# Single-Electron Charging and Periodic Conductance Resonances in GaAs Nanostructures

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Narrow channels interrupted by two controlled potential barriers and having a tunable electron density were made in GaAs, and their conductance was measured at low temperatures. Reproducible and accurately periodic oscillations of the conductance with changing density are found to correspond to the sequential addition of single electrons to the segment of the channel between the barriers. Detailed examination of the line shape of the conductance versus density provides new insight into the transport mechanism.

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Recent experiments on narrow electronic channels in semiconductors[1-3] with variable density revealed a surprising new phenomenon, namely, that the conductance along the channel oscillated *periodically* with the electron density at low temperatures. The generality of this phenomenon was established by its observation in electron[1] and hole[3] inversion layers in Si, as well as in GaAs heterostructures.[2] Several models have emerged to explain this effect.[3] Common to all explanations was that the occurrence of two charged impurities along the narrow channel created a partially isolated segment. The oscillations in the conductance $G$ were suggested to arise from sequential quantized charging of that segment as the density is increased—presumably, one electron per oscillation. Although this two-barrier picture was the only one that could account for the periodic oscillations, the evidence for the existence of the two barriers, induced by random impurities, remained circumstantial.

Here we report a new set of experiments in which the source of such conductance oscillations is controlled. By making narrow electronic channels interrupted by two *intentional* barriers, we show that a reproducible periodic dependence of $G$ on density indeed arises from the presence of two potential barriers. This new situation, in which the locations of the two barriers are known, establishes the relation between the period of oscillation and the length of the segment between the barriers, and allows us to conclude that each cycle does correspond to the addition of *one electron* to that segment.

While previous work[4,5] on small multiterminal structures revealed variations of conductance that could be ascribed[6,7] to single-electron charge increments in an isolated section, the modulations in those experiments were a small part of the total conductance. In the present work, the conductance is a periodic sequence of extremely sharp resonances: $G$ varies by a factor well over 100 when the chemical potential is changed by an amount that corresponds to adding a small fraction of an electron to the isolated segment in the structure.

A study of the line shape of the resonances reveals that they are accurately described by the Fermi-Dirac distribution function. The temperature dependence of the resonance width, together with the determination that there is precisely one electron added per resonance, shows that the simple models[3,8] that have been previously proposed to explain the oscillatory conductance are incomplete.

In order to create a narrow electron channel with a tunable density and controlled potential barriers along it, new devices were made in the following way: We started with the same inverted semiconductor-insulator-semiconductor (ISIS) heterostructure[9] of GaAs and AlAs used in Ref. 2 and illustrated schematically in Fig. 1. A two-dimensional electron gas (2DEG) forms at the interface between the top layer of undoped GaAs and the AlGaAs layer, and its density is controlled by the gate voltage $V_g$ applied to the conductive substrate. In order to create narrow channels in this ISIS structure, we deposited metal electrodes on the surface. A negative voltage

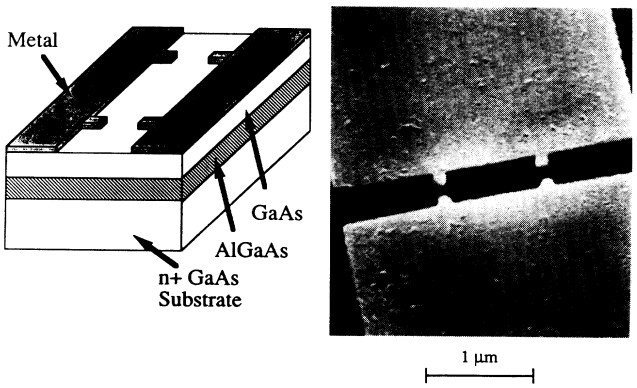


FIG. 1. Schematic drawing of device structure along with a scanning electron micrograph of one of the samples. An electron gas forms at the *top* GaAs-AlGaAs interface, with a density controlled by the substrate voltage $V_g$. The patterned electrodes on top define a narrow channel with two potential barriers.

$V_b$ applied to the metal depletes the 2DEG underneath. Schottky-barrier electrodes have been used before by several groups to confine a 2DEG in conventional GaAs modulation doped heterostructures.[10] By using the ISIS layer configuration we obtain additional control of the electron density, which is crucial for this experiment. The electrode pattern is formed by electron-beam lithography, followed by the deposition of a thin film of TiAu and lift-off. Figure 1 shows the device geometry, as well as a scanning electron micrograph of one of the samples. The gap between the two electrodes defines the channel, but the electronic channel width is considerably less than that of the gap in the metal. The key to this experiment is the two constrictions in that gap, each about 100 nm long, defining a segment of length $L_0$ between them. When a negative $V_b$ is applied, these constrictions induce saddle-shaped potential barriers for electrons moving along the channel.

