Signatures of the discrete level spectrum in temperature-dependent transport through open quantum-dot arrays

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Temperature-dependent studies of the resistance of open quantum-dot arrays reveal a regime of intermediate temperature (~1–5 K), over which the resistance *increases* exponentially with decreasing temperature. In this Brief Report, we explore the origins of this unexpected localization by studying its correlation to the temperature-dependent variation of the magnetoconductance. Based on these studies, we suggest that the exponential regime corresponds to that over which we transition from strongly broadened to energetically resolved levels in the dots. In order to provide further support for this interpretation, we perform numerical studies of temperature-dependent transport through the quantum dots, and discuss the role that many-body effects may play in giving rise to the behavior found in experiment.

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Interest in the study of electron interactions in weakly disordered systems has recently been revived by the experimental confirmation of a metal-insulator transition in two dimensions.[1] While originally observed in studies of Si metal-oxide-semiconductor field-effect transistors, this transition has now been found to occur in a variety of semiconductor systems when the carrier density is varied in a regime in which the interaction parameter r_s is very much larger than unity ($r_s \approx 20$). More recently, however, we have demonstrated behavior reminiscent of a metal-insulator transition in *weakly interacting* ($r_s \approx 1$) two-dimensional systems, when their carriers are confined within ballistic quantum dots.[2–4] The metallic or insulating behavior is manifest as a logarithmic variation of the conductance at low temperatures (<1 K), the sign of which alternates between positive and negative[4] as the gate voltage is used to sweep the discrete density of states past the Fermi level.[5] The amplitude of the logarithmic term is found to scale inversely with system size[4] and is also found to be insensitive to the application of magnetic fields sufficient to break time-reversal symmetry.[3,4] For these reasons we have previously speculated that this term results from a confinement-induced enhancement of the effective electron-interaction strength in the open dots.[4]

While the logarithmic term provides the main contribution to the temperature-dependent variation of the conductance at temperatures below a Kelvin, very different behavior is observed at higher temperatures than this. Here, the resistance is found to *increase* exponentially with decreasing temperature, in *both* the metallic and insulating states.[2–4] Motivated by studies of the metal-insulator transition in two dimensions,[1] we have suggested that this variation of the conductance may be fitted by the following functional form:[2,3]

$$G \propto \Delta G \exp\left[-\left(\frac{T_0}{T}\right)^p\right]. \tag{1}$$

In studies of the metal-insulator transition, exponential variations of the form of Eq. (1) are usually considered to indicate a transport process that involves the excitation of carriers across some characteristic energy gap ($k_B T_0$).[1] In one recent numerical study, it was suggested that the origin of the energy gap in these dots may simply be the discrete nature of their density of states[6] (this report did not consider the possible influence of many-body effects, however). In this Brief Report, we therefore perform experimental and numerical studies to cast further light on the origin of the exponential resistance variation. Our studies focus, in particular, on the influence of temperature on the *magnetoresistance* of the arrays. At temperatures in excess of 4 K, this magnetoresistance varies smoothly with magnetic field, indicative of a low degree of electron phase coherence in the dots. At lower temperatures, however, reproducible fluctuations emerge in the magnetoresistance, indicating that the density of states becomes well resolved.[5,7–9] Significantly, the characteristic range of temperature over which these fluctuations develop is found to correspond quite well to that for which the exponential increase of resistance is seen in the temperature sweeps. These studies therefore suggest that the exponential variation is associated with a transition from thermally broadened to energetically discrete quantum levels within the dots. Support for this argument is provided by the results of quantum-transport simulations, which reveal a general trend for increasing resistance with decreasing temperature, over the range relevant to experiment.

Quantum-dot arrays were realized using the split-gate technique, in which metal gates with a fine-line pattern defined by electron-beam lithography are deposited on the sur-

