Evidence for a reentrant metal-insulator transition in quantum-dot arrays

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We present evidence for gate voltage-induced localization, and a possibly re-entrant metal-insulator transition, in linear quantum dot arrays that are realized using the split-gate technique. No evidence for the localization is observed prior to biasing the gates of the array, and the details of this behavior are found to be strongly device dependent. The metal-insulator transition is thought to arise as the gate voltage sweeps the discrete level spectrum of the array past the Fermi surface, mapping out regions of localized and extended states. In the metallic regime, the resistance varies logarithmically with temperature, behavior which is not seen in the underlying two-dimensional electron gas, but which is consistent with recent predictions for a correlated electron liquid. [S0163-1829(99)15747-3]

I. INTRODUCTION

In the scaling theory of localization, the distinction between an insulator and a metal is made at the absolute zero of temperature, where an insulator is a system with infinite resistance while a metal is one with finite resistance.[1] Interest in the scaling theory has been revived in recent years, by the observation of an unexpected metal-insulator transition in a variety of two-dimensional carrier systems.[2–13] In these experiments, the transition to a metallic state is inferred as a change in the sign of the temperature coefficient of the resistance, which occurs as the carrier density is varied by suitable means. This transition cannot be accounted for within the framework of the original single-parameter scaling theory, which derives from an assumption of non-interacting electrons and predicts that, in the presence of even the smallest amount of disorder, all states should be localized in dimensions less than or equal to two $(d \leqslant 2)$.[14] While a number of experiments have suggested that that the metallic state is unique to systems in which carrier interactions play an important role, the details of the mechanism that drives the transition remains the subject of continued debate.[15–20]

In spite of current interest in the metal-insulator transition in two-dimensional systems, to the best of our knowledge, little interest to date has focused on the possibility of observing a similar transition in systems of even lower dimensionality $(d<2)$. Resonant tunneling and variable-range hopping have been studied in mesoscopic Si-metal-oxide semiconductor field-effect transistor (MOSFET's), but no evidence for a metallic state was found in these disordered structures.[21–23] In this report, we describe the observation of novel localization, and present possible evidence for a metal-insulator transition, in studies of split-gate quantum dot arrays. These devices are realized in the two-dimensional electron gas (2DEG) of a GaAs/$Al_xGa_{1-x}As$ heterojunction, which reveals no evidence for the localization prior to biasing the gates. Once the array is formed, however, its resistance shows evidence for localization, the details of which vary significantly from one device to another. In devices incorporating significant disorder, the localization persists over the entire range of gate voltage for which the array is defined. Less-disordered arrays, on the other hand, show possible evidence for a *re-entrant* metal-insulator transition. The transition is induced as the gate voltage is swept, giving rise to reproducible oscillations in the resistance of the array. At gate voltages corresponding to a local resistance maximum, behavior characteristic of an insulating system is found. At certain resistance minima, however, metallic behavior is seen that is quite distinct to that exhibited by the underlying 2DEG. Based on our observations, we speculate that a metal-insulator transition occurs as the gate voltage sweeps the density of states of the array past the Fermi surface. In those regions of the spectrum where the density of states is low, remnant disorder in the structures is thought to induce localization, while leaving states extended in more degenerate regions. In this regard, the metal-insulator transition ob-

