Metal-Insulator Transition at B=0 in an AlGaAs/GaAs Two-Dimensional Electron Gas under the Influence of InAs Self-Assembled Quantum Dots

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We report the observation of a metal-insulator transition in zero magnetic field in a two dimensional electron gas under the influence of a plane of InAs self-assembled quantum dots located at 30 Å below the AlGaAs/GaAs heterointerface. The transition is observed as a function of temperature and electric field at B=0. A scaling analysis yields exponents similar to those obtained for Si MOSFET's . We suggest that the disorder introduced by the quantum dots plays a crucial role.

I Introduction

In an important paper of 1979 based on scaling theory of localization, Abrahams *et al.* have shown that a two-dimensional system without interactions was expected to behave as an insulator in zero-magnetic field [1]. Since then, it has been a general belief that there is no metallic regime in 2D at T = 0, contrary to what happens in the 3D case. The metal-insulator transition (MIT) at B = 0, first reported for a Si metal-oxide-semiconductor field-effect transistor (MOSFET) by Kravchenko *et al.* [2], has thus generated a great interest in the field. Experimentally, the MIT was further confirmed not only in Si MOSFET's [3-6] but also for holes in SiGe quantum wells [7] and holes in AlGaAs/GaAs structures [8,9]. All the samples used there were optimized towards low disorder (clean samples) and large electron-electron (e-e) interaction (large effective carrier masses). It was also clear that a scaling analysis of the data (as a function of temperature or electric field) is essential to characterize the metallic and the insulator states [4], even when including interactions [10,11].

Coulomb interaction is believed to be in the heart of the MIT [12,13] and, in fact, the reported ratio E_{e-e}/E_F is of the order of 10 for a MIT [3-9]. Very recently, however, we have reported on the observation of a MIT in an AlGaAs/GaAs two-dimensional electron gas (2DEG) under the influence of InAs self-assembled quantum dots (SAQD) [14]. This result is striking because our samples' parameters are rather different from the ones in the previous studies. First, the 2DEG is highly disordered due to the proximity of the SAQD. Second,

$$\frac{E_{e-e}}{E_F} \propto \frac{m^*}{\varepsilon\sqrt{N_s}} \qquad (1)$$

and, for electrons in GaAs, one has a smaller effective mass m^* and a slightly higher dielectric constant ε than in the previous papers. Since the present MIT occurs for about the same carrier density N_s, in our samples the e-e interaction energy E_{e-e} is of the order of the electronic kinetic energy E_F ($E_{e-e}/E_F \simeq 0.9$). It seems unlikely that this weak e-e interaction could be solely responsible for the observed metallic phase. In this paper we show the results of a scaling analysis and suggest that the presence of the SAQD might drive the observed MIT.

The samples used in this work are described in detail in Ref. 15. A layer of InAs SAQD is embedded 30 Å from the interface AlGaAs/GaAs where the 2DEG forms. Since the substrate was not rotated during the growth of the dot layer, we found a gradient of dot density across the wafer [15]. We will concentrate on the first and second highest dot density samples, A ($1 \cdot 10^{11}$ dots/cm^2) and B ($7.9 \cdot 10^{10}$ dots/cm^2). Gated Hall-bar geometries (20 μm width, 40 μm between voltage probes) were defined by conventional photolithography. The samples were immersed in the mixing chamber

of a dilution refrigerator (base temperature 60 mK). Standard low-frequency lock-in techniques were used to measure the four-point resistivity, keeping the current as low as 1 nA. A dc setup was also used for double-checking and no quantitative differences were found.