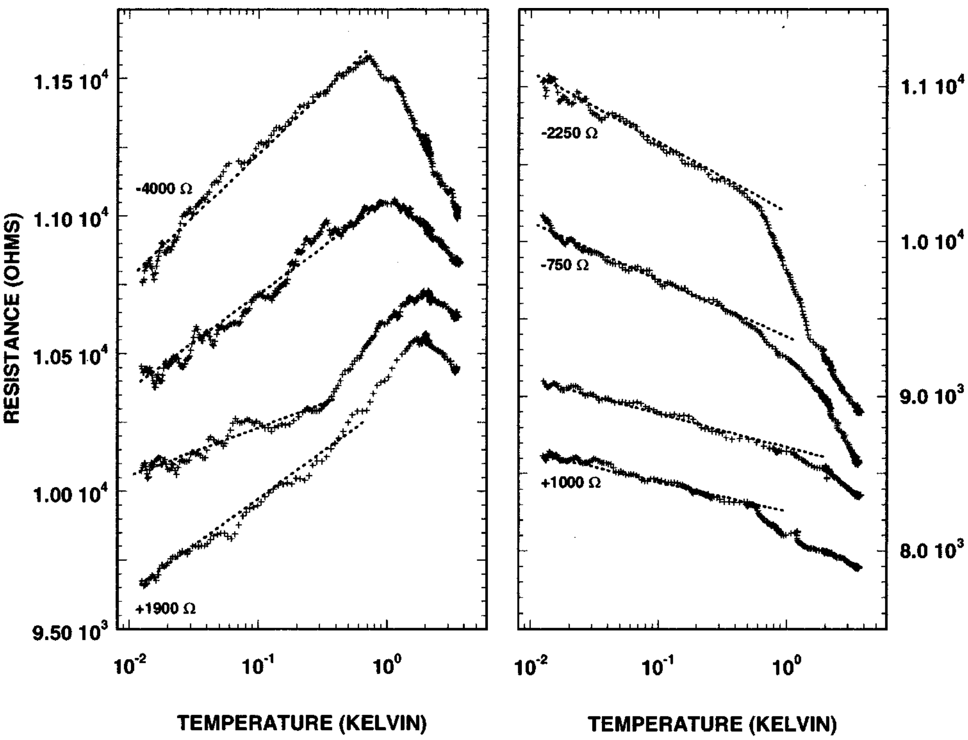

FIG. 1. Variation of resistance with temperature, measured in a three-dot array with lithographic dot dimensions of $0.6\times1.0\,\mu m^2$ (for further details on how such curves are obtained we refer the reader to Refs. 2–4). The dotted line on each of the curves indicates the region of logarithmic conductance variation.

face of a high-mobility $GaAs/Al_{1-x}Ga_xAs$ heterojunction.[2–4] From measurements of the different samples, performed at 4 K, the carrier density and mobility were determined to be $3.8\times10^{11}\,cm^{-2}$, and $0.2-1.2\times10^6\,cm^2/Vs$, respectively. The arrays consisted of three or four series-connected dots, each with nominally identical lithographic dimensions. After biasing the gates to form the arrays, the carrier density within the dots was found to remain essentially unchanged from the bulk value, at least for the range of gate voltages studied here. The samples were mounted in a dilution refrigerator and temperature-dependent measurements of their resistance were made using low-frequency lock-in detection, with small constant currents ($\sim$1 nA) to avoid unwanted heating. Temperature sweeps were undertaken in several different ways, including cooling to the cryostat base temperature over several days to ensure that the sample resistance was accurately, and reproducibly, reflected by the sensing thermometer.

In measurements performed at milliKelvin temperatures, the resistance of the arrays is found to exhibit reproducible oscillations as a function of gate voltage,[2–4] which result as the discrete density of states in the dots is swept past the Fermi level.[5,7–9] By setting the gate voltage to correspond to a local *minimum* in the low-temperature resistance and measuring the resulting resistance variation as a function of temperature, we obtain the metalliclike curves plotted in the left-hand panel of Fig. 1.[4] By biasing the voltage at a local *maximum*, on the other hand, we obtain the insulatorlike curves shown in the right-hand panel. In both of these plots, the dotted lines indicate the logarithmic variation of the resistance at low temperatures, the characteristics of which we have recently discussed.[2–4] Of interest here, is the monotonic increase of resistance with decreasing temperature that we observe in *all* cases, when the temperature is varied in the range of a few Kelvin. As we illustrate in more detail in Fig.