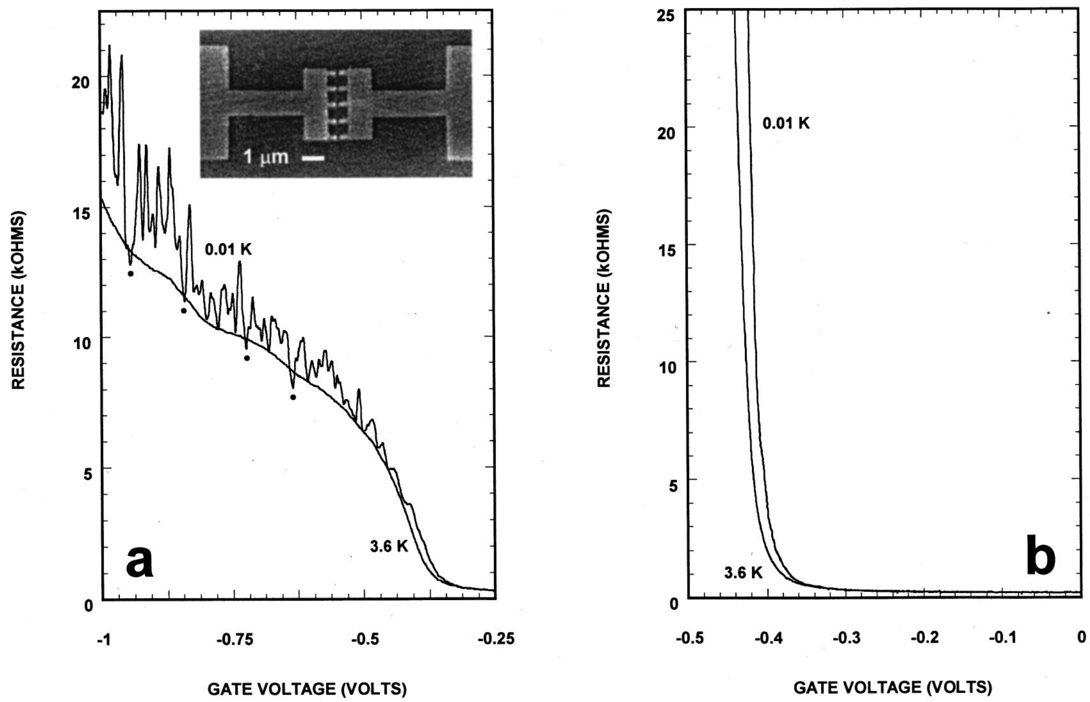

FIG. 1. (a) Resistance gate-voltage characteristic of array *A*, measured at two different temperatures. The symbols indicate the gate voltages at which a possible metal-insulator transition occurs. (b) Resistance gate-voltage characteristic of array *C*, measured at two different temperatures.

served in the arrays appears consistent with previously developed models for localized systems.[24]

II. BASIC EXPERIMENTAL TECHNIQUES

The devices we study are split-gate quantum dot arrays, formed in the 2DEG of a GaAs/$Al_xGa_{1-x}As$ heterojunction. Here, we present results from three arrays, which were patterned on the same wafer and which we refer to as devices *A*, *B*, and *C*. As can be seen from the micrograph shown in Fig. 1(a), each array consisted of series-connected dots, of length 0.6 μm and width 1 μm. The wafer was mounted in good thermal contact with the mixing chamber of a dilution refrigerator and cooled in the dark to 4.2 K, where its carrier density was $3.7\times10^{11}\,\mathrm{cm}^{-2}$ and its mobility was 210,000 cm^2/Vs. Unless stated otherwise, all measurements presented here were obtained *prior* to low-temperature illumination of the sample (we discuss the effects of illumination in § 3.4 below). Resistance measurements were performed using low-frequency lock-in detection with small constant currents to avoid electron heating (the results of current heating studies will be discussed in a separate publication).[25] Temperature sweeps were performed in several different ways, including cooling to base temperature over several days to ensure that the sample resistance was accurately reflected by the sensing thermometer. All connections to the sample were made using coaxial cables, which were filtered at room temperature using RF-feedthroughs. These lines are further filtered at low temperatures due to dielectric loss in the screened cables employed inside the cryostat.[26]

III. EXPERIMENTAL RESULTS

A. Device dependent variations in behavior

In Fig. 1, we show the variation of resistance with gate voltage, measured in arrays *A* and *C* at two distinct temperatures. If we adopt the convention common to experiment, that metal and insulating states are distinguished by the temperature coefficient of their resistance, it is clear the two devices exhibit very different localized behavior. In Fig. 1(a), localization occurs for gate voltages less than -0.4 V, but at higher gate voltages a transition to a new regime is observed. This is identified by the emergence of reproducible oscillations in the resistance, whose minima drop below the high temperature curve at the indicated gate voltages. These points are suggestive of a metal-insulator transition. Similar oscillations have also been reported in studies of single quantum dots and have been attributed to density-of-states fluctuations, which arise as the gate voltage sweeps discrete dot states past the Fermi surface.[27,28] In the sense that the oscillations reflect the discreteness of the array states, we take their observation in Fig. 1(a) as an indication of the low level of disorder in this particular device (although not shown here, similar oscillations were also found for array *B*). In contrast, in Fig. 1(b) the resistance varies purely monotonically with gate voltage, which we interpret as reflecting a higher degree of disorder in this device. Indeed, it is well understood that the introduction of disorder mixes the discrete states of small dots,[29] ultimately giving rise to a featureless density of states.

To further illustrate the role of device dependent variations, in Fig. 2 we show the results of magnetoresistance measurement of the two arrays shown in Fig. 1. In these measurements, the voltage applied to the gates of the arrays has been adjusted in order to obtain roughly similar resistance values at zero magnetic field. Consistent with the behavior found above, the magneto-resistance shows large fluctuations in Fig. 2(a), which are clearly absent in Fig. 2(b). Since these fluctuations may also be thought of as aris-

