Metal-Insulator Transition in a Disordered Two-Dimensional Electron Gas in GaAs-AlGaAs at Zero Magnetic Field

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A metal-insulator transition in two-dimensional electron gases at $B = 0$ is found in Ga[Al]As heterostructures, where a high density of self-assembled InAs quantum dots is incorporated just 3 nm below the heterointerface. The transition occurs at resistances around h/e^2 and critical carrier densities of 1.2×10^{11} cm^{-2}. Effects of electron-electron interactions are expected to be rather weak in our samples, while disorder plays a crucial role. [S0031-9007(98)08278-7]

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The metal-insulator transition (MIT) is one of the central elements in the understanding of two-dimensional systems [1]. Theoretically it has been shown that a two-dimensional system without interactions is expected to behave as an insulator [2]. Recent experiments on silicon metal-oxide-semiconductor field-effect transistors (MOSFETs) with low disorder [3–6] have clearly demonstrated a MIT at zero magnetic field ($B = 0$). Meanwhile, metallic phases have also been found with holes in SiGe quantum wells [7] and holes in Ga[Al]As heterostructures [8,9]. Scaling theory has been crucial in order to characterize the metallic and the insulating states [1,2], even in the presence of interactions [10–12]. The resistivity has been found to scale with temperature T as well as with electric field E, in agreement with theoretical considerations [1,13]. By studying both scalings, the dynamic exponent z and the correlation length exponent ν can be obtained independently [14]. In general, samples in which a MIT at $B = 0$ was experimentally observed were optimized towards low disorder and large electron-electron interaction, i.e., clean samples with large effective carrier masses and low carrier densities have been used.

Here, we report on the observation of a MIT in a disordered two-dimensional electron gas (2DEG) in a Ga[Al]As heterostructure, both as a function of temperature and electric field at $B = 0$. The MIT in our samples is observed at a critical carrier density of $N_C = 1.2 \times 10^{11}$ cm^{-2}, a mobility of 2000 cm^2/V s and at resistances of the order of h/e^2. At the transition point, the elastic mean free path l_e is 11.5 nm and hence $k_F l_e \approx 1$, as in the experiments cited above. Our samples are very different to the ones used in previous work in two respects. First, the electron-electron interaction energy E_{ee} is comparable to the kinetic energy E_F of the electrons. In our samples, the ratio $E_{ee}/E_F = (e^2/\varepsilon_0 h^2)(m^*/\varepsilon N_C^{1/2})$ is only 0.9 (ε denotes the dielectric constant of GaAs, i.e., $\varepsilon_{\mathrm{GaAs}} = 12.8$, and the effective electron mass in GaAs is $m^* = 0.067 m_0$, where m_0 is the free electron mass); this ratio is ≥ 10 in the samples studied in Refs. [3–9,14]. Second, the disorder in our samples is generated by a layer of InAs self-assembled quantum dots (SAQDs) located at the site of the electron gas. The SAQDs show a very narrow distribution in size and electronic structure, and they are all located at the same position in the growth direction. The details of the scattering centers, namely, attractive InAs dots filled with electrons, are thus rather different from conventional disorder predominately originating from residual doping atoms. We observe the MIT at $B = 0$ only in samples with very high dot densities of about 5×10^{10} cm^{-2}. Scaling behavior in electric field is found. Scaling in temperature is difficult to confirm because of a poorly defined fix point in the temperature dependence. Nevertheless, we can estimate z and ν and find values in the same range as those reported in Ref. [14].

The layout of the paper is as follows: first, we describe the samples and the experimental setup. We proceed by discussing the temperature dependence of the MIT, followed by its electric field dependence. We speculate on a possible explanation and conclude with a summary.

