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Effects of quantum levels on transport through a Coulomb island

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Transport measurements are used to study the quantized energy levels in a small electron gas, referred to as a Coulomb island. First, large-bias measurements reveal the excitation spectrum of the island. Second, small-bias measurements probe the intrinsic line shape of energy levels. Line shapes are generally fit well by thermally broadened Lorentzians. In addition, a decrease in the charging energy of the island is observed as the coupling to its leads is increased. This effect is shown to be consistent with a dramatic increase in one of the island-lead capacitances.

Conductance studies have demonstrated that transport through a small electron gas is strongly regulated by Coulomb interactions.[1] Initially, much of this behavior was interpreted through the theory of the Coulomb blockade,[2] a classical theory in which the discreteness of the energy spectrum of the electron gas is ignored. In metals, where the separation between energy levels is generally negligible, this has proven to be an excellent approximation. In submicrometer semiconductor systems, however, the spacing between energy levels can be orders of magnitude larger and must be taken into account. Consequently, several models have recently been introduced which extend the Coulomb-blockade model to include the effects of quantized energy levels in the limit that kT is much greater than the intrinsic energy width of the levels.[3–6] Some of the predictions of these models have been verified by experiments in small, two-dimensional electron gases (2DEG), which we refer to as Coulomb islands, when the Coulomb energy is larger than the level spacing.[7–9]

In this paper we report effects of quantized energy levels on transport through a Coulomb island. First, large-bias measurements are employed to map the discrete *excitation* spectrum of a Coulomb island. Specifically, this is the spectrum of excited states of the island when the number of charges on the island is constant. This is in contrast to previous experiments which measured the spectrum of states for adding additional charge to the island.[8] Second, low-bias measurements are used to probe the intrinsic line shape of transmission resonances through the island; the line shapes are in general fit well by thermally broadened Lorentzians. Last, we observe a vanishing of the Coulomb charging energy as the coupling through one of the tunnel barriers is increased. This behavior is shown to be consistent with a dramatic increase in the measured value of the capacitance between the island and one of its leads.

The device studied is shown schematically in the inset to Fig. 1(a) and has been discussed in detail elsewhere.[10] Briefly, the density of the 2DEG in an inverted $GaAs/Al_xGa_{1-x}As$ heterostructure is varied by a voltage V_g on the substrate of the device. The density of the 2DEG is $\sim 2\times10^{15}$ m^{-2} and varying V_g by 1 mV changes the density by $\sim 1\times10^{13}$ m^{-2}. A negative bias V_e applied to an electrode on the top of the device