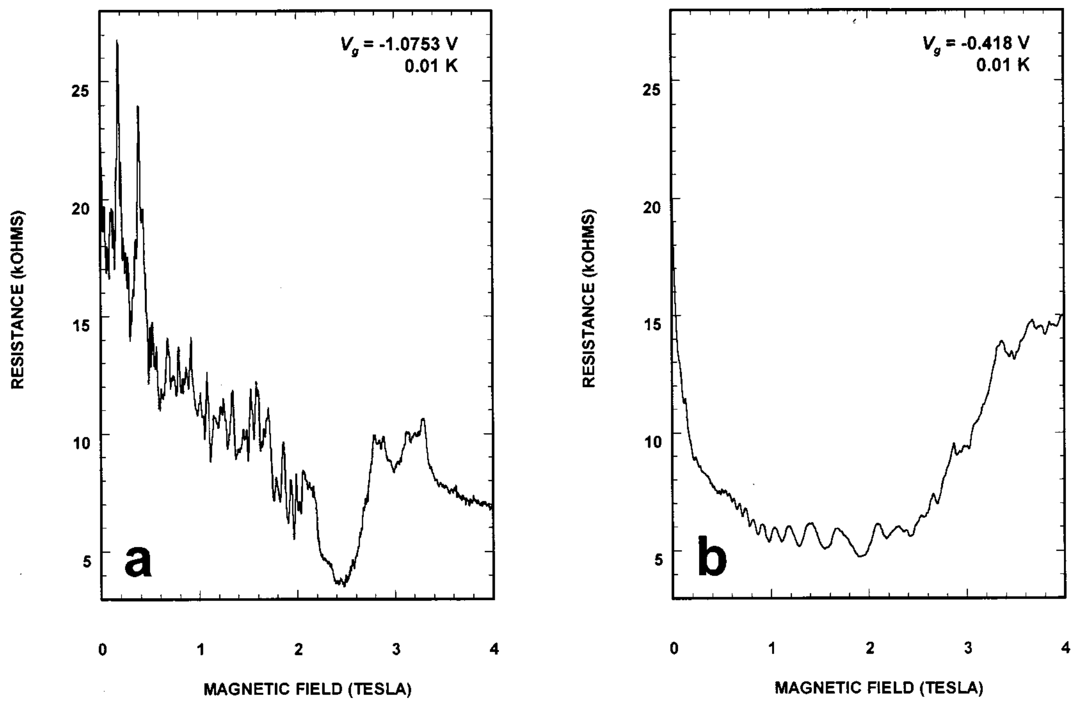

FIG. 2. (a) Magnetoresistance of array *A* measured at 0.01 K and for a gate voltage of −1.0753 V. (b) Magneto-resistance of array *C* measured at 0.01 K and for a gate voltage of −0.418 V.

ing from a density of states oscillation,[27] their absence in Fig. 2(b) provides further evidence for a higher degree of disorder in array *C*.

B. Localized behavior in the quantum dot arrays

As we have mentioned already, before crossing over to the metal-insulator regime, arrays *A* and *B* show evidence for localized behavior. Array *C*, which is though to be more disordered, on the other hand, shows localized behavior at all gate voltages for which it is defined. To illustrate the localization exhibited by these arrays, in Fig. 3 we show the variation of resistance with temperature, measured in two of the arrays at a number of gate voltages. With the gates unbiased, the resistance is essentially independent of tempera-

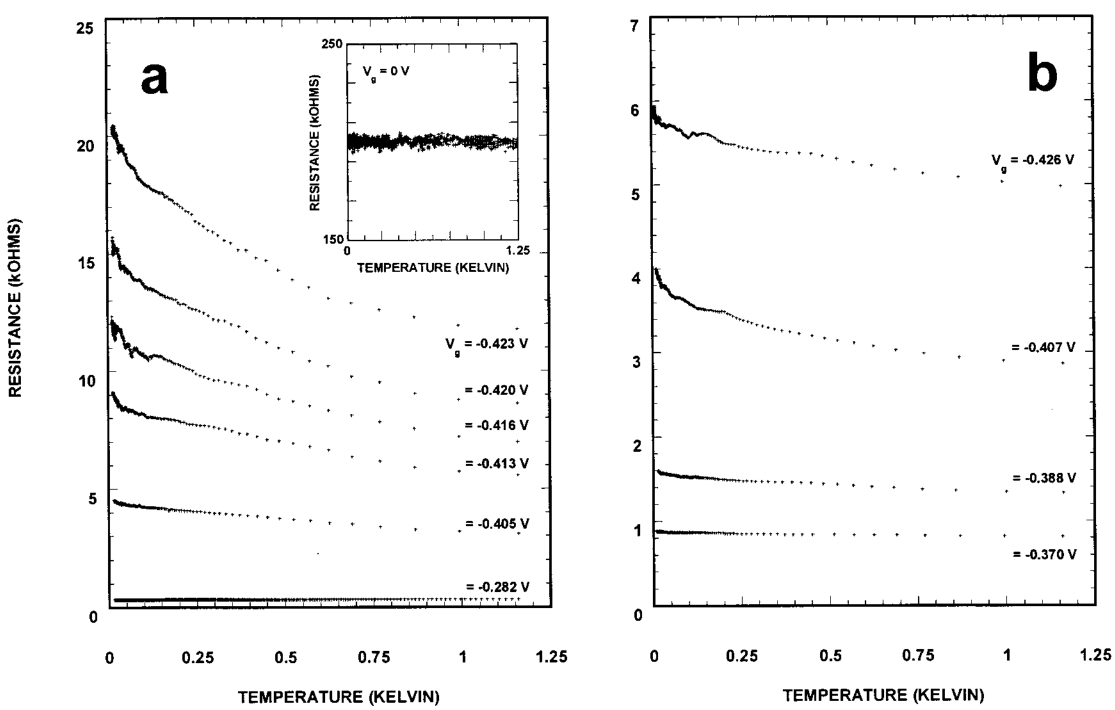

FIG. 3. (a) Variation of resistance with temperature, measured in array *C* at a number of different gate voltages (indicated). The applied magnetic field is zero. The inset shows the temperature dependence of the resistance measured with all gates grounded. (b) Similar plot for array *B*.

