/h$. Most importantly, as shown in Figs. 5(a) and 5(b) peaks 31–48, where $G > 2e^2/h$ (shown in the uppermost curve), all gradually evolve into conductance oscillations for $G < 2e^2/h$ due to Coulomb charging[6–8) as the barrier heights and thickness increase. This result strongly suggests that the conductance oscillations (for peak 31–48 in the uppermost curve shown in Fig. 5(a)) and the oscillations shown in the lowermost curves (Fig. 5(b)) are of the same physical origin-Coulomb charging, compelling experimental evidence for charging effects in the presence of fully transmitted 1D subbands at zero magnetic field.

Finally we present clear experimental evidence that coherent resonant transport and Coulomb charging effects co-exist in our system. Figure 6 shows $G(V_{F2})$ for $V_{F1} = -1.941$ V, $V_{SG} = -0.3$ V and $V_{F3} = -1.776$ V when the dot is defined. Periodic and continuous conductance oscillations superimposed on weak resonant features are clearly observed. Decreasing V_{F2} has two effects. First, it depletes the electrons within the open quantum dot, causing successive conductance oscillations due to Coulomb charging effects over the whole measurement range. Second, it also reduces the number of transmitted 1D channel through the dot. The latter effect gives rise to the slowly-varying background—Fabry-Pérot type resonant effects[20) between the entrance and exit to the quantum dot. The maxima (minima) in conductance correspond to constructive (destructive) electron-wave interference effects. This interpretation is further supported by recent theoretical work of Tkachenko and co-workers.[21) Thus in order to model our experimental results, the co-existence of coherent transport and Coulomb charging effects must be taken into account.

In conclusion, we have presented low-temperature experimental results on an open quantum dot device electrostatically defined by a split-gate, and overlaying finger gates