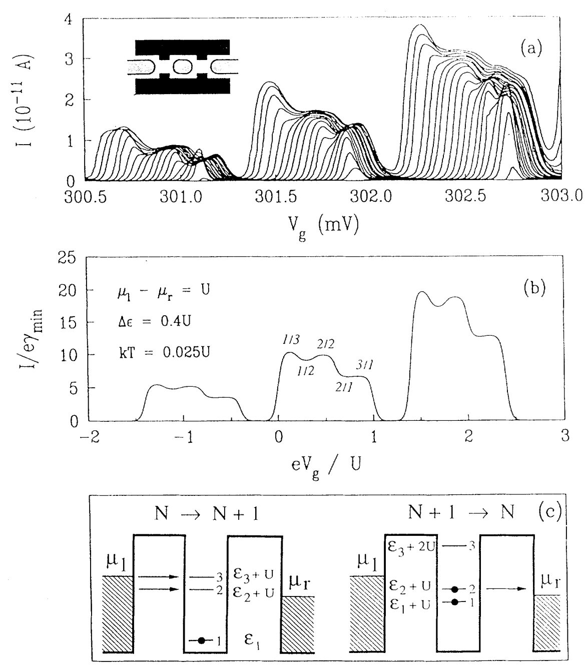

FIG. 1. (a) The current as a function of gate voltage V_g for drain-source biases V_{ds} ranging from 50 to 500 μV in increments of 25 μV. Inset: A schematic top view of the device (not to scale) showing *e*-beam patterned gates (opaque) and 2DEG (shaded). (b) The current, calculated from the model described in the text, in units of $I/e\gamma_{min}$ where γ_{min} is the tunneling rate of the lowest active level through the right barrier. The notation n/m labeling the extrema in the overstructure denotes that electrons can tunnel into n single-particle levels in the island and out from m levels. (c) A schematic of the "2/1" tunneling processes. Only the levels active in transport are shown. Increasing V_g lowers the energy of levels relative to $\mu_{l,r}$ ultimately changing the set of active levels.

confines electrons to the island geometry with lithographic dimensions 450×500 nm^2. In this configuration the island is separated from its leads by tunnel barriers. The current I, which flows through the island in response to a bias between the right and left leads V_{ds}, is typically measured, with a high-precision, low-noise current amplifier. The output of the current amplifier was measured by a lock-in amplifier, which also provided the ac drain bias. The device is cooled in a 12-mK base-temperature dilution refrigerator. Due to residual electron heating, the resulting electron temperature, as determined from the temperature evolution of conductance peaks, is 60 mK at low bias.[11]

We begin by discussing large-bias transport measurements which reveal the discrete excitation spectrum of the island. The current as a function of gate voltage is plotted in Fig. 1(a), for V_{ds} ranging from 50 to 500 μV in increments of 25 μV in zero magnetic field. The periodic spacing of the current peaks at low V_{ds} reflects the quantization of charge on the island.[10] As V_{ds} is increased, the low-bias peaks broaden, take on an asymmetric profile, and exhibit a modulated overstructure. This overstructure persists to $T\sim250$ mK and is observable in both zero and finite magnetic fields.[12]

Figure 1(b) shows the current versus gate voltage calculated from a generalized Coulomb-blockade model in which quantized levels have been included.[3,13] The levels are spaced by $\Delta\epsilon=0.4U$, where U is the Coulomb-blockade charging energy required to increase the charge of the island by e. To reflect the reduction of the tunnel barrier heights with increasing level energy, the tunneling rates across the barriers are increased in the calculation by a factor of 1.2 for each higher level. As shown in Fig. 1(c), the current rises (falls) when a level is pulled below the higher (lower) chemical potential and becomes accessible (inaccessible) for tunneling. This simple model is clearly consistent with the observed modulations of the current in Fig. 1(a). We therefore interpret the modulations in the data as arising from a discrete set of well-coupled, single-particle levels in the island. Furthermore, we point out that unlike previous experiments,[8] these data probe the quantized levels of the island in zero magnetic field. To match the experimental results, it is necessary to assume that for each level the tunneling rate through the barrier on the left is larger than that on the right by a factor of 10.

The excitation spectrum of the well-coupled, single-particle levels of the island is also manifest in I versus V_{ds} measurements at fixed V_g. The inset to Fig. 2(a) shows $|I|$ versus V_{ds} for $V_g=304.06$ mV and $B=3.35$ T. The suppression of current in the neighborhood of $V_{ds}=0$ is due to the Coulomb blockade and the large rise in current at $V_{ds}\approx1.1$ mV is a manifestation of the Coulomb staircase.[2] Additional fine structure, seen most clearly in the plot of dI/dV_{ds} in Fig. 2(a), arises from the discrete excitation level spectrum. A peak in dI/dV_{ds} occurs each time a level in the island is aligned with the Fermi level in the biased lead.[14] Similar observations have been reported in vertical quantum-dot structures.[7] The V_{ds} of peaks in dI/dV_{ds}, multiplied by a factor $e\beta$, are plotted as a function of V_g in Fig. 2(b). The factor

