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Photon-induced conductance steps and *in situ* modulation of disorder in mesoscopic electron systems

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We study the conductance of a disordered two-dimensional electron system (2DES) at a mesoscopic length scale in which the localization length can be controlled and varied during an experiment. The localization is induced by a quantum dot layer adjacent to the 2DES, whose charge occupancy can be controlled optically. Under illumination the 2DES conductance increases in sharp steps due to the discharging of individual dots by single photo-excited holes. As the 2DES localization length increases, electron transport evolves from hopping through a small network to direct tunneling across the sample.

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As the dimensions of electronic circuits continue to shrink, device dependent differences in their characteristics become increasingly problematic. For example, statistical variations in the number and location of electron localization centers can be expected to lead to a variation in the conductance of different devices. Al'tshuler predicted that for disordered metals near the Anderson transition the variation in conductance between samples in the limit of zero temperature should be of the order of (e^2/h).[1] It is well known that the particular arrangement of localization centers within a sample produces conductance fluctuations as a function of gate bias or magnetic field which are unique to each mesoscopic sample.[2–5] In this letter we present an experiment in which the configuration of localization centers can be varied systematically at the single electron level within a single sample, during a single experiment. We show that the magnitude of the resulting changes in conductance provides a sensitive probe of the underlying conduction mechanisms.

Conduction in strongly localized electron systems at low temperatures can be described by variable range hopping (VRH)[6–9] over localized states with energies close to the chemical potential μ. In VRH the average hopping length and resistance increases as the sample temperature is reduced, because fewer states lie within k_BT of the chemical potential. In the two-dimensional case of Mott VRH,[10] the resistivity ρ, of the sample is given by $\rho=\rho_0\exp(T_0/T)^{1/3}$, where T is the sample temperature. Although this relationship was derived for non-interacting electrons, it has been found to describe an interacting case.[7] The characteristic temperature T_0 is related to the localization length ξ via[11] $T_0=\beta/g(\mu)k_B\xi^2$, where $g(\mu)$ is the density of states evaluated at the chemical potential and the constant $\beta=13.8$. In turn the hopping length r is approximately given as

$$r \simeq \xi\left(\frac{T_0}{T}\right)^{1/3}. \quad (1)$$

We study here the evolution of electron transport in a strongly localized two-dimensional electron system (2DES) as the localization potential is altered site-by-site at the single electron level *during an experiment*. This exploits the fact that we can tailor the localization potential created by a layer of charged self-assembled InAs quantum dots adjacent to the 2DES with photo-excited holes. Under weak illumination we observe step-like increments in the 2DES conductance, due to the reduction of the charge in one of these dots by one electron. By analyzing the magnitude of these conductance increases caused by the discharge of a single remote charge center, as well as the temperature dependence of the 2DES conductance, we elucidate the transport mechanisms in this structure. The experiments suggest that illumination results in an evolution of the mechanism from a modified picture of variable range hopping through a small network to direct tunneling between the contacts.

Previous studies of transistor structures containing a layer of quantum dots have demonstrated that the 2DES conductance is bistable, due to trapping of charge within the dots.[12–14] When the quantum dots are placed in close vicinity to the 2DESs, several conduction band levels of the dots lie below the Fermi energy and they trap several excess electrons.[14] These charged quantum dots limit the mobility of the 2DES, and can lead to a metal insulator transition.[15] The charge state of the quantum dots can be controlled by optical illumination and applied gate bias. Photo-excited holes created, either within the AlGaAs barriers or GaAs channel, by optical illumination, are attracted to the negatively charged dots. After capture of a photo-excited hole and subsequent recombination, the net negative charge of a dot is reduced by one electron. This reduces the electrostatic effect of the dot upon the 2DES and thereby increases the 2DES conductance. The dots can be recharged with electrons by applying a positive bias to the gate, returning the 2DES to its low conductance state. It was observed that this bistability in the conductance of the 2DES can persist over a period of weeks at 4.2 K.

