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Hopping conduction and magnetoresistance of a GaAs/Al$_x$Ga$_{1-x}$As quantum well with embedded InAs dots

L. Li,[1] Gil-Ho Kim,[1,*] K. J. Thomas,[1] and D. A. Ritchie[2]

[1]*Department of Electronic and Electrical Engineering, and Sungkyunkwan University Advanced Institute of Nanotechnology, Sungkyunkwan University, Suwon 440-746, Korea*

[2]*Cavendish Laboratory, J J Thomson Avenue, Cambridge CB3 0HE, United Kingdom*

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Magnetoresistance and temperature-dependent conductance are measured in the sample made of a GaAs/Al$_x$Ga$_{1-x}$As quantum well with self-assembled InAs dots. Conductance is analyzed by Mott's hopping theory; the localization lengths have been extracted at various gate voltages. The sample is in the transition from near to metal-insulator to the deeply hopping regime with the combined effect of the long- and short-range scattering potentials. The magnitude of the negative magnetoresistance increases with increasing negative gate voltage. The magnetic-field dependence of the resistance can be explained by the theory of the interference model of hopping electrons.

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The advancement of semiconductor technology allowed us to achieve a variety of electron systems, one of which is the self-assembled InAs quantum dots embedded in two-dimensional (2D) electron gases formed in GaAs/Al$_x$Ga$_{1-x}$As heterostructures. In recent years there has been increased interest in the quantum transport properties of these systems. The InAs dots can be considered as random repulsive scattering centers that interact with the electrons in the 2D system and modify the scattering potential.[1,2] It has been shown that this system has the charge trapping effect, which holds the potential to be used in low power memory devices.[3]

In this work, we study the electron transport in the variable range hopping (VRH) regime. The conventional picture of hopping considers that localized states are formed by individual impurities. The lower the temperature, the larger the separation of the localized states between which a typical hop can take place. When lowering temperature further, the conductivity of a strongly localized systems tends to zero. Applying a magnetic field has several effects on the hopping process of an electron. First, the magnetic field shrinks the wave function of the localized states[4] and results in a positive magnetoresistance (MR). Second, the destructive interference effect from different possible tunneling paths can be destroyed by applying a magnetic field (B), causing negative MR linear or parabolic with B.[5,6] In an approach by the authors of Ref. 7 from the interference model, it is found that the magnetic field can lead to a correction to the localization length in 2D samples that results in negative MR with a field dependence $\ln(\frac{\rho(B)}{\rho(0)}) \sim B^{1/2}$.

The 2D electron system is formed in a GaAs quantum well (100 plane). The 20-nm-wide quantum well is modulation-doped from both sides and separated by spacer layers of thickness 40 nm. In the middle of the quantum well, a few monolayers of InAs are introduced. Due to lattice mismatch, a strain is produced in the material that results in the formation of InAs dots after an initial 2D wetting layer.[8] Figure 1 is the transmission electron microscope (TEM) image of the sample showing the interface where the InAs dots are formed. The majority of dots have a size of 28 nm in diameter. Dots are not evenly distributed in the whole area. In densely populated areas, the dot density is about 1×10^{10} cm^{-2}, thus the average separation is about 50 nm. In sparsely populated areas the average separation is larger. The sample has a Hall bar geometry with a width 60 μm and a length 616 μm. A metallic gate is deposited on the top of the surface to control the 2D electron density. Measurements were done with the low-frequency lock-in technique in a variable temperature insert with a base temperature of 1.4 K.

At zero gate voltage, resistivity ρ of the sample at 2.0 K is 7.83 kΩ; from $\rho = \frac{h}{e^2}\frac{1}{k_F l}$, the parameter $k_F l$ is found to be 3.3, where k_F is the Fermi wave number and l the mean free path. In a metallic state, $k_F l >> 1$, i.e., the momentum scattering length is much larger than the wavelength. The above calculated $k_F l$ indicates that transport is close to the metal-insulator transition at $V_g = 0$ V. The electron density of the sample is measured from low-field Hall resistance. As an approximation, we use the free-electron model ($R_{\text{Hall}} = \frac{B}{en}$) to obtain the electron density $n = 1.6 \times 10^{11}$ cm^{-2}. It has been shown that for noninteracting fermions, this expression is valid within localization theory.[9] For this electron density in modulation-doped GaAs/Al$_x$Ga$_{1-x}$As structures with a spacer layer, the typical mobility would be (1–10) $\times$ 10^5 cm^2 V^{-1} s^{-1} in the absence of InAs dots in the well.[10] In contrast, the mobility of our sample is 5.2×10^3 cm^2 V^{-1} s^{-1}. The large decrease in the mobility is due to scattering from the InAs dots, which act as short-range scattering centers.

