Coulomb Blockade as a Noninvasive Probe of Local Density of States

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We show that a system of two closely separated two-dimensional electron gases in a GaAs/AlGaAs system in which one is formed into a quantum dot can be used as a Coulomb blockade electrometer. The blockade is used to explore the density of states of the other electron gas which is patterned as a wire. Electron localization is observed and shows behavior in a magnetic field arising from the destruction of quantum interference and subsequent wave-function shrinkage. The dimensionality of the transport changes as the carrier concentration is increased, with the inferred density of states changing from quasi-one-dimensional to two dimensional. [S0031-9007(96)00643-6]

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Direct transport measurements can often disrupt the system being measured and only reveal information about the diffusivity of electrons in states contributing to conduction. The use of a "noninvasive" technique in which the local conditions in one circuit affect a nearby measuring circuit lets the system remain undisturbed, and allows the study of transport in samples where the current is too low to be measured conventionally [1]. One such class of noninvasive measurement is the determination of the screening ability of a sample by capacitance techniques. In this paper we use a two-dimensional electron gas (2DEG) to screen a perpendicular electric field between a gate and a Coulomb blockade (CB) electrometer fabricated in a second 2DEG 200 Å above the screening layer. The high sensitivity of the electrometer allows changes in capacitance as low as 1 aF to be detected. Using samples with two independently contacted 2DEG's with a patterned $n+$ layer as a back gate [2] allows the capacitance between the upper 2DEG and the back gate to be measured and the density of states of the screening layer to be inferred [3–5].

Using a GaAs-GaAlAs system a sample was grown by molecular beam epitaxy which comprised two 200 Å quantum wells a distance of 200 Å apart, and a back gate 3300 Å beneath the lower 2DEG. The mobility of the upper layer was 7×10^5 cm^2/V s at a carrier concentration $N_t = 4.5 \times 10^{11}$ cm^{-2}, while the lower layer had a low mobility of 3×10^4 cm^2/V s at the same carrier concentration $N_b = N_t$. The carrier concentration in the lower layer was controllable via the back gate, with depletion occurring at approximately -1.4 V.

The sample was patterned into a narrow structure (nominally 0.6 μm wide by 2 μm long) by *in situ* low energy gallium ion beam damage [2] after growth. Electron beam lithography was used to pattern two independently contacted Schottky gates of width 500 Å which cross the surface of the narrow channel a distance of 0.4 μm apart. Using these surface gates a quantum box [6] can be induced in the upper 2DEG, the completed device is shown schematically in Fig. 1(a). The measurements were made in a dilution refrigerator at a base temperature of less than 50 mK and the conductance of both the upper and lower 2DEG were measured simultaneously by ac phase sensitive detection using an excitation voltage of 10 μV.

The quantum box in the upper 2DEG exhibits Coulomb blockade oscillations [7] as a function of back gate voltage. In this way the capacitance between the dot and the back gate can be determined, and the value obtained will include the screening effects of the intervening, lower, 2DEG. By making the back gate voltage extremely negative, the carriers in the lower 2DEG can be depleted out and the direct capacitance between the back gate and the quantum box measured in the absence of such screening. Similarly, applying a voltage directly to the

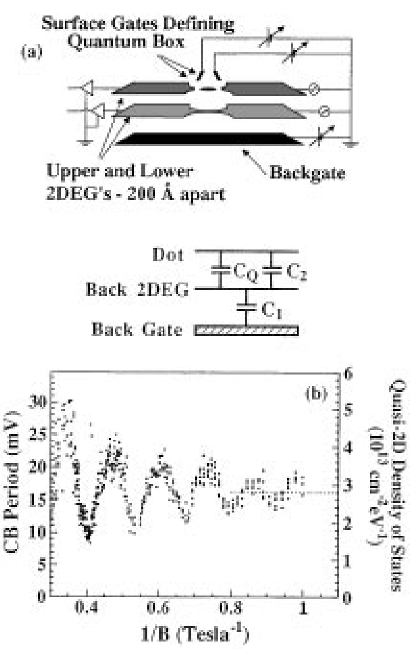

FIG. 1. (a) A schematic diagram of the double 2DEG device. Inset: The equivalent circuit for the total capacitance seen by the back gate. (b) The CB period as a function of inverse magnetic field at zero applied bias on the back gate. The extracted density of states on the right hand axis is quasi-2D since the cyclotron radius is always smaller than the wire width.

