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Localization effect in mesoscopic quantum dots and quantum-dot arrays

L.-H. Lin, N. Aoki, and K. Nakao
Department of Materials Science, Chiba University, 1-33 Yayoi, Inage, Chiba 236-8522, Japan

A. Andresen, C. Prasad, F. Ge, J. P. Bird, and D. K. Ferry
Department of Electrical Engineering and Center for Solid State Electronics Research, Arizona State University, Tempe, Arizona 85287-5706

Y. Ochiai
Department of Materials Science, Chiba University, 1-33 Yayoi, Inage, Chiba 236-8522, Japan

K. Ishibashi, Y. Aoyagi, and T. Sugano
Nanoelectronic Materials Laboratory, Frontier Research Program, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
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We discuss the observation of an unusual type of localization in split-gate quantum dots and quantum-dot arrays. While no evidence for its existence is found prior to biasing the gates, the localization persists to conductance values as high as $50\,e^2/h$ and is not destroyed by the application of a weak magnetic field. The carrier density in the dots remains constant over the range of gate bias studied and these characteristics suggest that the localization is quite distinct to that studied previously in two-dimensional semiconductors. We suggest that a confinement-induced enhancement of the electron-electron interaction may be responsible for the localization and propose a simple functional form which allows us to account for its variation as a function of either temperature or source-drain voltage. [S0163-1829(99)52848-8]

Recent interest in the study of localization has been stimulated by the observation of a metal-insulator transition in two dimensions, which may be induced as the carrier density is varied using some suitable gate.[1] In this paper, we discuss the observation of an alternative type of localization, whose characteristics are quite different from those reported in two-dimensional systems. The localization is observed in the low temperature conductance of split-gate quantum dots and quantum-dot arrays, which are mesoscopic devices in which the flow of electrical current is restricted to the undepleted region that is formed *between* two suitable gates. While no evidence for its existence is found prior to biasing the gates, the localization is observed for conductance values as high as $50\,e^2/h$ and is not destroyed by the application of a weak magnetic field. The carrier density in the dots remains constant over the range of gate bias studied and these characteristics suggest that the localization is quite distinct from that studied previously in two-dimensional semiconductors. Indeed, we suggest that a confinement-induced enhancement of the electron-electron interaction may be responsible for the behavior we observe. We also propose a simple functional form for the localization which allows us to account for its variation as a function of either temperature or source-drain voltage.

Electron-beam lithography and liftoff were used to deposit split-gate quantum dots and quantum-dot arrays on the surface of $GaAs/Al_xGa_{1-x}As$ heterojunction substrates with prepatterned Hall-bar geometries.[2] The main results presented here were obtained in studies of three different arrays [Fig. 1(b), left inset], whose lithographic dimensions are summarized in Table I. In order to allow a meaningful comparison of their behavior, these arrays were fabricated on the same chip, in close proximity to each other. The chip was mounted in good thermal contact with the mixing chamber of a dilution refrigerator and cooled in the dark with the gates grounded. Prior to the application of a gate bias, the two-dimensional electron gas (2DEG) was found to have a carrier density of $3.7\times10^{11}\,cm^{-2}$ and a mobility of $210\,000\,cm^2/Vs$, as determined from *in situ* Shubnikov–de Haas and Hall measurements at 4.2 K. With a voltage applied to the gates to form the arrays, similar measurements could also be used to determine the carrier density in the dots, which *was not found to vary over the entire range of gate voltage considered here*.[3] The resistance of the arrays was measured in a four-probe geometry, using standard lock-in detection techniques and constant currents of varying magnitude. With all of the gates grounded, the resistivity of the 2DEG was approximately 80 Ω per square and this value was found to be independent of temperature over the entire range studied [Fig. 1(a)]. The gate voltage could be used to pinch off the quantum point contact (QPC) leads of the component dots completely, although this approach was not adopted here, where we chose to focus instead on the behavior exhibited by *open* arrays whose *total* resistance is less than h/e^2. (In this regime, the transport properties should not be influenced by the Coulomb blockade effect.[4,5])