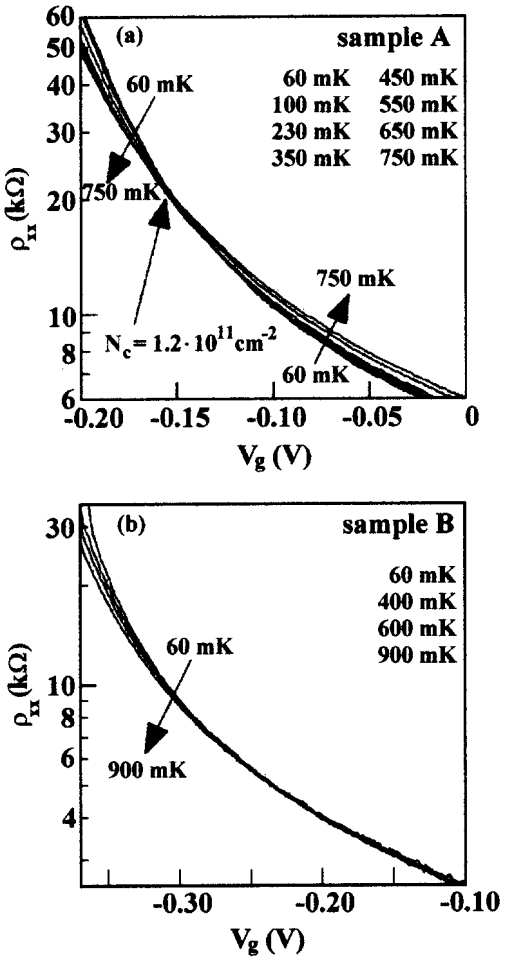

Figure 1. Temperature dependence of the resistivity as a function of gate voltage for samples (a) A and (b) B. A crossing point of the traces in (a) characterizes a MIT.

Fig. 1 shows traces of the longitudinal resistivity ρ_{xx} as function of gate voltage, taken at increasing temperatures T for samples A [Fig.1(a)] and B [Fig. 1(b)]. The last exhibits the "usual" behavior for 2DEG's: the resistivity increases as the temperature decreases (the insulator behavior predicted by Abrahams *et al.* [1]), for all the measured N_s. Sample A however, shows a crossing point of the resistivity traces at a critical carrier density $N_c = 1.2 \cdot 10^{11}$ cm^{-2}. This crossing point occurs close to $\rho_{xx} = h/e^2$ and divides the data into two distinct regions: $N_s < N_c$, where ρ_{xx} decreases for increasing T (insulator); and $N_s > N_c$, where ρ_{xx} surprisingly increases for increasing T, characterizing the existence of a metallic phase. Although being similar to the data of Kravchenko *et al.* [3], the temperature dependence of ρ_{xx} is weak in our sample. As a consequence, the crossing point is blurred and an error bar should be included for N_c.

A similar feature is observed for the electric-field (E) dependence of ρ_{xx} for a fixed T. Fig. 2 shows ρ_{XX} vs. E traces for different N_s plotted from the original i vs. V curves. Again, sample A [Fig. 2(a)] exhibits a region where ρ_{xx} decreases for decreasing E (metallic), in addition to the usual insulator behavior is present. Sample B, in other hand, shows no signs of a metallic phase, consistent with the T-dependence data. The ρ_{xx} vs. N_s traces for increasing current (not shown) exhibit a crossing point similar to the one in Fig. 1(a), at $N_c = 1.2910^{11}$ cm^{-2}.

To further reinforce that our data shows an actual MIT we carried out a scaling analysis. According to Ref. 4, the resistivity is expected to scale with temperature as

$$\rho_{xx}(T, N_s) = f\left(|\delta|/T^{\frac{1}{\nu z}}\right) \qquad (2)$$

and with electric field as

$$\rho_{xx}(E, N_s) = g\left(|\delta|/E^{\frac{1}{\nu(z+1)}}\right), \qquad (3)$$

where $\delta = (N_s - N_c)/N_c$, ν (z) is the correlation length (dynamical) exponent [16]. Comparing the results of both scaling processes it is possible to determine the exponents separately. Let us focus on the data of Fig. 2(a). Scaling according to (3) would be successful when by choosing the appropriate exponent $\frac{1}{\nu(z+1)}$ all the curves collapse into two distinct (metallic and insulator) branches. Fig. 3 shows ρ_{xx} as a function of $\frac{|\delta|}{T^{\frac{1}{\nu(z+1)}}}$ corresponding to the best collapse of the data of Fig. 2(a), which yields $\nu(z+1) = (4.5 \pm 0.3)$. Applying the same procedures to the T dependence of ρ_{xx}, we find $z\nu = (2.6 \pm 0.8)$ (the large error bar reflects the uncertainty in N_c, as discussed above). The final values for the scaling exponents are $z = (1.4 \pm 1.2)$ and $\nu = (1.9 \pm 1.1)$, in the same range as those reported for Si MOSFET's [4]. They also approach the theoretical values $z = 1$ (interacting system [16]) and $\nu = 4/3$ (from percolation theory [13]). Although the scaling results might give us a hint on the origin of the MIT in our sample, we do not attempt to interpret these numbers due to their large error bars.