The details of our samples are described in [15], but the crucial parameters are given below. A layer of InAs SAQDs is embedded in the GaAs buffer layer 3 nm from the $Al_xGa_{1-x}As$/GaAs interface where the 2DEG forms (upper right inset in Fig. 1). The substrate was not rotated during growth of the dot layer, leading to a gradient in dot density across the wafer from 3×10^9 dots cm^{-2} up to 5×10^{10} dots cm^{-2}. From transmission electron microscopy studies and transport measurements, the dot density is known within a factor of 2 for each part of the wafer. A δ-doping (n-type with Si) layer within the $Al_xGa_{1-x}As$ 30 nm from the interface provides the carriers for the 2DEG. The MIT at $B = 0$ was observed for the sample with the highest density of dots, namely, sample 7 from [15]. To ensure a homogeneous dot density, the sample size was kept sufficiently small. The width of the Hall geometries is 20 μm, while the voltage probes

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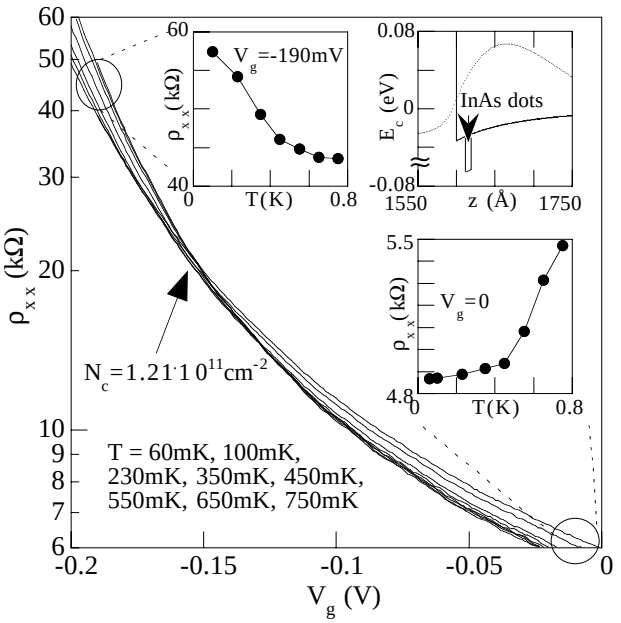

FIG. 1. ρ_{xx} as a function of gate voltage for a set of temperatures ranging from 60 to 750 mK. Enlargements of the insulating and conducting regime are shown as insets (solid lines are guides to the eye). Upper right inset: Sketch of the band structure around the heterointerface, including the potential of a InAs self-assembled quantum dot, and the wave function of the lowest subband (dotted line).

used to measure ρ_{xx} are separated by 40 μm. Gate electrodes are used to change the carrier density N_S. The samples are immersed in the mixing chamber of a ^{3}He/^{4}He dilution refrigerator with a base temperature of 60 mK. Resistivities were measured at low frequencies (13 Hz) in a four-probe configuration at a current level of 1 nA. For the electric field scaling, the dc bias current was swept and the voltage drop was measured.

In the following, we focus on the sample with the high dot density. Figure 1 shows traces of the longitudinal resistivity ρ_{xx} as a function of gate voltage V_g at zero magnetic field for temperatures T between 60 and 750 mK. The traces cross each other at $\rho_{xx} = (20.5 \pm 2)$ kΩ, a value slightly below h/e^2, and at $V_g \approx -160$ mV, corresponding to $N_C = (1.21 \pm 0.08) \times 10^{11}$ cm^{-2}. At lower densities ($V_g < -160$ mV), the sample behaves insulating, i.e., ρ_{xx} increases with decreasing T (upper left inset in Fig. 1). At densities above the fix point, ρ_{xx} drops with decreasing T, indicating a metallic character (lower right inset in Fig. 1). As T is reduced below 450 mK, the T dependence of ρ_{xx} becomes much weaker in the metallic phase. This effect is *not* due to current heating, since the same traces do not saturate in the insulating regime. Rather, the T dependence can be fitted by $\rho = \rho_0 + \rho_1 e^{-T_0/T}$, as observed in [9] and predicted theoretically from two different models [13,16]. Since the fix point of the MIT is poorly defined, scaling according to $\rho(T, N_S) = f_1(|\delta_N|/T^{1/z\nu})$ [$\delta_N = (N_S - N_C)/N_C$; f_1 denotes the scaling function in T] is difficult to confirm, although from scaling attempts (not shown) we can estimate $z\nu = 2.6 \pm 0.8$. Samples with lower dot density from the same wafer did not display a MIT at $B = 0$. They displayed insulating behavior for all available carrier densities, with the T dependence of ρ_{xx} becoming very small for high carrier densities.