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lower 2DEG allows it to be used as a gate, allowing the capacitance between the lower 2DEG and the dot to be measured as well as the active area, $A = 0.51 \times 0.51\ \mu\text{m}^2$, of the dot. This value agrees with that obtained from Aharonov-Bohm oscillations as a magnetic field is swept [8] with the dot in the edge state regime.

The total capacitance seen by the back gate can be modeled by the equivalent circuit proposed by Luryi [9] and shown in the inset to Fig. 1(a). The capacitances C_1 and C_2 are the geometric capacitances per unit area. The extra "quantum" capacitance C_Q in parallel with C_2 is due to the extra energy required to place electrons in the quantum well and is given by

$$\frac{1}{C_Q} = \frac{1}{e^2}\left(\frac{1}{dN_b/dE}\right). \tag{1}$$

This was first measured by Smith *et al.* [3] and calculated explicitly by Büttiker [10], who also derived the full 3×3 capacitance matrix for this system. This equivalent circuit can be inferred from that matrix. Effects due to electron-electron interactions or the nonzero extent of the wave function perpendicular to the 2DEG were considered explicitly elsewhere [5].

For a two-dimensional (2D) density of states the quantum capacitance becomes [5,9,10]

$$C_Q = e^2\left(\frac{m^*}{\pi\hbar^2}\right). \tag{2}$$

The induced charge density in the upper layer σ_t for a charge density on the back gate σ_{bg} is $\sigma_t = -\sigma_{\text{bg}}[C_2/(C_2 + C_Q)]$ [9]. For one CB oscillation the change in the charge density in the upper layer is e/A and the period of CB oscillations will be

$$\Delta V = -\frac{e}{AC_1C_2}(C_1 + C_2 + C_Q). \tag{3}$$

Since there are gates above the upper 2DEG, we must consider electric field penetration from the back gate through the upper 2DEG as well as through the lower 2DEG. This effect must be small since the area A measured by the Coulomb blockade period between the lower 2DEG and the dot agrees with that measured by the Aharonov-Bohm effect. We further note that the fraction of electric field that penetrates a single 2DEG is of order 10%, and therefore the correction term in including penetration of the field through both 2DEGs is of order 1%. Therefore any term due to the density of states in the dot is ignored in Eqs. (1) and (2).

The geometric capacitances C_1 and C_2 can be inferred directly; C_1 from the separation of the back gate from the lower 2DEG; $C_1 = 2.56 \times 10^{-4}\ \text{F m}^{-2}$. C_2 from the period of CB oscillations on applying a voltage directly to the lower 2DEG we find $C_2 = 2.88 \times 10^{-3}\ \text{F m}^{-2}$.

Figure 1 shows the measured CB period for small voltage swings (± 0.075 V, about nine oscillations) of the back gate around $V_{\text{bg}} = 0$, with the lower 2DEG grounded, as a function of inverse transverse magnetic field B. When the lower 2DEG is depleted ($V_{\text{bg}} \leq -1.4$ V) the CB period is not affected by the magnetic field, whereas for $V_{\text{bg}} > -1.4$ V the CB period oscillates periodically with $1/B$, the period $0.135\ \text{T}^{-1}$ gives a carrier concentration of $3.5 \times 10^{11}\ \text{cm}^{-2}$. This is to be compared with an average concentration of $2.7 \times 10^{11}\ \text{cm}^{-2}$ obtained from Shubnikov–de Haas measurements. However, as the dot is not aligned with the narrowest portion of the ion beam defined channel in the lower 2DEG we would expect such a discrepancy.

The density of states can be extracted from the observed period of CB oscillations as the back gate voltage is swept with the lower 2DEG grounded. Using 2D screening the model predicts a constant CB period of 39.3 mV. The data displayed in Fig. 2 show a period slowly increasing from 7 mV at a back gate voltage of -1.4 V to 16 mV at a back gate voltage of -0.2 V and then remaining approximately constant. Inclusion of the Hartree-Fock correction into the density of states predicts that the period should rise as the back gate is made more negative (following the function $1/[1 - (N_c/N)^{1/2}]$, $N_c = \text{const} < N$, appearing in dN/dE) [5]. The corrections due to the exchange and correlation energies, together with effects due to charge movement perpendicular to the 2DEG within the confines of the well, will tend to reduce the capacitance [3,5]. In this experiment there is also a direct parasitic capacitance between the back gate and the dot due to the small size of the screening region between the dot and the back gate. To deal with this previous authors [3,5] have introduced a numerical factor γ to the quantum capacitance C_Q, which brings the results into line with the 2D theoretical density of states $m^*/\pi\hbar^2$. If γ were about 0.4, this model would explain the period at $V_{\text{bg}} = 0$, but it does not account for the observed downward slope or the structure in the data which is discussed later.