Samples were cooled in a dilution refrigerator, and the conductance $G$ of the channels was measured by applying a small bias between two contacts to the 2DEG at opposite ends of the channel. We measured $G$ as a function of density by ramping $V_g$, while $V_b$ was held fixed, typically at about $-0.5$ V.

In the first set of samples, channels with $L_0 = 1$ $\mu$m were fabricated and measured alongside narrow channels without constrictions. A later set was made with variations of $L_0$. Figures 2(a) and 2(b) show data for two samples from the first batch, which had identical geometry. The periodic oscillations are clearly seen, with the same period in both samples. The channels without constrictions had monotonic dependence or, occasionally, random fluctuation patterns, but no similar periodic behavior. Figures 2(c) and 2(d) show results for samples from the second set with progressively shorter lengths and correspondingly longer periods, consistent with the geometry.

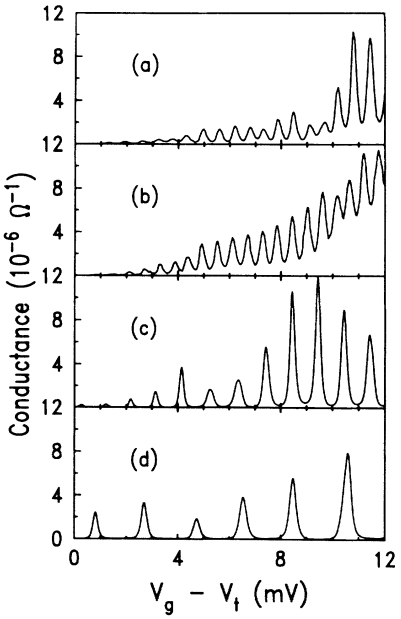


FIG. 2. Periodic oscillations of conductance vs gate voltage $V_g$, measured from a sample-dependent threshold $V_t$. (a) and (b) are for two samples with the same electrode geometry and hence show the same period. (c) and (d) show data for progressively shorter distances between the two constrictions, with a corresponding increase in period. Each oscillation corresponds to the addition of a single electron between the barriers. Measurements were made at $T \approx 50$ mK.

The oscillations in Fig. 2 recurred with the exact same period even after samples were warmed to room temperature and cooled again, as shown in Fig. 3. In previous experiments, such thermal cycling invariably led to random changes or total disappearance of the periodicity, understood as the result of the redistribution of interface charges.[3] Here no such randomness is seen. This fact, together with the correspondence between the period and the sample geometry, distinguishes these results from oscillations observed in previous experiments. Thus, for the first time, we can control the period of the oscillations by the geometry of the devices.

A question that naturally arises is why impurities do not cause additional oscillations with randomly varying periods, as found previously in narrow channels without constrictions. The ISIS material used for these channels is rather clean, making the incidence of charged impurities in the channel less common than in Si inversion layers. In fact, most of the straight narrow channels in GaAs did *not* show oscillations, if no artificial barriers are fabricated. However, several samples—especially in the second batch, which may have had more impurities—*did* show oscillations with periods unrelated to $L_0$, but the latter did *not* recur after thermal cycling, allowing us to distinguish them from the periods that did correspond to $L_0$.

Having established the correlation between $L_0$ and the period of oscillation, we still have to show that each os-

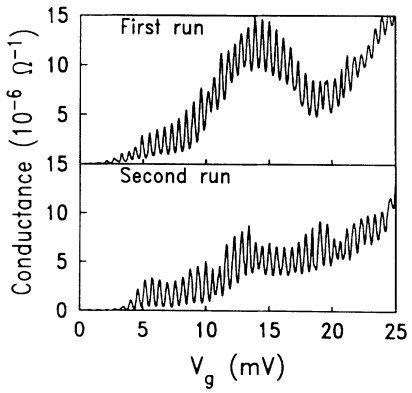


FIG. 3. Conductance vs gate voltage for one sample taken in different runs, between which the sample was warmed to 300 K. The recurrence of the same period is evidence that, unlike previously reported periodic oscillations (Refs. 1–3), these are not induced by random impurities, but by the intentional barriers.

cillation corresponds to precisely *one* electron added to the system. We extract a period $\Delta V_g$ from the data by Fourier transform, and compare its value to an estimate of the increment in $V_g$ required to add one electronic charge to the segment of the channel between the two constrictions. Three-dimensional computer simulations of these structures[11] give us estimates of the relation between $V_g$ and the total charge in the channel. Such estimates are known from past experience to be very reliable for this purpose. For all samples shown the estimated charge increase per $\Delta V_g$ is remarkably close to *one electron*—within 10% for most samples. The possibility of *more* than one electron per $\Delta V_g$ is outside the error margin. We see this as very strong evidence that each oscillation period corresponds to an increment of one electron to the section between the barriers.