The sample under study is a modulation doped GaAs/AlGaAs quantum well grown by molecular-beam epitaxy containing a layer of InAs self-assembled quantum dots within one of the barrier layers. The layer structure grown on top of a GaAs buffer was 250 nm $Al_{0.33}Ga_{0.67}As$, 40 nm (n-type Si doped 10^{24} m^{-3}) $Al_{0.33}Ga_{0.67}As$, 40 nm $Al_{0.33}Ga_{0.67}As$, 20 nm GaAs channel, 10 nm $Al_{0.33}Ga_{0.67}As$,

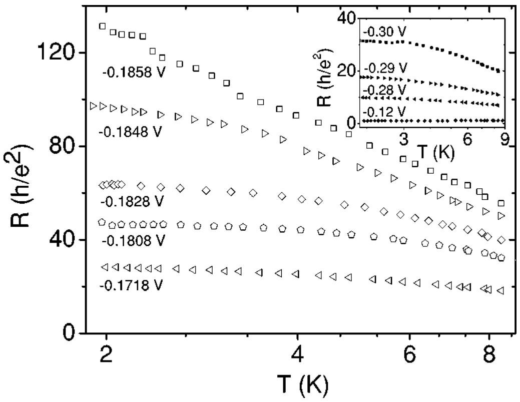

FIG. 1. Resistance as a function of temperature for the mesoscopic sample prior to illumination. Increasing gate voltage shows weaker dependence signifying the tunneling regime. The inset shows the temperature dependence of the mesoscopic sample following illumination. More negative gate voltages were required to observe an activated dependence.

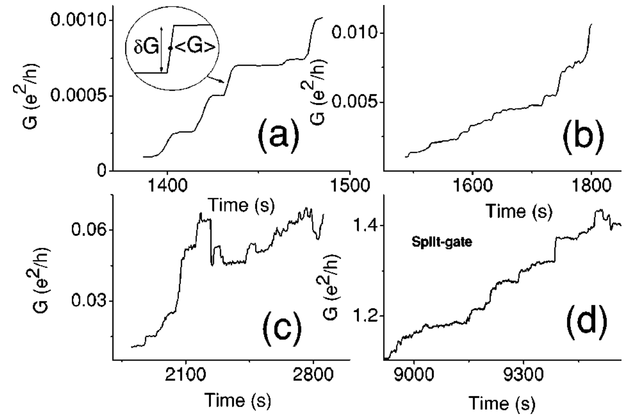

FIG. 2. (a)–(c) Conductance evolution of the mesoscopic sample whilst subject to ultra-low intensity illumination. The three segments are from a single experimental run each spanning an order of magnitude in units of e^2/h. (d) Conductance evolution of an independent sample defined by a split-gate technique.

InAs QD layer, 60 nm $Al_{0.33}Ga_{0.67}As$, 30 nm (*n*-type Si doped 10^{24} m^{-3}) $Al_{0.33}Ga_{0.67}As$, 10 nm GaAs. Transmission electron micrographs indicated that the density of quantum dots was 1.25×10^{14} m^{-2}. The 2DES sheet density and mobility of an ungated structure at 4.2 K, after photoionization of the *DX* centers, were 2.3×10^{15} m^{-2} and 8.2×10^{3} $cm^2\,V^{-1}\,s^{-1}$. Optical lithography was used to fabricate transistor structures, with a 1-μm-wide mesa between the source and drain, covered by a 1-μm-long, semitransparent NiCr gate. Measurements were taken using a standard low-frequency ac lock-in technique. Illumination was provided by a red LED emitting at 650 nm. Following each cool-down, the sample was flashed with illumination to ionize the *DX* centers. For determining the temperature dependence of the sample resistance the power dissipated was kept less than 30 fW.

The resistivity of a macroscopic 2DES with dimensions 750 μm $\times$ 1500 μm fabricated from the same wafer displays a strong temperature dependence. After charging the quantum dots with electrons, so as to form a strongly localized 2DES, the temperature dependence was found to obey the Mott VRH formula closely. Fitting a characteristic temperature to this dependence allowed the average localization length to be determined at different gate biases. As expected, the localization length, and hence hopping length, is seen to increase with the 2DES density.[7] Changing the gate bias from $V_g=-0.18$ V to -0.155 V increased the localization length from $\xi=245$ nm to 530 nm, corresponding to an increase in hopping length at 4.2 K from 700 nm to 900 nm. Thus by altering the gate bias, we can vary the average hopping length around the dimensions of the mesoscopic sample.

Figure 1 plots the temperature dependence of the resistance of the mesoscopic 2DES, recorded for different gate biases. At the lowest 2DES density ($V_g=-0.1858$ V) in Fig. 1, the resistance increases monotonically with decreasing temperature. For higher 2DES densities a plateau with reduced temperature dependence develops at the lowest temperatures.