In Fig. 2a, ρ_{xx} as a function of the electric field E is shown for various values of N_S. Again, a MIT is clearly visible, similar to the results in [14]. N_C and ρ_{xx} at the transition are $(1.29 \pm 0.05) \times 10^{11}$ cm^{-2} and (23 ± 3) kΩ, respectively, both slightly higher as found in the

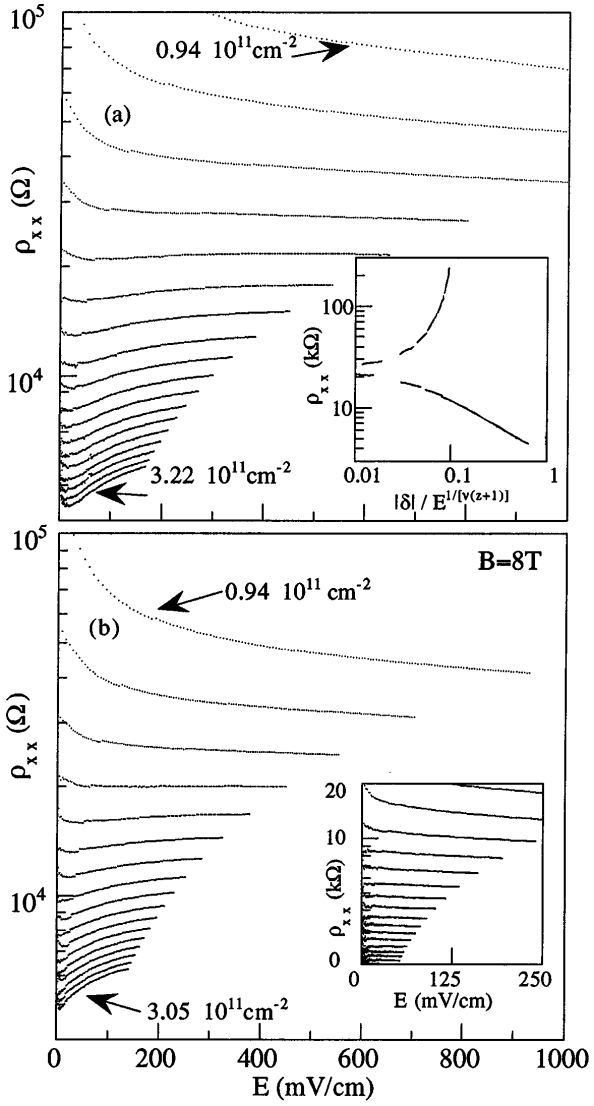

FIG. 2. (a) $\rho_{xx}(E)$ at carrier densities of 0.94 (uppermost curve), 1.05, 1.16, 1.27, 1.38, 1.50, 1.62, 1.75, 1.88, 2.01, 2.15, 2.29, 2.44, 2.59, 2.74, 2.89, 3.05, and 3.22 (lowermost curve), in units of 10^{11} cm^{-2}. Inset: Scaling plot of the data. (b) $\rho_{xx}(E)$ in a parallel magnetic field of $B_\parallel = 8$ T. The electron densities are the same as in the main figure, except that the trace for the highest density is left out. Inset: $\rho_{xx}(E)$ of a sample with a lower density of SAQDs. The carrier densities are identical to those in (a).

T dependence. At small electric fields ($E < 20$ mV/cm), $\rho_{xx}(E)$ increases slightly for all N_S as E is reduced, thus masking the phase transition. Because of the small sample size, however, the experimental error is large at these small electric fields. This low-electric field regime at high N_S needs further study and is not discussed here. The inset in Fig. 2a shows the result of scaling according to $\rho(E, N_S) = f_2(|\delta_N|/E^{1/(z+1)\nu})$. Here, the low electric field data where no metallic behavior is visible have been omitted. For the best visual collapse of the curves onto one trace, we find $(z + 1)\nu = 4.5 \pm 0.3$. The scaled curves show a stronger asymmetry than those obtained from scaling in Si MOSFETs [14], but similar to that one observed for hole systems in GaAs [8]. This asymmetry is a measure for the nonlinearity of the β function around the critical point [11]. Combining the results for the scaling exponent obtained from electric field scaling and the estimated value for the temperature scaling as described above, we find $z = 1.4 \pm 1.0$ and $\nu = 1.9 \pm 0.9$. Because of the large error bars, we do not attempt to give a detailed interpretation. However, these numbers are in agreement with the values reported in [14] and in agreement with theoretical considerations, i.e., $z = 1$ for an interacting system [1] and $\nu = 4/3$ from percolation theory [13].