As seen in Fig. 2, the conductance peaks become well separated for shorter $L_0$. This allows us to examine the line shape of the conductance oscillations, especially the well isolated peaks at low $V_g$. Figure 4 shows an expanded plot of a single peak, measured at two temperatures. We also show a fit, at both temperatures, by the functional form

$$G(\mu) \propto \frac{\partial F}{\partial E} \propto \cosh^{-2}\left(\frac{E-\mu}{2kT}\right), \quad (1)$$

where $F(E-\mu,T)$ is the Fermi-Dirac (FD) distribution function, $E$ the single-particle energy in an electron gas, and $\mu$ the electrochemical potential. We assume that $V_g$ scales with $\mu$, at least for small changes in $V_g$. The fit is so accurate that it can hardly be distinguished from the data. For comparison, a fit by the Lorentzian line shape is shown in the inset of Fig. 4.

A line shape proportional to $\partial F/\partial E$ is theoretically expected when the conductance between two fermion baths is limited by tunneling through a narrow transmission resonance if the natural width of the resonance is $\ll kT$. For noninteracting electrons (1) can be obtained from the finite-$T$ Landauer formula.[12] The essential point is that the conductance is the sum of the transmission probabilities of electrons over all energies, weighted by the required fermion occupation numbers on both sides of the channel at each energy.

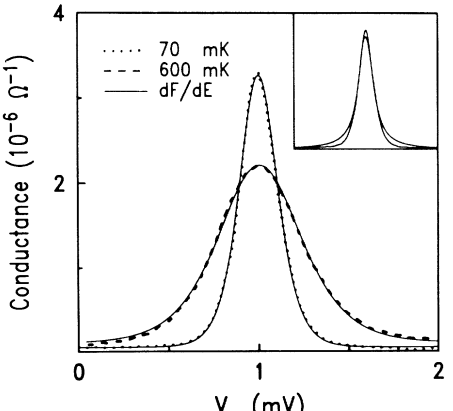


FIG. 4. Expanded view of a single peak at two temperatures [from the sample in Fig. 2(d)]. The dotted line shows data taken at 70 mK; the dashed line at 600 mK. The solid lines show fits to the derivative of the Fermi-Dirac distribution, centered at the peak (after subtraction of a background of $\sim 1\%$). The *heights* of different peaks showed different $T$ dependence. Inset: Best fit by a Lorentzian resonance line shape. Clearly the Lorentzian tails are larger than the data.

Important work, both experimental and theoretical,[13-15] has been done in the past on resonant tunneling (RT) of *noninteracting* electrons in semiconductor microstructures. Fowler *et al.*[13] reported sharp conductance peaks whose behavior was consistent with the picture of Azbel and DiVincenzo[14] of RT through localized states with resonant widths $\ll kT$. One remarkable feature of Fig. 4 is the high quality of the data, in which the measured conductance so clearly reflects the FD distribution. In more recent experiments, Kopley, McEuen, and Wheeler[15] observed Lorentzian line shapes in transport through short inversion layers. Smith *et al.*[5] found small modulations of the conductance which they ascribed to tunneling through quantized states in a GaAs 2DEG.

However, the simple RT picture of noninteracting electrons is inconsistent with the conclusion that each resonance corresponds to the addition of a single electron, since spin degeneracy allows two electrons to occupy each resonant state. This point has been argued before[3,7] on the basis of magnetic-field studies in simpler structures. Nevertheless, the line shape of (1) is not a unique feature of RT through localized quantum states. The arguments leading to (1) are quite general and can apply to transmission via excitations of an interacting system.[16-18]

The observation of the line shape of (1) provides a new way to look at the temperature dependence of $G$. In effect, $G(T)$ can be accounted for in the valleys by the FD tails of the two neighboring resonance peaks. Figure 5 shows how a single parameter—an effective-temperature width $W$, common to all peaks—can provide a fit for $G$ over several periods at $T=800$ mK. The conductance at the minima results from the exponential tails of $\partial F/\partial E$, and hence appears activated, $\ln G \propto T^{-1}$, over some range, as was found previously.[1-3]

The width $W$ thus extracted provides an effective electronic temperature. We plot $W$ versus the ambient temperature $T$ in the inset of Fig. 5. While at higher temperatures $W \propto T$, we find that as the temperature is lowered there is an increasing deviation from this relation. This deviation, which approaches 200 mK at the lowest temperatures, is probably the result of electron heating by residual electrical noise. We can use $W(T)$ to evaluate the true *electronic* temperature in the system.