In Fig. 1(b), we illustrate how the resistance of one of the arrays varies as a function of gate voltage and measurement temperature. The resistance increases as the gate voltage is made more negative, consistent with reducing the number of occupied modes in the QPC leads. The resistance also increases as the temperature is lowered and such behavior is typically associated with a localization effect.[1] In analogy to the localization exhibited by two-dimensional systems,[1] we

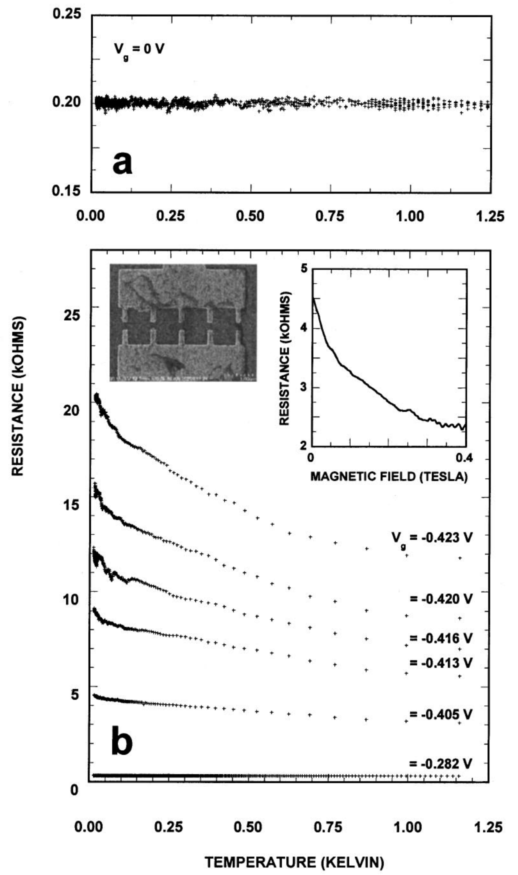

FIG. 1. (a) Temperature dependence of the resistance measured with all gates of the arrays grounded. (b) Main panel: Variation of the resistance of array W with temperature at a number of different gate voltages. Left inset: SEM micrograph illustrating the gate geometry of the arrays. Right inset: Magnetoresistance measurement obtained for array W. All data plotted in (a) and (b) were obtained for a measurement current of 1 nA.

find that the temperature (T) dependent variation of the dimensionless conductance (G) may be fit as

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

In experiment, G_0 varies continuously with gate voltage and is thought to represent the QPC contribution to the overall conductance. The logarithmic term is dominant at low temperatures and is also observed in studies of the two-dimensional metal-insulator transition in metal-oxide-semiconductor field-effect transistors (MOSFET's).[1] The physical origin of this term remains unclear at present, although it may be related to an electron-electron interaction effect.[6] Finally, the exponential term in Eq. (1) represents the thermal activation of carriers across some energy gap (k_BT_0), whose origin is also undetermined at present. Illustrative fits to the form of Eq. (1) are shown in Fig. 2 and the agreement with experiment is clearly good. In Table I we summarize the fit parameters obtained for the three arrays, in measurements performed at a number of different gate voltages. In the lower inset of Fig. 2, the relative magnitude of the exponential term is plotted as a function of gate voltage for the three arrays. The data clearly fall on a single curve with very little scatter, suggestive of a common origin, and reveal that the exponential localization grows in relative magnitude as electrons are more strongly confined in the arrays. Nonetheless, a surprising feature of the localization is its persistence to conductance values that *greatly exceed* e^2/h. In Fig. 1(b), for example, an expanded plot of the data obtained at the gate voltage of -0.282 V shows clear evi-

TABLE I. Fit parameters obtained for the three arrays studied here.