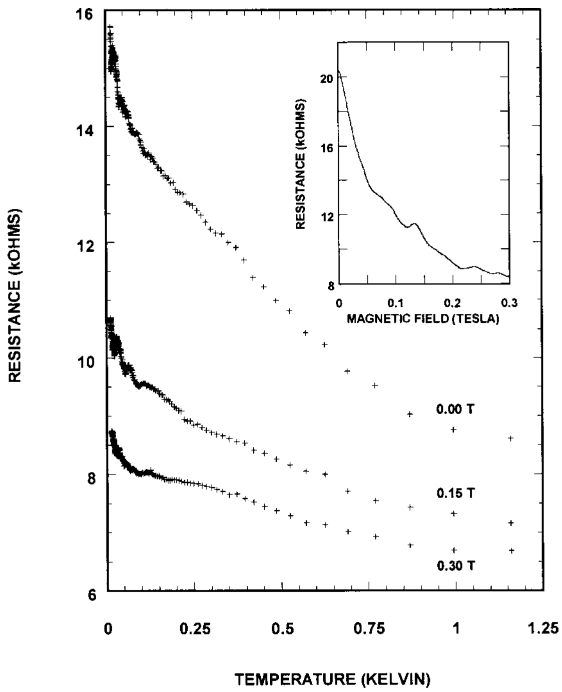

FIG. 4. Variation of resistance with temperature, measured in array C at three different magnetic fields (indicated). In these measurements the gate voltage is -0.4198 V. Inset: low field magnetoresistance measured in array C at 0.01 K at a gate voltage of -0.418 V.

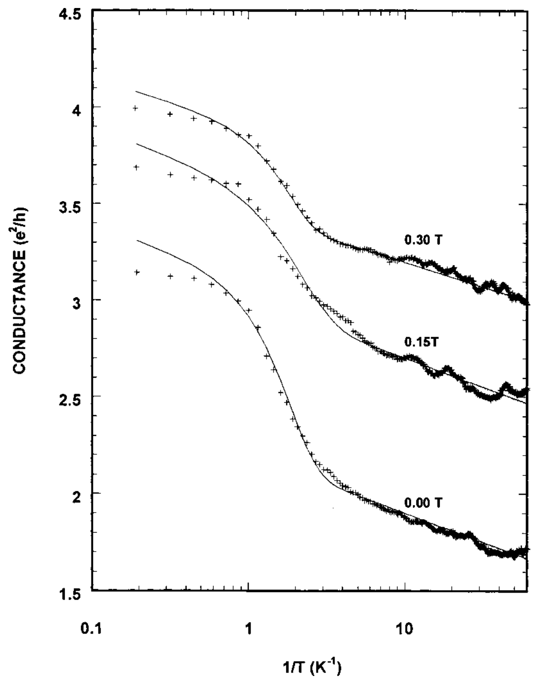

FIG. 5. In this figure, the data of Fig. 4 is replotted along with fits to the form of Eq. (1). 0 T: $G_0=2.2e^2/h$, $G_1=0.13e^2/h$, $G_2=0.90e^2/h$, $T_0=0.54$ K, and $p=2.4$. 0.15 T: $G_0=3.0e^2/h$, $G_1=0.13e^2/h$, $G_2=0.60e^2/h$, $T_0=0.45$ K, and $p=2$. 0.30 T: $G_0=3.5e^2/h$, $G_1=0.11e^2/h$, $G_2=0.45e^2/h$, $T_0=0.55$ K, and $p=2.6$.

ture over the entire range studied in experiment [Fig. 3(a), inset]. When the gates are biased to form the array, however, the resistance *diverges* with decreasing temperature, showing no evidence for saturation at low temperatures. The implication of the curves shown in Fig. 3 is that application of the gate voltage induces a transition from a metallic 2DEG to an insulating quantum dot array. As can be seen from Fig. 4, evidence for the localization persists at magnetic fields as high as 0.3 T, indicating it to be unrelated to a weak-localization effect.

Motivated by studies of the metallic state in two-dimensional electron systems,[11] and by the special symmetry known to exist between the metallic and insulating states,[30] we fit the variation of dot conductance with temperature (T) using the following form:

$$G=G_0+G_1\ln(T)+G_2\exp\left[-\left(\frac{T_0}{T}\right)^p\right]. \qquad (1)$$

Since Eq. (1) contains as many as five independent fitting parameters (G_0, G_1, G_2, T_0, and p), it is worth taking some time to explain how it is obtained. G_0 is thought to represent the contribution of the quantum point contacts to the overall device conductance and is not really a free parameter at all, since its value can be inferred directly from the experimental data. The logarithmic term dominates the conductance at very low temperatures and has also been observed in studies of two-dimensional Si MOSFET's.[11] While the origin of this term remains unclear, it is found to be only weakly affected by a magnetic field and may be associated with a Coulomb interaction effect.[31,32] At intermediate temperatures ($T\geqslant T_0$), the exponential term dominates and is presumed to describe the excitation of carriers across some characteristic energy gap (k_BT_0). While three parameters are used to fit this term, there is actually little flexibility in these. G_2 gives the amplitude of the exponential change, while T_0 determines its onset temperature and p defines the steepness of its variation.