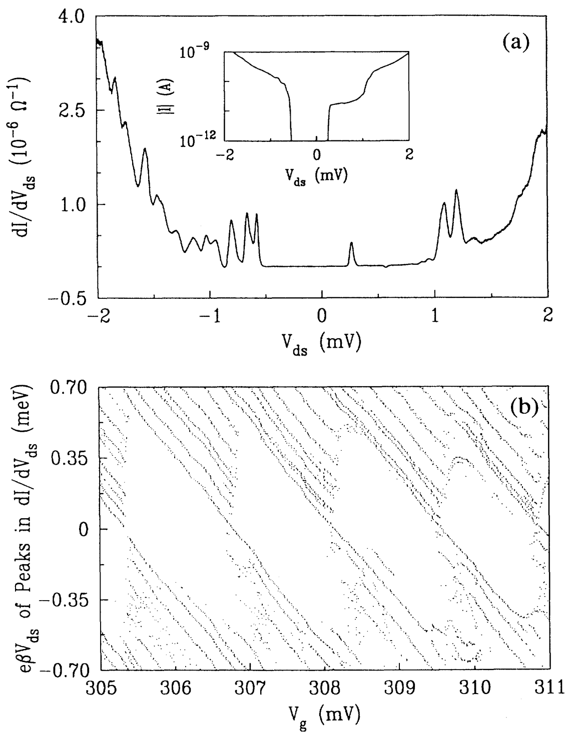

FIG. 2. (a) dI/dV_{ds} as a function of V_{ds} for $V_g=304.06$ mV and $B=3.35$ T. Inset: $|I|$ vs V_{ds} for the data in (a). (b) The energy of peaks in dI/dV_{ds} as a function of V_g. The V_{ds} of a peak is converted to an energy via the factor β described in the text. The lines represent the single-particle excitation spectrum of the island as a function of V_g. Note that the Coulomb gap decreases with V_g.

$\beta=-0.80$ relates V_{ds} to the actual change in the Fermi energy of the biased lead relative to the island.[15] The lines in Fig. 2(b) show the single-particle excitation spectrum of the island as a function of V_g.[16] The Coulomb-blockade gap in the tunneling density of states and the downward shift in energy of excitation levels with increasing V_g are clearly visible. The typical level spacing is seen to be $\Delta\epsilon\approx0.1$ meV. Also evident is the realignment of the Coulomb gap when the charge state of the island increases by e and levels shift by U.

We now discuss measurements which probe the intrinsic line shapes of transmission resonances of the island. Figure 3(a) shows the low-bias ($V_{ds}=2.5$ μV) conductance of the island as a function of V_g at $B=2.53$ T. At high V_g the peaks broaden, the valley conductances increase, and the peak to valley ratios decrease from values greater than 10^3 at low V_g to ~10 at higher V_g. Figure 3(b) is an expanded view of a low V_g conductance peak from Fig. 3(a), for which the coupling to the island is still relatively small and hence so too is its intrinsic width. This peak is fit well with the line shape of a purely thermally broadened resonance[10] in the limit that the resonance width is much less than kT,