Array	Number of dots	Dot size (μm)	G_1 (e^2/h)	G_2 (e^2/h)	T_0 (K)	p
W	4	1.0×0.6	0.20±0.09	1.7±0.8	0.7±0.2	2.3±0.2
X	3	1.0×0.6	0.25±0.30	4.3±1.4	1.4±0.4	1.1±0.3
Y	3	1.0×0.6	0.30±0.05	4.7±0.9	1.4±0.2	1.3±0.2

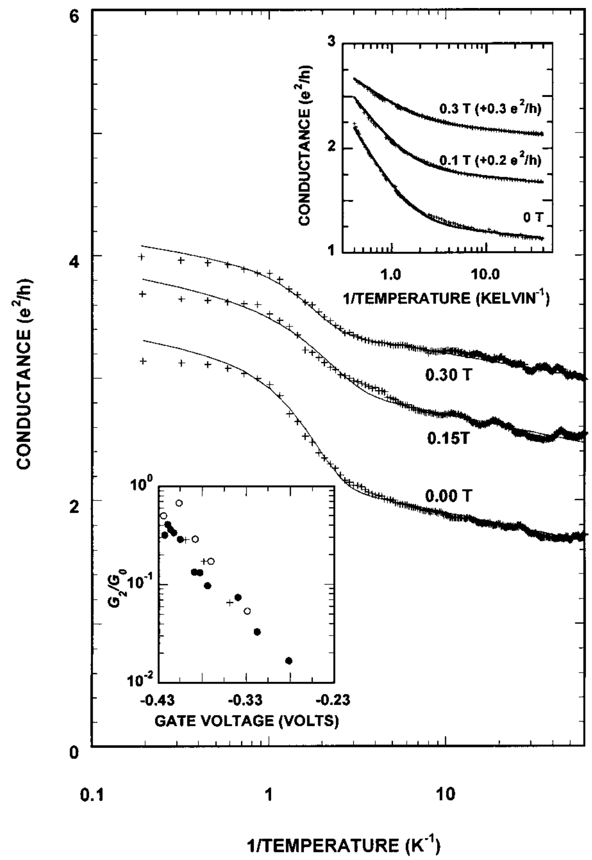

FIG. 2. Main panel: In this figure the variation of conductance with inverse temperature is plotted to illustrate the fits (solid lines) to the form of Eq. (1). The data were obtained for array W at a gate voltage of -0.42 V and a measurement current of 1 nA. Upper inset: Measured variation of conductance with temperature in a 0.6 μm split-gate quantum dot. The data of Fig. 1 are presented along with fits (solid lines) to the form of Eq. (1). 0 T: $G_0=1.30\ e^2/h$, $G_1=0.10\ e^2/h$, $G_2=2.50\ e^2/h$, $T_0=2.8$ K, and $p=0.65$; 0.1 T: $G_0=1.63\ e^2/h$, $G_1=0.10\ e^2/h$, $G_2=1.85\ e^2/h$, $T_0=2.9$ K, and $p=0.65$; 0.3 T: $G_0=1.98\ e^2/h$, $G_1=0.10\ e^2/h$, $G_2=1.05\ e^2/h$, $T_0=3.0$ K, and $p=0.58$. Lower inset: The ratio G_2/G_0 as a function of gate voltage. Results from all three arrays are plotted. Array W: filled circles. Array X: open circles. Array Y: crosses.

dence for the localization, even though the conductance is larger than 50 e^2/h! This characteristic seems to suggest that the localization is associated with the confinement of electrons in the arrays, rather than the depletion of carriers in the QPC's, and we speculate that a geometry-induced enhancement of the effective electron-electron interaction may be responsible.[7] (In two dimensions, for example, it is known that Coulomb interactions should open an energy gap near the Fermi surface.[8])

In the right-hand inset of Fig. 1(b), we show the result of a magnetoresistance measurement of one of the arrays. No evidence for a sharp resistance peak is found near zero magnetic field, suggesting that the temperature dependent variations we observe do *not* result from a weak localization effect.[9,10] This conclusion is further supported by Fig. 2, in which we plot the results of temperature dependent measurements of the resistance at three different values of the magnetic field. The amplitude of the total conductance variation exceeds 1.5 e^2/h at zero field and is significantly larger than theoretical predictions for the weak-localization effect in open dots.[11] (Indeed, although not shown here, measurements at less-negative gate voltages reveal conductance variations as large as 5 e^2/h!) As can be seen from Fig. 2, application of the magnetic field causes a general enhancement of the conductance, which we attribute to the well-known suppression of back scattering at the QPC's.[12] Even at 0.3 T, however, the temperature dependent variation of the conductance is still found to be well described by the form of Eq. (1) (with roughly the same values of G_1, T_0, and p). Such robustness to the application of a magnetic field further suggests that the effects we observe are not related to weak localization. (For the dots we study here, it is expected that a magnetic field of just a few mT should be sufficient to suppress the weak-localization effect.[9])