The slope at high $T$, in the inset of Fig. 5, gives us a conversion ratio between $e\,dV_g$ and $d\mu$. For the sample shown $e\,dV_g/d\mu = 3.5 \pm 0.2$. This conversion ratio im-

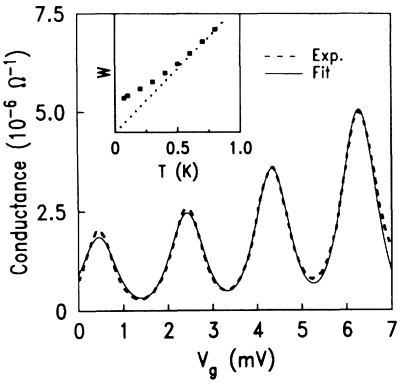


FIG. 5. The effect of thermal broadening is seen in data taken at $T=800$ mK (dashed line). The data fits remarkably well, at valleys as well as at peaks, to the sum of Fermi-Dirac distributions centered at each peak, with the *same width W*. Peak heights and positions are taken from the data, so this is essentially a one-parameter fit. Such a fit can be obtained at all temperatures. Inset: Relation obtained between $W$ and $T$. The deviation at low $T$ is probably a result of electronic heating.

plies that the effective activation energy for $G(T)$ in the minima is 3.5 times *smaller* than the Coulomb charging energy $\approx e^2/2C_g$ (in these structures the gate capacitance $C_g$ is virtually equal to the *total* capacitance, which determines the charging energy). This smaller energy scale cannot be accounted for by the Coulomb-blockade (CB) picture.[19] The *lack* of observation[1-3] of stepwise structure in the current-voltage characteristic, which is associated with the CB in a two-junction system,[20] raises further doubt about the applicability of that approach to the phenomenon reported here.

Several questions remain open. The height of the peaks as a function of $T$ is not understood. Indeed, some peaks, like that in Fig. 4, decrease with rising temperature at low $T$ and then increase again at higher $T$. Others, however, do not show such a decrease at low $T$. The random variation of heights from peak to peak and their sensitivity to room-temperature cycling suggest that disorder is important.

The precise nature of the resonances is not clear yet. While the importance of Coulomb interactions is now apparent, the role of one dimensionality and electron correlations, which may lead to the formation of a charge-density wave,[3] as well as that of disorder, are not yet determined. Further experiments will be needed to address some of these questions.

In conclusion, by making narrow channels interrupted by two potential barriers we have shown that the conductance oscillations periodic in electron density correspond to the sequential increments of *one* electron between the two barriers. The shape of conductance peaks is precisely proportional to $\partial F/\partial E$. While this suggests that the charge transport is limited by sharp resonances, simple resonant tunneling cannot account for this phenomenon. On the other hand, the energy scale extracted from the line shape points to the insufficiency of the Coulomb-blockade model as well. Correlations and disorder may be essential to explaining our observations.

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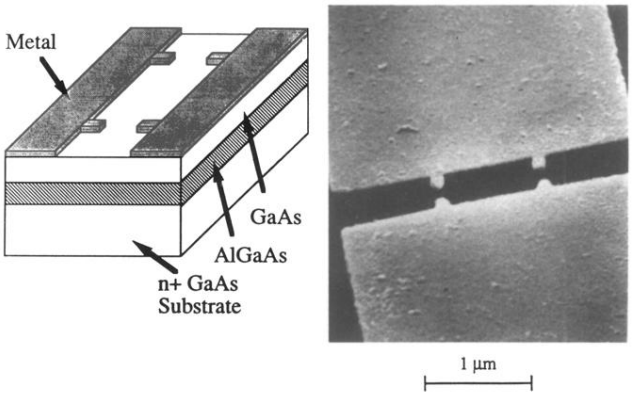


FIG. 1. Schematic drawing of device structure along with a scanning electron micrograph of one of the samples. An electron gas forms at the *top* GaAs-AlGaAs interface, with a density controlled by the substrate voltage $V_g$. The patterned electrodes on top define a narrow channel with two potential barriers.