In Fig. 5, we replot the data of Fig. 4 along with functional fits to the form of Eq. (1). The measured conductance variation is clearly well described by the fits, over the entire range of temperature studied and at each of the three magnetic fields. Focusing on the fit parameters obtained for the curves, we note that application of the magnetic field causes an increase in G_0, behavior that is evident as the negative magnetoresistance shown in the inset to Fig. 4. This enhanced conduction is thought to reflect a magnetically induced suppression of backscattering that occurs at the quantum point contacts of the array.[33] In contrast to this behavior, the parameters for the exponential and logarithmic terms are only weakly influenced by the magnetic field, and are also relatively insensitive to changes in gate voltage. The logarithmic term is of order $0.2e^2/h$ in this array, which is comparable to the value reported in studies of Si MOSFET's.[11] In arrays A and B, the localization is most clearly resolved in the low gate-voltage regime, as we illustrate in Fig. 6. This figure reveals a common feature of the localization, namely its persistence in cases where the array is very strongly coupled to its external environment. Also note the absolute magnitude of the conductance change with temperature, in excess of $5e^2/h$, which is more than an order of magnitude larger than theoretical predictions for the weak-localization effect in these structures.[34]

In Table I, we summarize the details of the localization

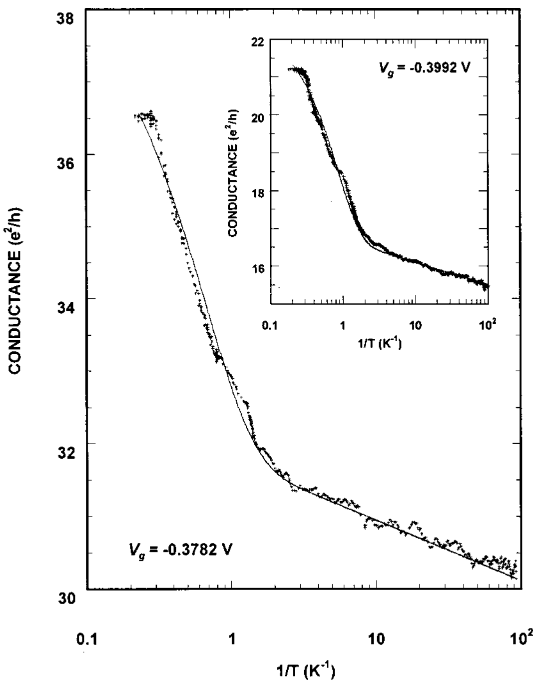

FIG. 6. Variation of resistance with temperature, measured in array A at two different gate voltages (indicated). $V_g = -0.3782$ V: $G_0 = 31.8e^2/h$, $G_1 = 0.36e^2/h$, $G_2 = 5.5e^2/h$, $T_0 = 1.5$ K, and $p = 1.3$. $V_g = -0.3992$ V: $G_0 = 16.7e^2/h$, $G_1 = 0.26e^2/h$, $G_2 = 4.8e^2/h$, $T_0 = 1.2$ K, and $p = 1.4$.

observed in the three arrays. The values shown for arrays A and B were obtained in the low gate-voltage regime, where the resistance shows purely localized behavior. At least within our experimental resolution, the amplitude of the logarithmic term does not seem to vary significantly between the different devices. The parameters for the exponential term are seen to be device dependent, however, which is thought to reflect the differing levels of disorder in the arrays. In Fig. 7, we plot the ratio G_2/G_0 as a function of gate voltage. Results for the three different arrays are shown and are seen to lie on the same curve, suggestive of a common origin. This figure shows that the relative magnitude of the exponential variation becomes more prominent as the arrays are pinched off.

C. Metal-insulator transition in the quantum dot arrays

In Fig. 1(a), the resistance measured at low temperatures falls below its high-temperature value at certain gate voltages, as might be expected for a metallic state. The position and depth of these local minima is found to be well reproduced on successive gate voltage sweeps, suggesting that the gate voltage may be used to induce a re-entrant metal-

TABLE I. Fit parameters obtained for arrays A, B, and C in the localized regime.