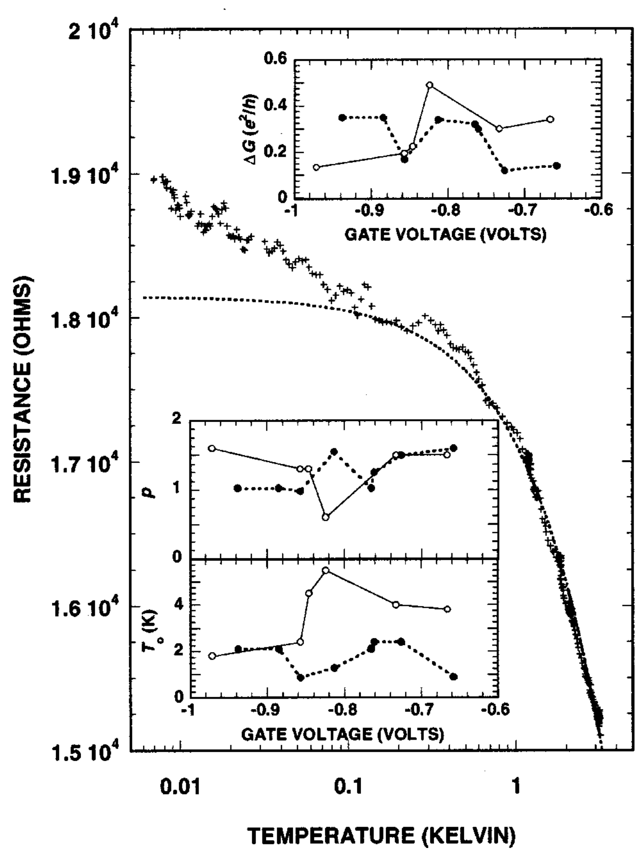

FIG. 2. In the main panel we show the result of fitting the exponential conductance variation of Eq. (1) to the temperature-dependent variation of resistance found in a four-dot array with lithographic dot dimensions of $0.6\times1.0\,\mu m^2$. The insets show the variation of the exponential fit parameters with gate voltage for a three-dot array with lithographic dot dimensions of $0.6\times1.0\,\mu m^2$.

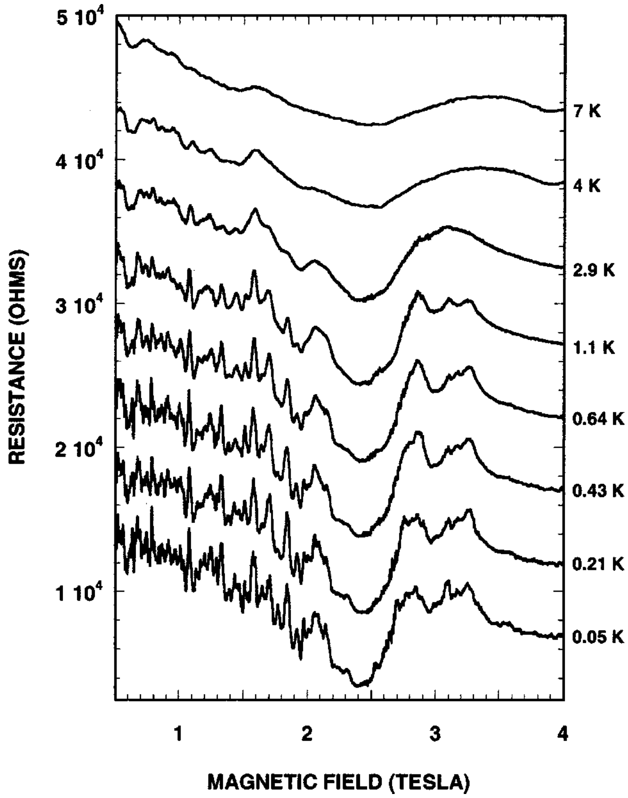

FIG. 3. Temperature-dependent variation of the magnetoresistance of a four-dot array with lithographic dot dimensions of $0.6 \times 1.0\ \mu\mathrm{m}^2$. For the sake of clarity, successive curves are offset from each other by 7500 Ω.

2, we are typically able to fit this resistance variation to the functional form of Eq. (1). In the various insets to this figure, we summarize the dependence of the exponential-fit parameters on gate voltage in one of the arrays. The general variations exhibited here were found to be quite common to all devices studied and may largely be attributed to the difficulty in obtaining reliable fits to the form of Eq. (1) over a limited range of temperature.

In Fig. 3, we plot the magnetoresistance of one of the arrays at a series of different temperatures. At temperatures in the range of a few Kelvin, where electron phase coherence is suppressed,[10] we see that the resistance varies relatively smoothly with magnetic field. As the temperature is lowered, however, reproducible fluctuations emerge in the magnetoresistance, indicating that the discrete density of states is gradually becoming energetically resolved.[5,7–9] The critical feature to note here is the characteristic range of temperature for which the fluctuations become resolved. In Fig. 3, the most dramatic growth of the fluctuations occurs when the temperature is reduced from 7 to ~1 K, which corresponds quite closely to the range over which the exponential increase of resistance is found in the temperature sweeps (Figs. 1 and 2). This observation leads us to suggest that the exponential resistance variation arises as the discrete density of states of the dots becomes energetically resolved.