$$G=(e^2/h)(1/4kT)A\cosh^{-2}[(e\alpha V_g-E_{res})/2kT]\ , \quad (1)$$

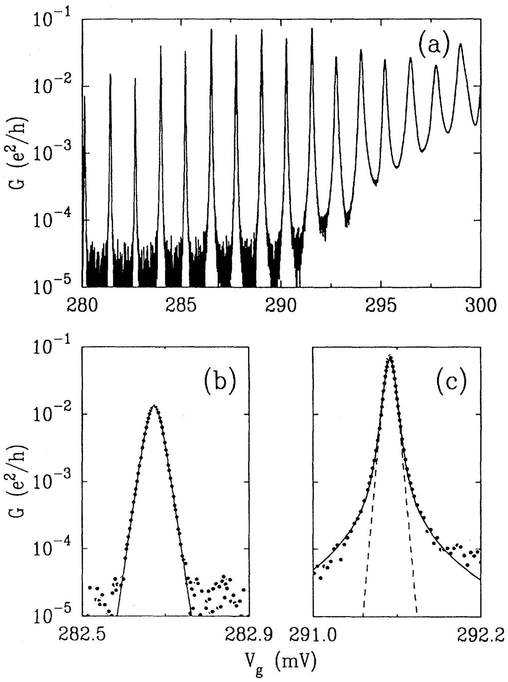

FIG. 3. (a) The low-bias conductance of the island vs V_g at $B=2.53$ T. [Note the alternation of peak amplitudes which arises from the spin splitting of levels (Ref. 17).] (b) A low V_g conductance peak from (a) shown fit to a thermally broadened resonance (solid line) in the limit that the intrinsic resonance width is much less than kT. (c) A conductance peak at higher V_g shown fit to a thermally broadened Lorentzian (solid line). The dashed line is the best fit using the same line shape as in (b).

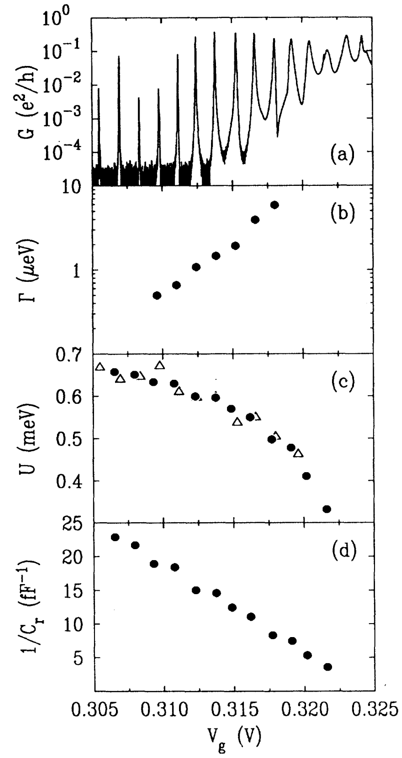

FIG. 4. (a) The low-bias conductance of the island vs V_g at $B=3.35$ T. Each peak in (a) is fit to a thermally broadened Lorentzian yielding values for Γ, the Lorentzian full width at half-maximum [plotted in (b)] and U, the charging energy of the island [open triangles in (c)]. (d) The reciprocal of the island-lead capacitance C_r^{-1} across the right barrier. U determined from the values of C_r in (d), as described in the text, is plotted as the filled circles in (c).

where $E_{\rm res}$ is the energy of the transmission resonance and A is the temperature-independent energy-integrated strength of the resonance. The factor α, in Eq. (1), relates a change in V_g to a shift in the energy of the island; $\alpha = U/e\Delta V_g$ where ΔV_g is the spacing between peaks.[18] From the fit we obtain $\alpha=0.52$ and hence $U=0.61$ meV. Figure 3(c) shows a peak at higher V_g, at which the island is more strongly coupled to its leads. A striking feature of this peak is that its tails do not fall off exponentially. Clearly, this line shape cannot be fit by the expression in Eq. (1); the intrinsic line shape of the resonance is influencing the conductance peak profile. We have fit the data in Fig. 3(c) to a thermally broadened Lorentzian parametrized by a full width at half-maximum Γ,

$$G=\frac{e^2}{h}\frac{1}{4kT}A\int_{-\infty}^{+\infty}\cosh^{-2}(E/2kT)\times\frac{(\Gamma/2)\pi}{(\Gamma/2)^2+[(e\alpha V_g-E_{\rm res})-E]^2}dE, \tag{2}$$

which describes resonant tunneling in noninteracting systems. The fit yields $\Gamma=5.0$ μeV and $\alpha=0.30$ giving $U=0.35$ meV. As seen in Fig. 4(a) peaks often exhibit asymmetries and other features which underscore the limitations of broadly applying the Lorentzian line shape.[11] Nevertheless, reasonable fits can be made with this line shape for many of the peaks observed. The success of the fit in Fig. 3(c) strongly indicates that transmission resonances in a Coulomb island have Lorentzian intrinsic line shapes despite the presence of interactions. In zero magnetic field, similar results are seen, though in general a larger percentage of peaks show deviations from the Lorentzian line shape.