Temperature-dependent conductances are measured from 3.4 to 40 K. With decreasing temperature, the conductance decreases at all applied gate voltages. In our sample, the dots are buried within an electron gas. Applying a negative gate voltage increases the strength of disorder due to reduced screening of the impurity potential. Therefore, electrons become strongly localized in impurity sites [in our case including the InAs dot states (short-range scatters) as well as the doped ion states (long-range scatters)]. At low temperatures in a process assisted by phonons or electrons, electrons hop from one site to another, depending on the spatial separation and energy of these two sites. This is the regime of variable range

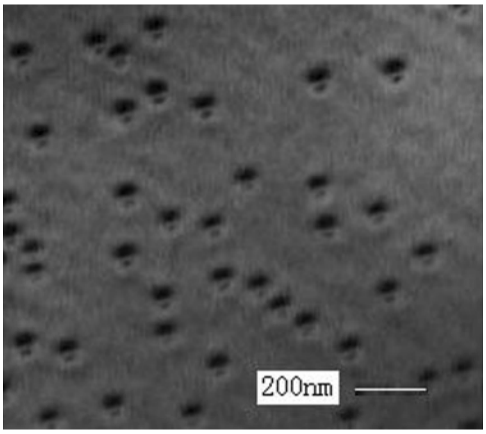

FIG. 1. TEM image of the InAs dots in the sample. The scale bar on the right bottom represents 200 nm.

hopping conduction of electrons. In the case of noninteracting electrons, the conductivity follows Mott's law,[11]

$$\sigma \sim \frac{\gamma e^2}{k_B T} \exp\left[-\left(\frac{T_0}{T}\right)^{1/3}\right], \tag{1}$$

$$T_0 = \beta_M (g_0 \xi^2)^{-1}, \tag{2}$$

where γ is a constant with dimension of frequency relating to phonon or electron energy while in phonon- or electron-assisted hopping, $\beta_M = 13.8$, and g_0 is the density of localized states at the Fermi energy. ξ is the localization length.

In the case of interacting electrons, there is a Coulomb gap appearing at the Fermi level, and the temperature-dependent conductance follows $\exp[-(T_0/T)^{1/2}]$. This is Efros-Shklovskii (ES) hopping, and in a GaAs/Al$_x$Ga$_{1-x}$As system, a clear transition from Mott hopping to ES hopping has been observed at low temperatures around 1 K.[12] Our results support Mott hopping rather than ES hopping behavior. Figure 2 shows that at lower temperatures, $\ln(GT)$ has a linear dependence on $T^{-1/3}$ (G is the conductance measured by the two-terminal method). Nonlinearity at the higher-temperature region shows the transport is entering into a different conducting regime, i.e., activated transport or nearest-neighbor hopping, which is not the subject of this paper. The linear region spans a larger temperature range at higher negative gate bias. From the linear fit of the low-temperature data, the Mott hopping parameter T_0 is obtained, which is 4.4×10^2 K for $V_g = -0.04$ V and 4.0×10^3 K for $V_g = -0.15$ V, respectively. The localization length ξ is then obtained from Eq. (2). Here we take the 2D constant density of states $g_0 = \frac{m^*}{\pi \hbar^2}$, where m^* is the effective mass of an electron, $0.067 m_0$. ξ changes from 35 to 12 nm when V_g is varied from -0.04 to -0.15 V (see details in the Fig. 2 caption). For $|V_g| < 0.04$ V, electron conduction is not VRH. This is examined by studying the plot of $\ln(GT)$ as a function of $T^{-1/3}$, which does not show the well-defined linear region. As V_g is varied from 0 ($k_F l = 3.3$) to -0.12 V ($k_F l = 0.14$), the system changes from near the metal-insulator transition to the deeply hopping regimes.

Typical hopping length can be estimated from $\frac{\xi}{3}(\frac{T_0}{T})^{1/3}$. It is found at 4.0 K to be 57 nm for $V_g = -0.04$ V and decreases to 39 nm for $V_g = -0.15$ V. Considering the average separation (50 nm) of the InAs dots, the hopping conduction must take place not only via the dot states solely, but also via other impurity states. An electron is "blind" in looking for the optimized hopping site. It is not able to "see" much difference between the dot site and the impurity site. What is important is the spacial position and the energy of these sites.

The localization lengths we extracted from our results are comparable with previous reports.[13,14] Reference 13 has a system of InAs dots buried between Al$_x$Ga$_{1-x}$As barriers with a dot density about 10^{11} cm^2 and gives the localization length of 25 nm. Reference 14 has a value of 25–105 nm with variation of gate voltages in a 2D gas formed in a GaAs/Al$_x$Ga$_{1-x}$As heterostructure with no InAs dots.