Localization with similar characteristics to that described above is also found in studies of *single* dots. In the inset of Fig. 2, for example, we show the results of temperature dependent measurements of the conductance of a square quantum dot of size 0.6 μm. The magnitude of the logarithmic term in this dot is comparable to that found earlier in the arrays and is similarly insensitive to magnetic field (at least up to 0.3 T, where the cyclotron orbit begins to fit inside the dot). The exponential fit parameters are also consistent with the trend revealed in Table I. From studies of more than ten different dots, we have found that the localization is strongly device dependent, with some devices failing to show any evidence for its existence whatsoever. Since a detailed discussion of the role of sample dependent variations is given in a separate publication,[13] here we simply note that such sensitivity suggests that a subtle interplay of geometry- and disorder-dependent factors is in fact responsible for the localization.

We have also studied the influence of the measurement current on the localization in the arrays (Fig. 3, inset) and find that this data may be fitted from the obvious connection from Eq. (1) to the form

$$G=G_0+G_1\ln(V)+G_2\exp\left[-\left(\frac{V_0}{V}\right)^q\right]. \tag{2}$$

(V is the measurement voltage.) The general form of Eq. (2), with the values of the prefactors taken from the temperature

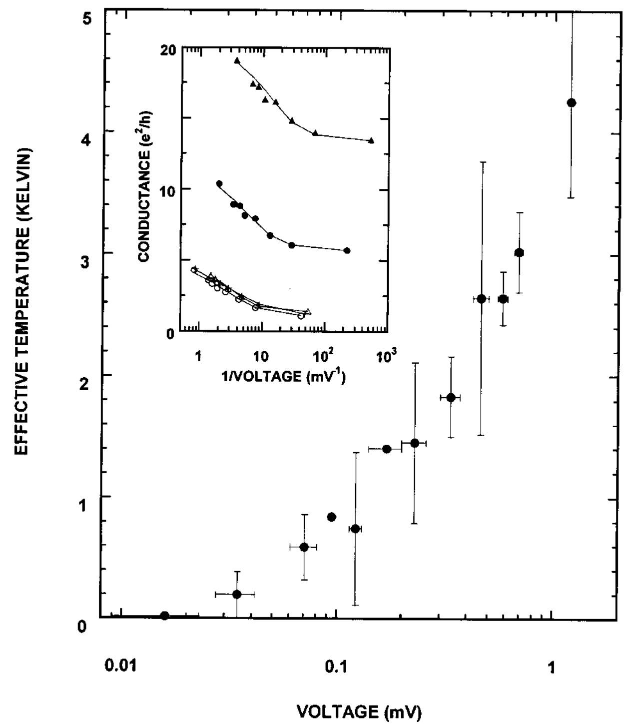

FIG. 3. Main panel: Variation of the effective electron temperature with bias voltage, measured in array W. Inset: Variation of the conductance of array W as a function of the inverse bias, measured at a number of different gate voltages. The symbols are experimental data points while the solid lines are fits to the form of Eq. (2).