We can interpret this behavior within a variable range hopping framework which takes into account the mesoscopic dimensions of the sample. The average hopping length increases as the temperature is reduced, according to Eq. (1). For the most negative gate biases in Fig. 1 ($V_g=-0.1858$ V) the transport proceeds by a series of hops across the sample at all temperatures studied, leading to a monotonic increase in resistance with decreasing temperature. For less negative gate biases (higher 2DES density) the localization length is longer. For these gate biases the hopping length can be comparable to the gate length at the lowest temperatures. Thus we associate the plateau regions observed at low temperature with tunneling directly between the contacts.[16] This process is essentially temperature independent because of the availability of a continuous density of states in the contact regions. Consistent with this explanation, the width of the temperature independent region increases with 2DES density in Fig. 1, due to the associated increase in localization length.

The inset to Fig. 1 displays the temperature dependence of the resistivity of the mesoscopic 2DES after relatively strong illumination for 5 s. Illumination reduces the electron occupation of the quantum dots, which smoothes the localization potential induced by the dots and thereby greatly enhances the localization length at a fixed gate bias. This is readily apparent in the inset of Fig. 1 where a more negative gate bias (lower 2DES density) is required to recover activated behavior.

The evolution of the conductance *G*, at 4.2 K while subject to a continuous very weak photon flux is shown in Figs. 2(a)–2(c). For this experiment the quantum dots were first repopulated with electrons by applying a pulse of positive bias to the gate. The gate bias V_g was then set to -0.23 V and the sample subject to a weak photon flux at 650 nm of ~0.8 s^{-1} μm^{-2}. After switching on the illumination, *G* was observed to increase in a series of discrete steps over ~3 orders of magnitude. Each step represents a change in *G* due to a change in the impurity configuration by one. Similar behavior was seen for a wide range of gate biases. Notice

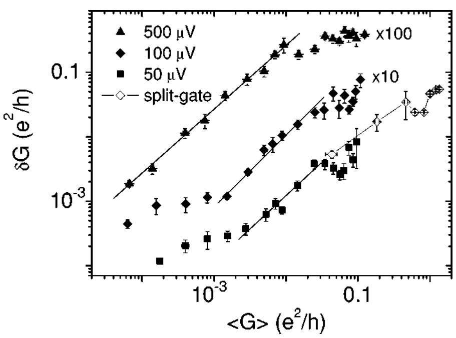

FIG. 3. Statistics at 4.2 K of single-photon induced conductance steps for three different source-drain voltages. Also shown are the statistics of single-photon induced conductance steps in a sample defined with split-gates. Solid lines are fit to the data with slopes $\lambda=1.0$, 1.12, and 1.04 from top to bottom.

that during the initial stages of the experiment (Fig. 2(a)), the conductance increases in a series of relatively large steps. During the later stages (Figs. 2(b) and 2(c)), the *fractional* change in the conductance due to each step is smaller. (Although, of course, the *absolute* changes in conductance are larger in Fig. 2(b) than Fig. 2(a).) At the end of the experiment, the conductance saturates at $G \simeq 0.1\ e^2/h$ whilst exhibiting random telegraph switching, resulting in downward as well as upward steps.[17,18]

The temperature dependence of Fig. 1 reveals that after charging the quantum dots with electrons, the 2DES will be strongly localized at $V_g=-0.23$ V. Thus we can expect the conduction to take place through a small hopping network in the early stage of Fig. 2. After strong illumination the inset of Fig. 1 shows that the resistivity is temperature independent at $V_g=-0.23$ V, demonstrating that tunneling between the contacts dominates. Thus we can access an optically induced crossover in the conduction mechanism during the course of the experiment in Figs. 2(a)–2(c).

A statistical analysis of the conduction steps provides further insight into the evolution of electron transport in the 2DES as the quantum dots causing the localization are discharged one by one. In order to obtain a statistically valid data set, each conductance trace shown in Figs. 2(a)–2(c) was repeated 10 times using identical experimental conditions. This typically yielded 500 steps for analysis at a particular set of conditions. The height of each step (δG) was determined as a function of its midpoint ($\langle G \rangle$), as defined in the inset of Fig. 2. The results of counting the steps at three different source-drain voltages $V_{SD}=50, 100$, and 500 μV are shown in Fig. 3. Each point was obtained by averaging the total number of steps in a suitable conductance window and is shown with the corresponding standard error in $\langle G \rangle$ and δG. The points for $V_{SD}=100$ and 500 μV are offset in Fig. 3, by multiplying δG by factors of 10 and 100, respectively.