Figure 2 shows the CB period as the back gate is swept from -1.5 to $+0.8$ V at zero magnetic field and is seen to change dramatically from 7 to 2 mV at a back gate voltage of -1.39 V corresponding to depletion of the lower 2DEG [Fig. 2(b)]. A sweep showing CB oscillations is displaced in Fig. 2(c). The variation of the carrier concentration in the lower 2DEG with back gate voltage explains the feature at $V_{\text{bg}} = +0.6$ V [Fig. 2(a)] where the carrier concentrations in the upper and lower 2DEGs will be equal and resonant tunneling between the two 2DEGs occurs [11,12], effectively shorting the two layers together, the sharpness arises from the wide (20 nm) barrier. The wave function is now hybridized between the two 2DEGs, but the coupling is sufficiently small that CB is still present in the dot.

At a back gate voltage of -1.39 V the carrier concentration is reduced sufficiently that the electrons in the lower 2DEG become localized; here the term "localized" means

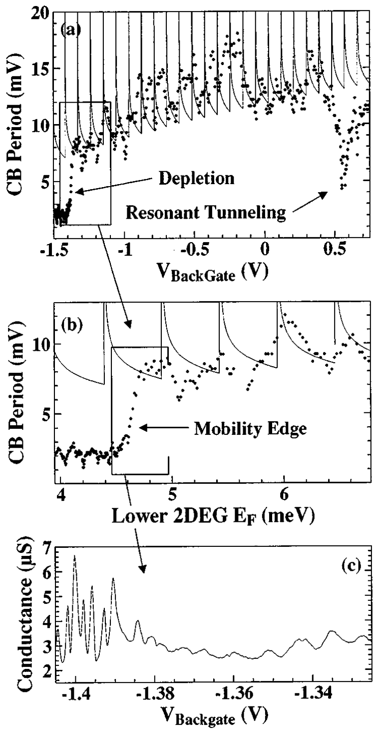

FIG. 2. (a) The Coulomb blockade period as a function of back gate voltage at $B = 0$. The depletion of the lower 2DEG is seen at -1.4 V and a sudden drop in the CB period at $+0.6$ V due to resonant tunneling between the 2DEGs. The solid line is the modeled CB period using a 1D density of states, including a numerical prefactor $\gamma = 0.6$, in C_Q. (b) An enlarged section of the top figure. The horizontal axis has been recalibrated in terms of the Fermi energy of the lower 2DEG. The sudden drop in period at the point of depletion (4.6 meV) is consistent with the Fermi energy reaching the mobility edge. (c) The dot conductance as a function of back gate voltage is shown at the point of depletion showing the CB oscillations as the lower 2DEG is depleted.

that the electron can no longer rearrange to equalize the potential to ground through the contacts and screen during the time it takes to sweep the back gate voltage through one CB period (approximately 1 s). As expected changing the sweep rate moves the observed point of localization by a small voltage. The conductance of the lower 2DEG dropped below the sensitivity of the measurement when $V_{bg} < -1.3$ V and so transport information can be extracted only by using the noninvasive probe. This technique allows transport to be measured when currents are of order 10^{-19} A, well into the strongly localized regime, where electrons move through the lower layer in a time scale of seconds.

The shift to localization is attributed to an Anderson transition [13], with screening then occurring by thermal activation of electrons to the mobility edge (in 2D this is produced by phase incoherent scattering), or by variable range hopping. The carrier density in the lower 2DEG at the transition point is obtained by extrapolating the dependence on back gate voltage and is found to be $N_b = 1.205 \times 10^{11}\ \mathrm{cm}^{-2}$. From the quantitative viewpoint the product $N_b^{1/2} a_B = 0.35$ (a_B being the Bohr radius corrected for dielectric constant and effective mass) is close to an expected value for a 2D Anderson transition of 0.27 [13]. Increasing the temperature moves the localization point to more negative gate voltages and flattens out the transition. The back gate voltage can be recalibrated in terms of the lower 2DEG Fermi energy [Fig. 2(b)] giving an estimate of the mobility edge at $E_c = 4.6$ meV.