dependent data [a small adjustment is made in G_1 as ln(V) obviously differs from ln(T)], is found to fit the data quite well, as expected. From the results plotted in Fig. 3, we obtain $V_0=0.52\pm0.11$ mV and $q=0.72\pm0.11$, neither of which values seem to be correlated to the conductance variation. In the main panel of Fig. 3, we plot the effective temperature that is inferred from the resistance at a given bias voltage, using the above fitting equations. The effective temperature is that at which the resistance of the array is the same as that obtained at the given bias voltage. This temperature clearly shows a critical value where the heating begins to appear. It should be noted that an equivalent plot of the effective temperature, in terms of the bias current, shows a nearly linear behavior of $T_e(I)$. Once the onset bias is passed, the temperature also rises to a linear dependence on the bias voltage. A general trend is that the heating is usually smaller as a function of current for higher conductance samples, but higher as a function of voltage, a result correlated more to the conductance values than to significant voltage or current effects. We can also determine an effective energy-relaxation time from the energy-balance equation[14]

$$e\mathbf{v}_d\mathbf{E}=\frac{k_BT_e}{\tau_\varepsilon}. \tag{3}$$

Of course, we measure neither the velocity nor the field, but Eq. (3) can be related to the measured current and voltage by multiplying both sides by the total number of particles in the device. While most of the voltage drop is in the QPC region, the carriers equilibrate at an effective temperature within the dots and the entire structure is assumed to be described by a

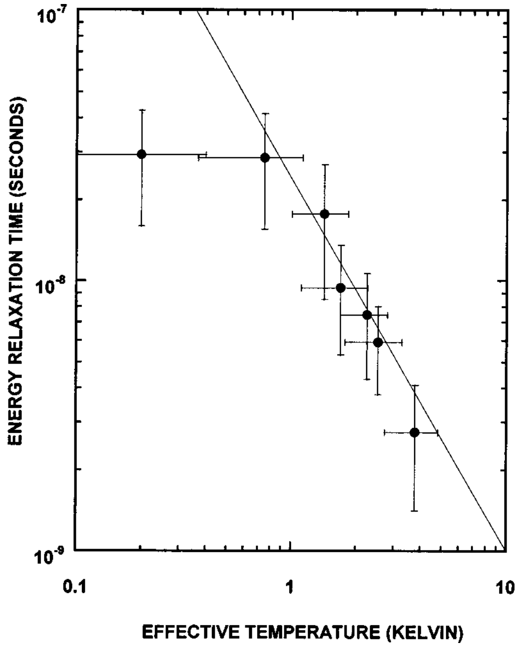

FIG. 4. Variation of the energy relaxation time deduced for array *W*, as a function of the effective electron temperature. The solid line indicates a $T^{-1.5}$ variation.

single temperature. The energy-relaxation time determined from Eq. (3) is plotted in Fig. 4 as a function of the effective temperature. Below a critical temperature, the relaxation time is essentially constant, and then decays with what appears to be a $T_e^{-3/2}$ dependence, as shown by the line. This transition from a constant form to a temperature decay has been seen previously in the phase-breaking time in open quantum dots,[15–17] although there is currently no good theory of either phase breaking or energy relaxation in such structures. The scatter in the data of the last two figures is comparable to the scatter in the values of the various parameter sets obtained from the fits, both in this array and others that have been measured. However, we note that the transition temperature in Fig. 4 is less than half the value of T_0, so that there does not appear to be any direct relationship between this transition and the latter parameter. This break is also well above the temperature corresponding to the mean-level separation in the dots themselves. Some care about the nature of the decay with temperature is also in order, as the selection of the break temperature affects significantly the actual inferred power of this decay. Further study is required to determine if, indeed, this inferred $T_e^{-3/2}$ is the correct behavior. If, for example, the energy is dissipated by the emission of acoustic phonons, a stronger temperature behavior is quite possible.[18]

In summary, we have observed evidence for an unusual kind of localization in mesoscopic quantum dots and quantum-dot arrays. The localization persists at conductance values far in excess of e^2/h and is not quenched by the application of a weak magnetic field. While the mechanism for the localization remains undetermined, we have speculated that a confinement-induced enhancement of the electron-electron interaction in the structures may be responsible. We have also studied the bias voltage-induced heating in the arrays, which appears to be described in terms of a single effective temperature for the electron gas system. Finally, we have also estimated the energy-relaxation time for the arrays, which is found to be larger, by an order of magnitude, than the phase-breaking times that have been measured in single dots.

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