We also measured the MR of the sample at 2.0 K in perpendicular magnetic field. The symmetry of the MR was checked by running the field to negative so that no Hall resistance is incorporated in MR. In all four fixed-gate voltages, results show large negative MR at low field with a traceable feature of the Shubnikov–de Haas (SdH) oscillations, see Fig. 3. Large negative MR is a typical feature for a GaAs/Al$_x$Ga$_{1-x}$As 2D system with large disorder, and has previously been observed with and without InAs dots in the structure.[14,15]

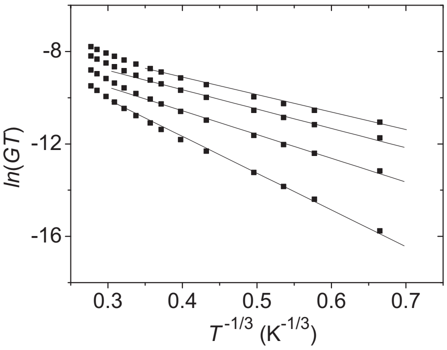

FIG. 2. Temperature-dependent conductance. From top to bottom, the gate voltage is set at -0.04, -0.08, -0.12, and -0.15 V. Symbols are measured results, and the curve is the linear fit of the data. For the four fixed-gate voltages from top to bottom, the localization lengths are 35, 31, 23, and 12 nm; typical hopping lengths are 57, 54, 49, and 39 nm.

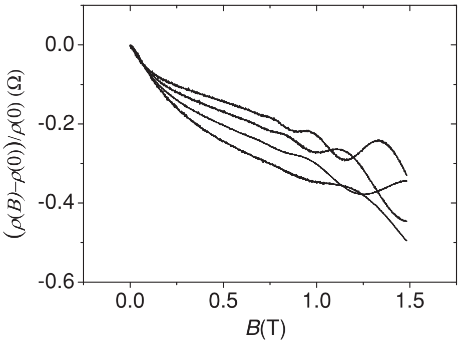

FIG. 3. Magnetoresistance as a function of magnetic field, B. The measurements are performed at 2.0 K. From top to bottom, the gate voltage is fixed at 0, -0.04, -0.08, and -0.12 V. For the gate voltage at 0 V, the sample does not show hopping behavior.

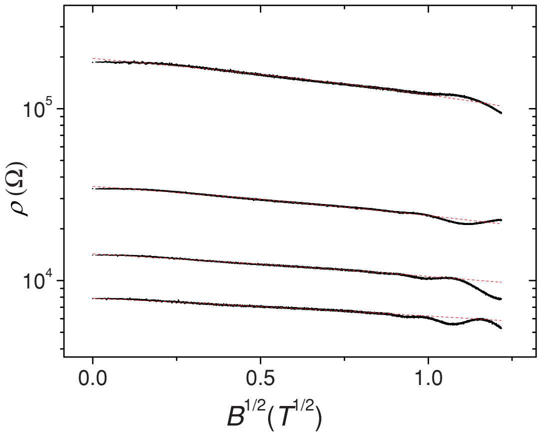

FIG. 4. (Color online) Magnetoresistance for four gate voltages $V_g = 0, -0.04, -0.08$, and -0.12 V from bottom to top. Dashed lines are linear fits of the resistance in logarithmic scale to $B^{1/2}$. Note in this plot at field $B > 0.01$ T, if we ignore the feature of the Shubnikov–de Haas oscillations of the resistance, the field dependence of the curves is linear and the slopes of the four sets of data are approximately the same.

Our results on the MR do not support the linear or parabolic field dependence as predicted by Refs. 6 and 5, but are in good agreement with the description of the interference model.[7,16] We plot the resistivity in logarithmic scale as a function of $B^{1/2}$ in Fig. 4. Except for the deviation at very small field $B < 0.01$ T, the linear dependence is well defined in the whole field range if we ignore the SdH oscillations for all four fixed-gate voltages. Even though for $V_g = 0$ the temperature-dependent conductance does not show well-defined VRH behavior, the magnetic-field dependence of MR is maintained. It has been predicted that the interference model applies to the deeply hopping regime as well as in the near metal-insulator transition in the hopping side, with minor modifications.[7] Inspired by this prediction, we assume that it may be possible for the electron to enter the VRH regime at zero gate bias when the temperature is decreased further. We leave this for future investigations. The slope of the linear dependence has a very slight increase when increasing negatively the gate voltage. Similar field dependence has been observed in Ref. 14 in a disordered GaAs/Al$_x$Ga$_{1-x}$As heterostructure in low magnetic field. In their sample, dopants are not separated by a spacer layer to enhance the impurity scattering strength. Similar results are also discussed in Ref. 17 in 2D thin indium oxide films.

In this work, we have carried out temperature-dependent conductance and magnetoresistance measurements in a 2D electron system with self-assembled InAs quantum dots. It is found that conduction at high negative gate voltages can be described by Mott's theory in the VRH regime. We have demonstrated that both the InAs dots and the impurities contribute to the electron transport. The negative MR is consistent with the interference model in the hopping regime. The same field dependence is observed when the transport is in the vicinity of the metal-insulator transition. Further theories are needed to fully understand the results.

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[*] Corresponding author: ghkim@skku.edu

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