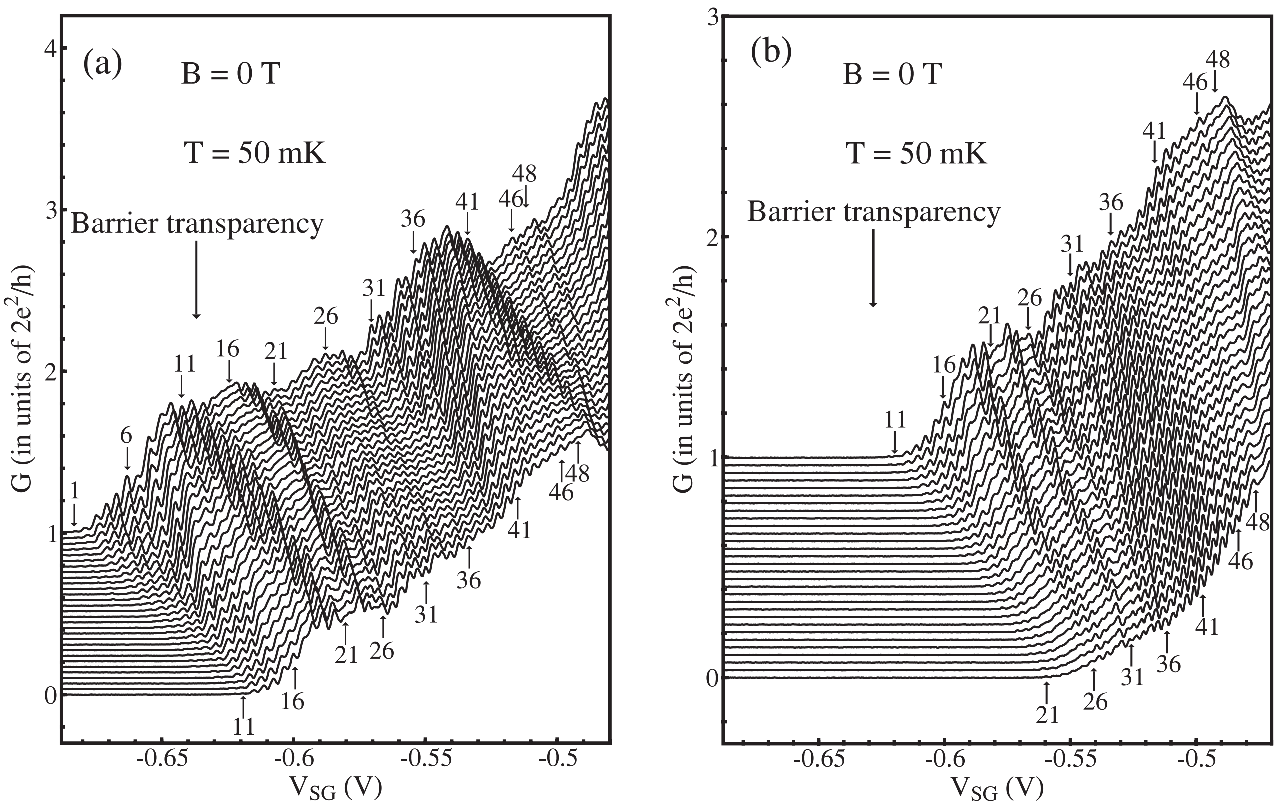

Fig. 5. (a) $G(V_{SG})$ at various voltages applied on F1 and F3 at zero magnetic field. From top to bottom: $V_{F1} = -1.907$ V to -1.965 V in 2 mV steps ($V_{F3} = -1.733$ V to -1.805 V in 2.5 mV steps) (b) Continuation of figure 5(a). From top to bottom: $V_{F1} = -1.965$ V to -2.023 V in 2 mV steps ($V_{F3} = -1.805$ V to -1.8775 V in 2.5 mV steps) Curves are successively offset by (0.0344) $(2e^2/h)$ for clarity. Conductance tunnelling peaks are numbered to serve a guide to the eye for the evolution of oscillating structures in $G(V_{SG})$.

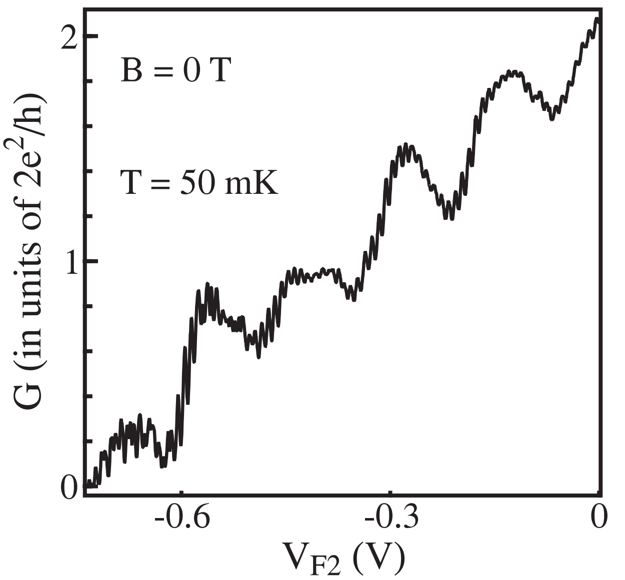

Fig. 6. $G(V_{F2})$ for $V_{F1} = -1.941$ V, $V_{SG} = -0.3$ V, and $V_{F3} = -1.776$ V.

which introduce tunnel barriers. Periodic and continuous oscillations superimposed upon ballistic conductance steps are observed even when the conductance through the quantum dot is greater than $2e^2/h$. At zero magnetic field, a direct transition of conductance oscillations for $G > 2e^2/h$ to those for $G < 2e^2/h$ due to Coulomb charging effects is observed with decreasing barrier transparencies. The temperature dependence of the observed oscillating features for $G > 2e^2/h$ excludes an interpretation that they are due to tunnelling through single-particle confinement energy states within the dot. Both results strongly suggest that at zero magnetic field charging effects can occur in the presence of of a transmitted one-dimensional channel, in contrast to the current experimental and theoretical understanding of Coulomb charging.

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