Array	G_1 (e^2/h)	T_0 (K)	p
A	0.23 ± 0.16	2.0 ± 0.8	1.3 ± 0.2
B	0.16 ± 0.09	1.4 ± 0.4	1.1 ± 0.3
C	0.20 ± 0.09	0.7 ± 0.2	2.3 ± 0.3

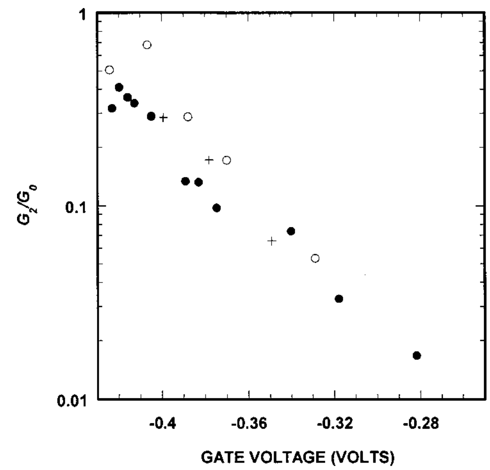

FIG. 7. The ratio G_2/G_0 as a function of gate voltage. Results from all three arrays are plotted here. Array A: crosses. Array B: open circles. Array C: filled circles.

insulator transition in the arrays. To further study this possibility, we have measured the temperature dependence of the resistance at a number of gate voltages for which the resistance shows a local maximum or minimum. In Fig. 8, for example, we show the results of such measurements for array A. At the gate voltages corresponding to a local peak, the resistance diverges with decreasing temperature, indicative of insulating behavior. Further analysis shows that the resistance variation obtained at the peaks can be fitted to the form of Eq. (1), using $G_1 = 0.035\pm0.01e^2/h$, $T_0 = 1.5\pm0.3$ K, and $p = 1.6\pm0.2$ K. While the parameters associated with the exponential term are comparable to those listed in Table I, G_1 is considerably smaller in this regime, suggesting that the localized state may somehow be less robust than that found at lower gate voltages. Also in Fig. 8, we show the temperature dependent variation of the resistance measured at two local minima. In these curves, the resistance tends to zero in the limit of zero temperature, as would be expected for a metallic system. By studying the temperature dependence of the resistance at all minima that drop below their high temperature (resistance-gate voltage) curve, we have been able to confirm the generic nature of this apparent metal-insulator transition. In Fig. 9, for example, curves for array B are plotted and once again show evidence for a metal-insulator transition, with similar characteristics to that noted in Fig. 8.

An interesting feature of the curves in Figs. 8 and 9, is a significant increase in the noise level that occurs at lower temperatures. Further studies of this noise have confirmed its time-dependent nature and reveal possible evidence for switching behavior on time scales faster than the kHz range. While the most likely source of this noise is charge-trapping generated by defects in the heterostructure, it is possible that it actually reflects the formation of novel metal and insulating states in the arrays. More detailed studies are required to confirm this possibility.

D. Influence of illumination and thermal cycling

Subsequent to the measurements described above, a red light-emitting diode was used to illuminate the sample at 0.01 K, increasing the carrier density of the 2DEG to 5.6×10^{11} cm^{-2}. In spite of a small shift in threshold voltage,