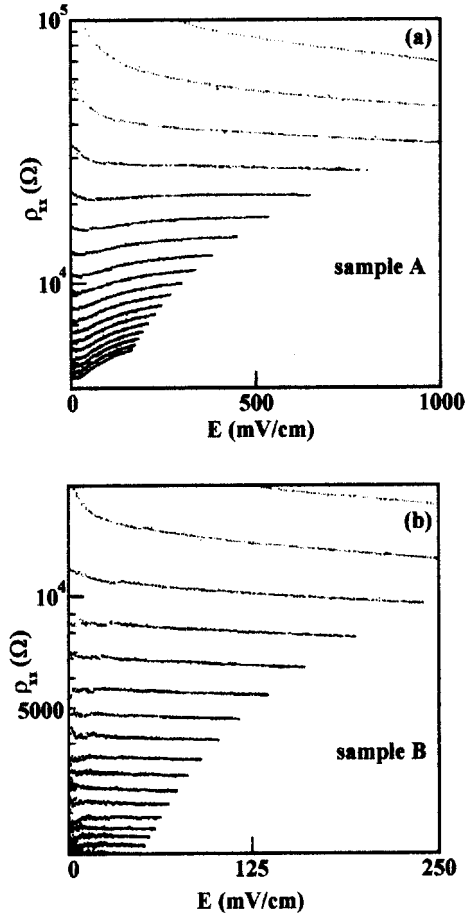

Figure 2. N_s dependence of ρ_{xx} as a function of the electric field for samples (a) A and (b) B. N_s values, from top to bottom: (a) 0.75 to 3.22 $\cdot 10^{11}$ cm^{-2}; (b) 0.87 to 3.11 $\cdot 10^{11}$ cm^{-2}.

There are also differences with respect to the previous MIT. First, the metallic phase is not destroyed by a parallel magnetic field up to 12 T. Second, samples from the same wafer but with lower dot density didn't displayed any MIT, making it clear that a high SAQD density is needed for this phenomenon. At present we don't have a full understanding of the metallic phase in sample B14. Its high density of SAQD means a high number of negatively charged scattering centers (up to 2 electrons per dot [15]), which goes against the main assumption of a recent model for Si MOSFET proposed by Altshuler and Maslov [17]. In this paper the authors propose that charge traps in the oxide layer could be neutralized as N_s increases, leading to less scattering and thus driving the MIT. In our case the situation is opposite. Since the wafer is homogeneous except for the SAQD layer and no MIT was found for low dot density samples, the dominant scattering mechanism are the SAQD, which are populated before the 2DEG starts to form. Thus the higher the SAQD density the higher is the scattering [15] and the suggestion of Ref. 17 is difficult to apply. The quantum dots filled with electrons could enhance spin interactions, recently suggested to be essential to the formation of a metallic phase [12]. We have also proposed an explanation in terms of quasibound minibands that might form in the continuum of the quantum dots and within the range of the Fermi energy [14]. These states could scatter resonantly the electrons of the gas [18], thus increasing the resistivity. Decreasing the temperature would decrease the number of available states for scattering and thus the resistivity would decrease, giving rise to the observed metallic phase.

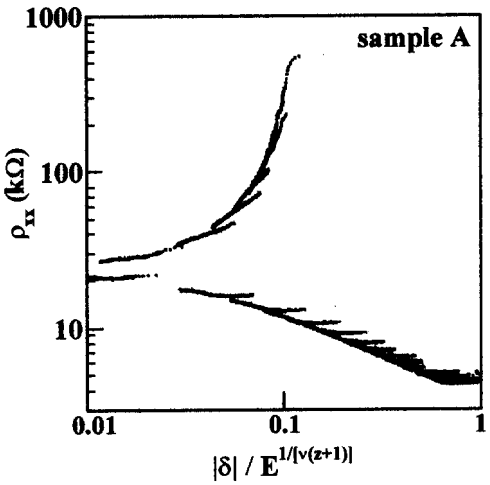

Figure 3. Resistivity of sample A as a function of the scaling argument to show the collapse of the traces into metallic and insulator branches.

In summary, our experimental data clearly show the occurrence of a MIT at B = 0 in a 2DEG under the influence of InAs SAQD. A scaling analysis yields results that are in agreement with previously reported values. We suggest that the special type of disorder in our samples (the SAQD) might be responsible for the observed metallic phase. In this sense, the MIT in 2D systems remains a topic far from being understood, requiring more experimental as well as theoretical work.

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