To provide further support for the analysis of the magnetotransport behavior, we have performed numerical studies

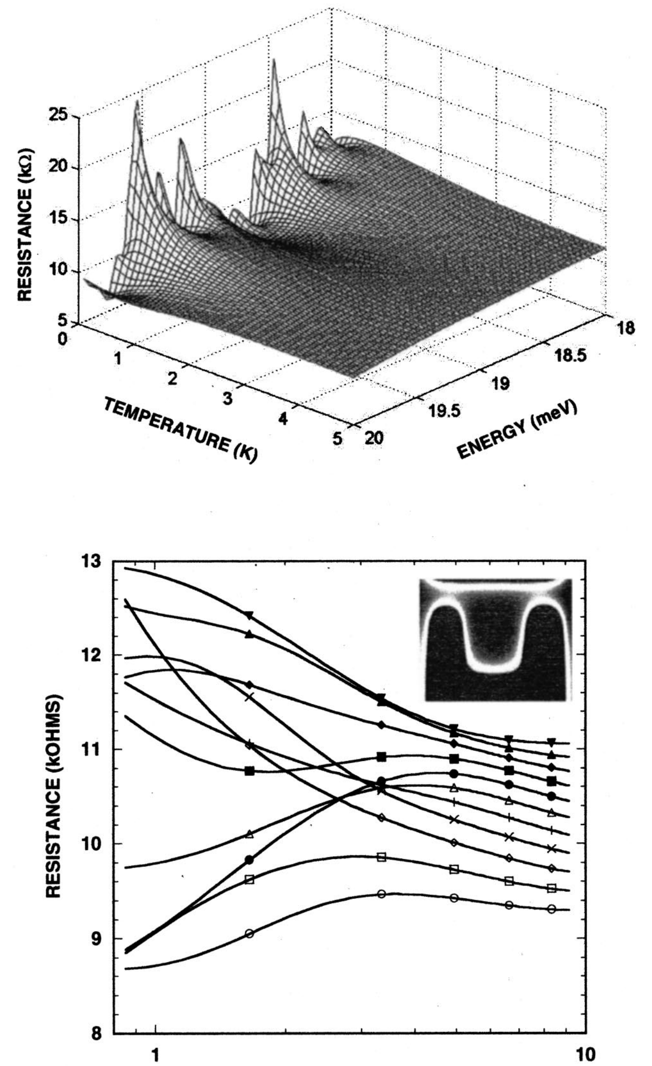

FIG. 4. Upper panel: Computed variation of resistance with energy and temperature for the dot geometry shown as an inset to the lower panel. Lower panel: individual temperature traces selected from the contour in the upper panel. The curves are chosen to correspond to 11, equidistantly spaced, energies between 18 and 20 meV (the bottom curve is for 20 meV, while the upper one is for 18 meV).

of transport in open-quantum dots and quantum-dot arrays. Similar qualitative behavior is found for both of these types of structures,[6] and here we present the results of calculations performed for a single dot with a self-consistently computed potential profile (see the inset to the lower panel of Fig. 4).[9] The calculations proceed by first of all computing the variation of the zero-temperature conductance with energy. A lattice discretization of the single-particle Schrödinger equation[11] is employed here,[7] and yields the transmission probability of the device at any specific energy. With the transmission probability determined in this way, the zero-temperature conductance is then obtained from the Landauer-Büttiker formula. To calculate the conductance at *nonzero* temperatures, the zero-temperature conductance is then convolved with the derivative of the Fermi function:[9,12]

$$G(T,E_F)=\int G(E)\left[-\frac{df(T,E-E_F)}{dE}\right]dE. \qquad (2)$$

Note here that, by implicitly assuming in Eq. (2) that the only effect of increasing the temperature is to introduce thermal smearing of the Fermi function, we neglect the influence of temperature-dependent scattering processes, such as electron dephasing. Previously, however, we have argued that these additional sources of broadening can be included in the convolution, simply by defining an *effective temperature* T^* that is *larger* than the actual temperature.[9]

In the upper panel of Fig. 4, we show the computed variation of the dot resistance as a function of energy and temperature. At the low-temperature end of the range, the resistance fluctuates as the energy is varied, indicating that the discrete density of states is well resolved. (Varying energy in the simulations essentially has the same effect as sweeping the magnetic field or gate voltage in experiment, as we have discussed in Refs. 5, 7, and 9.) At higher temperatures, however, the fluctuations are smeared out and it is the behavior of the resistance in this regime that is of interest here. In the lower panel of Fig. 4, we plot the variation of resistance with temperature at a number of different energies, which are chosen to uniformly cover the energy range between 15 and 20 meV. (While the Fermi level in experiment is closer to 14 meV, the qualitative behavior we discuss here is not found to depend significantly on the choice of Fermi level.) The temperature range plotted here is chosen to correspond roughly to that over which the exponential resistance variation is observed in experiment. At the low-temperature end of the figure, the fluctuating nature of the resistance is apparent in the different curves. At higher temperatures, however, the fluctuations are suppressed, indicating that the discrete nature of the dot states is similarly obscured. In this regime, regardless of their low-temperature behavior, each of the curves shows a region of increasing resistance with decreasing temperature, reminiscent of the behavior found in experiment (Figs. 1 and 2).