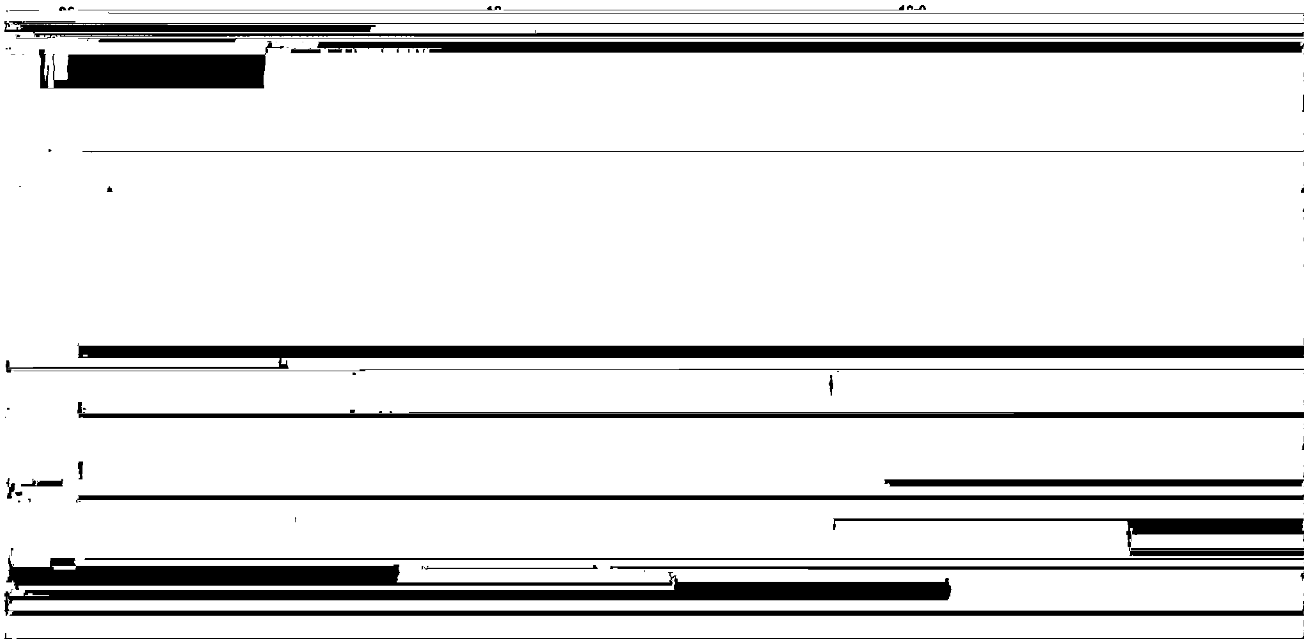

FIG. 8. Observation of a re-entrant metal-insulator transition in array *A*. (a) Expanded view of Fig. 1(a). (b), (c) Temperature dependence of the resistance measured at different resistance maxima and minima [gate voltages are indicated and correspond to the positions marked by the symbols shown in Fig. 8(a)].

the general behavior exhibited by the arrays was found to be unaffected by this illumination. Arrays *A* and *B* continued to show localization at low gate voltages, and a re-entrant metal-insulator transition at higher ones, while array *C* showed only evidence for localization. Similarly, thermal cycling of the sample to room temperature restored the carrier density near to its original value, but did not significantly affect the behavior exhibited by the arrays.

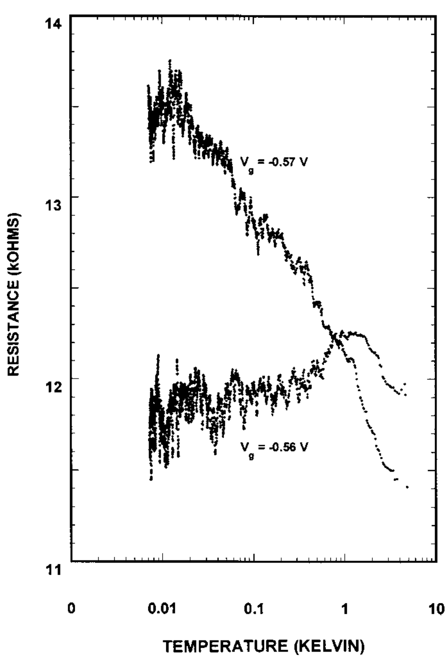

FIG. 9. Temperature dependence of the resistance measured in array *B* at a local resistance maximum ($V_g = -0.57$ V) and minimum ($V_g = -0.56$ V).

IV. DISCUSSION

In the above, we have presented evidence for novel localization, and a possible metal-insulator transition, in split-gate quantum dot arrays. No evidence for these phenomena is found prior to biasing the gates of the arrays, which, once formed, reveal strong variations in behavior from one device to another. In arrays that are thought to feature considerable disorder only localized behavior is seen as the gate voltage is varied, while in presumably less-disordered devices a possibly re-entrant metal-insulator transition is found. The observation of such a transition, in what is presumably a $d<2$ mesoscopic system,[35] has considerable implications for the single-parameter scaling theory of localization. In its original form, this suggested that, in the presence of even the smallest amount of disorder, all states in dimensions less than or equal to two should be localized.[14] A number of experiments have now convincingly confirmed the existence of a metal-insulator transition in two-dimensional systems,[2–13] and this has led to a reformulation of the scaling theory to allow for a change in the sign of the scaling function at some critical conductance.[15] To the best of our knowledge, however, the possibility of a similar transition occurring in systems of lower dimensionality has not been considered to date.

For a partial understanding of the behavior observed in experiment, we appeal to our knowledge of electron transport in open quantum dots.[27,28] The conductance of these devices also shows reproducible oscillations when the gate voltage is varied and these have been interpreted as arising from density of states oscillations.[27,28] The suggestion is that the conductance should be high at gate voltages for which the density of states at the Fermi level is high, while a low conductance is expected when this density of states is low.[27] In dots which incorporate moderate disorder, the first states to localize should be those for which the density of states is

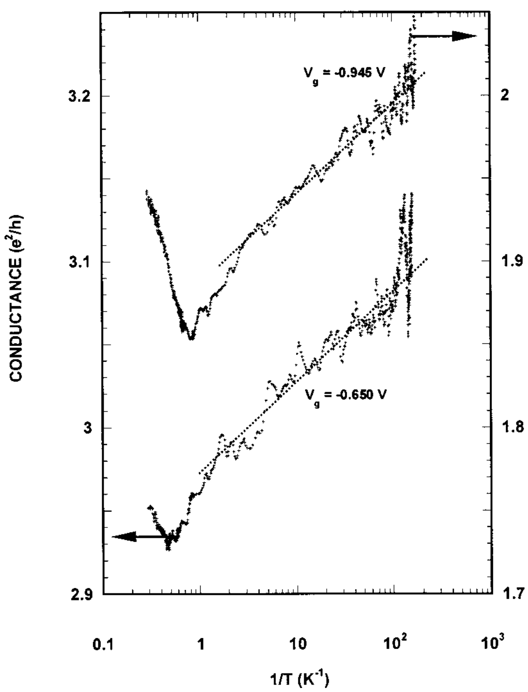

FIG. 10. In this figure, the conductance measured in the metallic regime is plotted as a function of temperature to reveal the logarithmic dependence (dotted lines) predicted in Eq. (2) (Ref. 15). Results shown are for array *A* and the gate voltages are indicated.