On increasing the magnetic field the localization point corresponding to the termination of screening shows the "reentrant" behavior (Fig. 3), similar to the phase diagram for 3D conductors undergoing an Anderson metal-insulator transition in a magnetic field [14–16]. Here a small magnetic field removes the quantum interference which enhances the localization of carriers, resulting in the localization length increasing and the mobility edge dropping. Further increases in field results in wave function shrinkage and enhancement of localization. In this work the initial decrease in the carrier density at the transition point is due to the magnetic field destroying quantum interference between hopping paths [17], the increase at higher fields is due to magnetic shrinkage of the wave function reducing the localization length. The gradient of the CB period with back gate voltage, which indicates the decrease in screening, is significantly larger with a magnetic field sufficient to destroy quantum interference and induce Landau levels. We can state that this arises from a decrease in electron diffusivity since the extracted density of states just before localization oscillates with magnetic field and is frequently larger than the zero field case, as shown in Fig. 1(b).

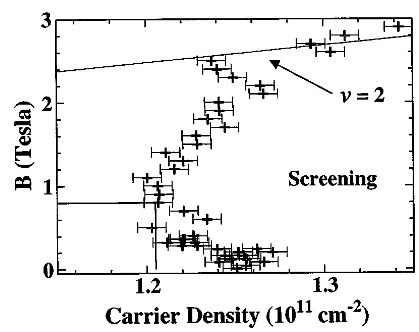

FIG. 3. The point of localization defining the ability of the lower 2DEG to screen on the measurement time scale plotted as a function of carrier density and magnetic field. The data show "reentrant" behavior due to destruction of quantum interference in the hopping conduction by low magnetic fields followed by wave function shrinkage. The plotted line is filling factor $\nu = 2$, the structure in the data may be due to a further mobility edge associated with second Landau level and a corresponding change of screening.

The magnetic length at the point where the quantum interference has been removed (which corresponds to the minimum carrier density at which the screening-nonscreening transition occurs) gives an estimate of the localization length in zero magnetic field without the quantum interference correction. This occurs at 0.8 T, giving a magnetic length of 28.7 nm. The carrier spacing at the transition point is given by the square root of the density and is equal to 28.8 nm. The good agreement of these two values indicates that the above premise is correct and furthermore indicates that the electron-electron interaction may play a significant role in localization. There is further structure in the data at filling factor $\nu = 2$. Theoretical work suggests that each defined Landau level has its own mobility edge [18] which would explain this structure as corresponding to a jump in screening. It is possible that there are similar smaller features at each integer filling factor that are obscured by the experimental error in determining the localization point. As mentioned earlier the density of state decreases as V_{bg} becomes more negative. This may be a band-tail effect or possibly incipient one dimensionality in the narrow electron gas.

The width of the screening channel is approximately 0.65 μm [19] and the Fermi wavelength in the wider leads at $V_{\mathrm{bg}} = 0$ is 420 Å. The screening channel is therefore of order 15 times the Fermi wavelength, in which case 1D behavior approximates to the 2D case. Using a parabolic well model there are 28 filled 1D subbands at $V_{\mathrm{bg}} = 0$; however, this number decreases as the back gate is made more negative and the density of states moves over from approximately 2D to quasi-1D.

To model this we modify Eq. (2) to use a bare 1D density of states multiplied by the width w of the screening wire. The only fitting parameter, $\gamma = 0.6$, is used to correct for the parasitic capacitance and other effects which are assumed to be constant. C_Q now becomes

$$C_Q = \frac{\gamma e^2}{w} \sum_n \left[\frac{4m^*}{2\pi\hbar^2} \left(\frac{\hbar^2}{2m^*(E - E_n)} \right)^{1/2} \right], \qquad (4)$$

where E_n are the subband energies calculated from the parabolic well model. The predicted CB period for a bare quasi-1D density of states is plotted as the dotted line in Fig. 2. In the presence of disorder the discontinuities at the subband energies will be smoothed out [20]. The overall slope of the curve is now in reasonable agreement with the model, the screening reflecting the depopulation of the 1D subbands.

The fine structure near depletion shown in Fig. 2(b) is reproducible. There are several possible explanations. Firstly, the structure in the quasi-1D density of states has not been completely removed by the disorder [20], altering the ability of the lower 2DEG to screen [21]. It is possible that due to inhomogeneities at low values of carrier concentration in the lower 2DEG, it displays CB effects, in which case the total screening will be modified by the lower 2DEG conductance oscillating with back gate voltage.

In conclusion, we have measured the density of states in a submicron area of a 2DEG using a noninvasive capacitance technique. Electron localization has been observed and we explore the role of quantum interference and reentrant behavior in a magnetic field. The sample shows screening behavior with distinct structure possibly arising from the 1D density of states.

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