Notice in Fig. 3 that the absolute step height δG generally increases with the conductance $\langle G \rangle$. The data taken for the lowest two source-drain biases show clear evidence for a cross-over of the dependence of δG upon $\langle G \rangle$. For low conductances, the step height shows only a weak dependence upon the conductance, while for higher $\langle G \rangle$, δG displays an approximately linear dependence on $\langle G \rangle$. Least squares fits to the latter portions of Fig. 3 yields slopes of $\lambda=1.0\pm0.1, 1.12\pm0.10$, and 1.04 ± 0.15 for the $V_{SD}=50, 100$, and 500 μV curves, respectively.

As discussed above we expect strong localization of the 2DES during the initial stage of the experiment when the conductance is low. This suggests that the low $\langle G \rangle$ part of the curve, for which δG increases only weakly with $\langle G \rangle$, is due to transport through a hopping network. In a hopping network, the transport can occur through several conducting paths across the sample. We suppose that during this phase of the experiment, discharge of some of the dots can alter the network of conducting paths across the sample or create new paths. This produces a relatively large change in the conductance whose magnitude depends only weakly on the conductance of the other paths in the network. This regime was not observed in the $V_{SD}=500$ μV case, which may be because energetic electrons can bypass some hops allowing direct tunneling across the sample.

As the experiment proceeds, the localization length (and thus the hopping length) increases. The hopping network reduces in complexity and eventually, the conduction will be dominated by tunneling directly between the contacts through the repulsive potential induced by the charged dots. It is unlikely that the tunneling probability will be uniform across the sample, but rather will be dominated by a "puncture" in the barrier of high transmissivity.[5,19] The sample retains single photon sensitivity in this regime, because discharging of a quantum dot by a photo-excited hole reduces the height of the tunnel barrier. We ascribe the portions of the curves in Fig. 3 showing a linear dependence of δG on $\langle G \rangle$ to this tunneling process. Such a linear dependence may be understood within a simple model of quantum mechanical tunneling through the potential barrier $V(x)$ induced by the negatively charged dots. Since $G \propto T \propto \exp(-\kappa a)$ where T is the transmission probability and $\kappa \propto \sqrt{V(x)}$, then in a first approximation $\log dG \propto \log\langle G \rangle$, in agreement with the fitted gradients. A complex dependence of δG upon $\langle G \rangle$ can be observed at the highest conductances ($>2\times10^{-2}\ e^2/h$). This may derive from competition between many tunneling paths penetrating the gated area of the sample.

Further evidence for a tunneling mechanism at high conductances is provided by a separate experiment on a quantum dot 2DES with a split gate geometry. This sample provides access to higher conductances than are possible with the full gate devices described above. The epitaxial layer structure of this sample, full details of which are given elsewhere,[20] is similar to that of the full gate structure, except that the dot density is lower. The gap between the split gate has a width of 400 nm and a length of 100 nm. Application of negative voltage to each arm of the split-gate reduces the 2DES density in the underlying regions, leaving a narrow conducting channel in the gap between the gates.[21] Further increasing this negative voltage results in lateral depletion of this narrow channel until the conduction band is raised above μ. Transport can then proceed via tunneling across the potential minimum, as is the case for our experiment.

The dimensions of the split gate ensure that the transport is dominated by tunneling. The split gate has a length of

100 nm, much less than the hopping length under these experimental conditions. We can therefore expect that conduction in the split gate will be controlled by tunneling through the potential barrier caused by the split gate potential and the negatively charged quantum dots. As shown in Fig. 2(d), the conductance of the split gate increases in a series of sharp steps under weak optical illumination, similar to those seen for the full gate device. Each step is due to the capture of a single photo-excited hole by a quantum dot, which reduces the height of the tunnel barrier through the split gate.[20] The height of the conductance steps which we observe under constant illumination at $V_{SD}=20\ \mu V$ for the split gate is also shown in Fig. 3. Notice that the magnitude of the conductance steps in the split gate follows the same trend as in the full gate 2DES. This is further evidence that tunneling dominates in both types of structure at these conductances.

In summary, we have presented a 2DES system in which the localization potential can be controlled optically. Through the capture of single photo-excited holes, remote charge trapped in a quantum dot layer can be reduced electron by electron, resulting in sharp step increases in the 2DES conductance. After charging the dots with electrons, the 2DES is initially strongly localized, and transport occurs via a small network of hops. This explains the observation of activated transport and a weak dependence of the magnitude of the photon induced steps on the conductance. When the hopping length approaches the gate length, conduction electrons can tunnel directly across the active area. This process is characterized by temperature insensitivity and a linear dependence of the photon induced conductance step heights on the conductance. These experiments are the first to access conductance fluctuations over such a wide range of conductance. This is a direct consequence of being able to repeatedly change the configuration of impurities in a single sample.

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