low. Consequently, we might expect that a series of metal-insulator transitions should occur as we use the gate voltage to transition between successive resistance maxima and minima. As the gate voltage is progressively lowered towards zero, however, the coupling-induced broadening of the level spectrum should increase. Since the effect of such broadening should be to lower the degeneracy of the density of states, it does not seem unreasonable that the arrays should then exhibit a crossover to purely localized behavior. Equivalently, in dots incorporating strong disorder, we can also understand why only localized behavior should be found as the gate voltage is varied; even when the coupling-induced broadening is reduced, disorder-induced mixing of the level spectrum will continue to be significant.

In discussions of the metal-insulator transition in two dimensions, the role of electron interactions has been strongly emphasized.[1] The strength of these interactions is characterized by the parameter r_s, which is the ratio of the Coulomb energy to the Fermi energy. For the heterostructure wafers we study here, the value of this parameter is of order unity, corresponding to the weakly interacting regime. *Crucially, however, we note that the metallic state observed in the arrays shows very different behavior to that of the undepleted* 2DEG. The resistance of the 2DEG is independent of temperature, while that in the metallic regime decreases *logarithmically* below some critical temperature, which is gate-voltage dependent (Fig. 10). For the curves shown in Fig. 10 this critical temperature is in excess of a degree Kelvin. At other gate voltages, however, it may be much less than 100 mK and further studies are required to establish the significance of this transition temperature. It is interesting to note that the logarithmic temperature dependence found in the metallic regime is similar to that expected for two-dimensional metallic systems, in which Coulomb interactions have been predicted to give rise to the formation of a novel electron state that is *quite distinct from a Fermi liquid*.[15] In this regard, it is tempting to suggest a connection to the Luttinger liquid, which is another correlated electron system that shows non-Fermi-liquid behavior.[36] While further theoretical studies are required to clarify this connection, we suggest that confinement of electrons in the array causes an enhancement of their interaction, compared to the unconfined two dimensional electron gas [i.e., $r_s(array) > r_s(\mathrm{2DEG})$]. According to Dobrosavljević *et al.*, the conductance in the metallic regime is expected to vary as[15]

$$G(T) \propto \ln^{1/\alpha}(T_0/T), \tag{2}$$

where α is a constant that parameterizes how the system approaches the metallic limit as $G \to \infty$. The dotted lines shown in Fig. 10 suggest that $\alpha = 1$ for the arrays, which is actually consistent with the experimental findings of Pudalov *et al.*, who studied Si MOSFET's with high r_s.[11] Our result is therefore suggestive of a cooperative interaction among the electrons in the confined arrays.

A number of features revealed in experiment are worthy of further study. In the localized regime, we are able to fit the temperature dependence of the resistance using the form of Eq. (1). In previous studies of two-dimensional systems, the power law in the exponential term has been found to be close to 0.5,[4,6,7,9] as predicted for variable-range hopping in the presence of a Coulomb gap.[37] The values we find here are somewhat larger than this ($p \sim 1-2$), however, and at present the significance of this variation remains unclear. Also unclear is the origin of the energy that is implied by the parameter T_0. Finally, the source of the disorder that so strongly influences the behavior of the arrays is not understood at present. The electrical properties of mesoscopic devices are known to be critically sensitive to the presence of *individual* impurities.[38] In studies of single quantum dots, we have reported large variations in the phase-breaking time in nominally identical dots.[39] In the GaAs/$Al_xGa_{1-x}As$ heterostructure system, an important source of disorder is the random distribution of Si dopants in the $Al_xGa_{1-x}As$ layer.[40,41] The robustness of the device-dependent variations in behavior to thermal cycling and illumination is inconsistent, however, with the effects of donor-induced potential fluctuations. Rather, a more robust form of disorder, whose origin remains unclear at present, is presumably required.

V. CONCLUSIONS

We have presented evidence for gate voltage-induced localization, and a possibly reentrant metal-insulator transition, in linear quantum dot arrays that are realized using the split-gate technique. No evidence for the localization is observed prior to biasing the gates of the array, and the details of this behavior are found to be strongly device dependent. While the form of the localized behavior can be understood within the framework previously developed for two-dimensional carrier systems, the source of the disorder that so dramatically influences the device behavior remains unclear. In those devices which appear to exhibit a re-entrant metal-insulator transition at higher gate voltages, we have suggested that the transition may arise as the gate voltage sweeps the states of the array past the Fermi surface. The temperature dependence of the resistance observed in the metallic regime is quite distinct to that of the underlying 2DEG, and is suggestive of the formation of a novel electron state. We have suggested that this many-body state may arise through an enhancement of the Coulomb interaction that is generated when electrons are confined in the array. We hope that the studies presented here will stimulate interest in the problem of localization in mesoscopic structures, which appear to provide a unique opportunity for investigating the properties of correlated electron systems.

ACKNOWLEDGMENT

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