Based on the above, we propose the following model to account for the different regimes of temperature-dependent resistance variation found in experiment. At temperatures where the quantum levels of the dots are obscured by thermal smearing (and/or collisional broadening), we expect the semiclassical transport behavior to be highly chaotic in nature.[13] As the temperature is lowered, however, the discrete levels become progressively resolved, and our studies here suggest that this transition is indicated in experiment by the exponential resistance variation. As was mentioned already, such variations are typically understood to result from the excitation of carriers across some characteristic energy gap. In the simple theoretical model developed here, the natural gaps that arise in the density of states of the dot already appear sufficient to give rise to conductance variations of the form described by Eq. (1). It is possible, however, that the nature of the actual gap is modified by Coulomb interactions,[14] and further theoretical studies are called for to clarify this issue. Finally, at sufficiently low temperatures where the density of states is strongly resolved, transport through the dots should depend sensitively on the nature of these discrete states, as well as their filling at the Fermi energy. It is in this regime that the logarithmic variation of the conductance is seen in experiment, which behavior is in many ways reminiscent of that found in studies of the Kondo effect in tunnel-coupled quantum dots.[15] This similarity suggests that the interaction between electrons that enter and leave the open dot should depend significantly on the occupation properties of quantum states at the Fermi energy. The nature of this interaction is not well understood at present, however. Further theoretical work is called for to clarify the details of the many-body interactions in this ultra-low-temperature regime.

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[1] For a recent review, see: E. Abrahams, Ann. Phys. (Leipzig) **8**, 539 (1999), and references therein.

[2] L.-H. Lin, N. Aoki, K. Nakao, A. Andresen, C. Prasad, F. Ge, J. P. Bird, D. K. Ferry, Y. Ochiai, K. Ishibashi, Y. Aoyagi, and T. Sugano, Phys. Rev. B **60**, R16 299 (1999).

[3] A. Andresen, C. Prasad, F. Ge, J. P. Bird, D. K. Ferry, L.-H. Lin, N. Aoki, K. Nakao, Y. Ochiai, K. Ishibashi, Y. Aoyagi, and T. Sugano, Phys. Rev. B **60**, 16 050 (1999).

[4] A. Shailos, M. Elhassan, C. Prasad, J. P. Bird, R. Akis, D. K. Ferry, L.-H. Lin, N. Aoki, Y. Ochiai, K. Ishibashi, and Y. Aoyagi, Phys. Rev. B **63**, 241302 (2001).

[5] J. P. Bird, R. Akis, D. K. Ferry, D. Vasileska, J. Cooper, Y. Aoyagi, and T. Sugano, Phys. Rev. Lett. **82**, 4691 (1999).

[6] F. Badrieh, R. Akis, and D. K. Ferry, Superlattices Microstruct. **27**, 337 (2000).

[7] R. Akis, D. K. Ferry, and J. P. Bird, Phys. Rev. B **54**, 17 705 (1996).

[8] I. V. Zozoulenko, A. S. Sachrajda, C. Gould, K.-F. Berggren, P. Zawadzki, Y. Feng, and Z. Wasilewski, Phys. Rev. Lett. **83**, 1838 (1999).

[9] J. P. Bird, R. Akis, and D. K. Ferry, Phys. Rev. B **60**, 13 676 (1999).

[10] D. P. Pivin, Jr., A. Andresen, J. P. Bird, and D. K. Ferry, Phys. Rev. Lett. **82**, 4687 (1999).

[11] T. Usuki, M. Saito, M. Takatsu, R. A. Kiehl, and N. Yokoyama, Phys. Rev. B **52**, 8244 (1995).

[12] M. Büttiker, Y. Imry, R. Landauer, and S. Pinhas, Phys. Rev. B **31**, 6207 (1985).

[13] R. A. Jalabert, H. U. Baranger, and A. D. Stone, Phys. Rev. Lett. **65**, 2442 (1990).

[14] M. Pollak and M. Ortuño, in *Electron-Electron Interactions in Disordered Systems*, edited by A. L. Efros and M. Pollak (Elsevier, Amsterdam, 1985), pp. 287–408.

[15] W. G. van der Wiel, S. De Franceschi, T. Fujisawa, J. M. Elzerman, S. Tarucha, and L. P. Kouwenhoven, Science **289**, 2105 (2000).