As a final consideration, notice the different values of U determined from the fits in Figs. 3(b) and 3(c), 0.61 and 0.35 meV, respectively. In order to understand this behavior we have fit a series of peaks, shown in Fig. 4(a), with the line shape of Eq. (2) and have extracted values of U and Γ. Figure 4(b) shows that Γ increases exponentially with V_g, consistent with tunneling through a saddle-point potential in a magnetic field.[19] Figure 4(c) shows that U (open triangles) diminishes with V_g. Within the context of the Coulomb-blockade model this implies that the total capacitance of the island, $C=e^2/U$, increases with V_g. We test this proposition by assuming that C is the sum of four capacitances, the island-gate capacitance C_g, the island-electrode capacitance C_e, and the island-lead capacitances to both the left and right leads C_l and

C_r, respectively. C_g and C_e are measured directly from ΔV_g, the spacing between low-bias peaks.[18,20] C_l and C_r are determined from the slope of the peak positions versus gate voltage, dV_{ds}/dV_g in measurements similar to those in Fig. 2(b). The Coulomb-blockade model gives

$$dV_{ds}/dV_g = C_g/(C - C_{bias}) , \quad (3)$$

where C_{bias} is the capacitance of the island to the biased lead.[1]

The above procedure gives $C_g = 0.124$ fF, $C_e = 0.025$ fF, and $C_l = 0.045 \pm 0.005$ fF independent of V_g. Surprisingly, however, C_r increases from ~ 0.045 to > 0.300 fF over the range of V_g in Fig. 4. U thus diminishes due to the increasing island-lead capacitance.[21] Figure 4(d) shows that C_r^{-1} goes to zero linearly in V_g. U, determined from the sum of C_g, C_e, C_l, and C_r, is plotted as the filled circles in Fig. 4(c). The agreement between this measure of U and that determiend from the fits confirms the accuracy of the above procedure for measuring the capacitances to the island.

In summary, the effects of quantized energy levels on transport through a Coulomb island have been characterized. Large-bias measurements reveal the quantized excitation spectrum of these levels, and low-bias measurements probe their intrinsic line shapes. In addition, a decrease in the charging energy of the island at larger island-lead couplings is consistent with an observed increase in the island-lead capacitance.

We recently received a copy of work by A. T. Johnson *et al.* of the Delft University of Technology which reports measurements similar to our results in Figs. 1(a) and 2(a).

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[12]In the device discussed here the modulated overstructure was not observed for fields $B \geq 4$ T. It is not yet known if this is a general feature of these systems.
[13]The division of the energy scales into separate Coulomb and single-particle pieces is an oversimplication. (See Ref. 17.) Nevertheless, the division is very illustrative and will be used exclusively in our discussion.
[14]In principle, peaks may also result from levels being brought into alignment with the unbiased lead due to the finite island-to-biased-lead capacitance. However, given the relatively small size of this capacitance such peaks occur rarely in Fig. 3.
[15]According to the Coulomb-blocade model $\beta = -(1 - C_{bias}/C)$, where C_{bias} and C are as defined later in the text.
[16]The results shown in Figs. 1 and 2 are from measurements on two different devices. This accounts for the different values of U and $\Delta\epsilon$ in Figs. 1 and 2.
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[18]A small contribution to the spacing between peaks ($\sim 10\%$) is due to the single-particle energy to add an electron to the island. (See Ref. 5.) Therefore, the minimum observed spacing between peaks is used for ΔV_g.
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[20]In a different study, a similar procedure was carried out except that the equivalents of C_l and C_r were assumed to be zero [L. P. Kouwenhoven *et al.*, Z. Phys. B **85**, 367 (1991)].
[21]The island-lead capacitances probably account for the missing stray capacitance discussed in Refs. 8 and 10.