The metallic phase, as evidenced in the electric field dependence of ρ_{xx}, is *not* destroyed by the application of magnetic fields in parallel to the electron gas. Figure 2b shows $\rho_{xx}(E)$ for the high dot density sample, while a parallel magnetic field of $B_\parallel = 8$ T is applied. N_C and ρ_{xx} at the transition are, within the experimental error, the same as under $B_\parallel = 0$. In fact, the perturbation observed for small electric fields at $B_\parallel = 0$ is reduced.

No metallic phase could be found in samples with lower density of SAQDs. The inset in Fig. 2b shows traces of $\rho_{xx}(E)$ at $B_\parallel = 0$ on a sample with a dot density of about 4×10^{10} dots cm^{-2}.

At present, we do not have a full understanding of the existence of a metallic phase in our samples. It is clear, however, that a high density of SAQDs is needed for its formation. In the following, we speculate on possible explanations on what the metallic phase consists of and discuss magnetoresistance measurements. Within a two-phase model [13], a gaseous phase can coexist with a liquid phase which can undergo a percolation threshold that defines the transition point from a metal to an insulator. In our sample, the liquid phase could be formed by the disordered electron gas, while the localized gas phase may consist of minibands or quasibound states that emerge from the SAQDs.

The conduction band is lowered in regions where the InAs dots form. For the first electron in the empty conduction band this leads to an attractive potential well. As more electrons populate the conduction band they first fill the InAs dots and then build up a Fermi sea. For the mobile electrons in the GaAs conduction band the filled InAs quantum dots now represent repulsive scattering centers. The potential landscape can be viewed as a random antidot lattice with possible short-range ordering. From our previous experiments we know that each dot is populated by about two electrons [15]. The depth of the InAs wells (100–200 meV) is about an order of magnitude larger than the Fermi energy ($\approx$5 meV).

However, the presence of the InAs dots can lead to quasibound states in the continuum of the dots close to the range of the Fermi energy. Since the InAs dots are rather homogeneous in size (the dot diameter varies by only about 7% [17]) and energetic structure [18], these quasibound states are expected to be rather narrow as well. In principle, mobile electrons can scatter into and out of such quasibound states which leads to a decreased conductivity compared to the 2DEGs without SAQDs. The states that are available for the electrons to scatter into are within an energy window of $k_B T$. In this picture, a lower electron temperature would lead to a smaller number of available states and thus to an increasing conductivity with decreasing temperature, as in a metallic state. A similar situation is considered in [19], where the structure of 2D electronic states in a strong magnetic field in the presence of a large number of resonant scatterers is calculated. So far, in transport experiments on electron gases with InAs SAQDs nearby [20], such states have not been observed; however, note that higher dot densities than in those experiments are needed. In case short-range order between the SAQDs exists, a local band structure may arise leading to an increased effective mass. This could give rise to an enhancement of the Coulomb interaction. In a recent paper [21], it has been suggested that the MIT in Si MOSFETs is probably a consequence of charged hole traps in the oxide layer. It remains to be seen whether this model can be applied to the above mentioned quasibound states. Clearly, the electrons form a quantum Hall liquid at sufficiently high perpendicular magnetic fields in all our samples. The longitudinal magnetoresistivity $\rho_{xx}(B_\perp)$ as well as the Hall resistivity $\rho_{xy}(B_\perp)$ for the sample with the high dot density is shown in Fig. 3. At $B_\perp = 0$, the sample is in a metallic state. Above $B_\perp = 4$ T, the sample is in a quantum Hall state with filling factor 2 (i.e., two Landau levels are occupied). In ρ_{xy}, a fix point occurs at $B_\perp = 2.85$ T as shown in the inset. Such magnetic field driven insulator to quantum Hall liquid transitions have been experimentally observed in other disordered 2DEGs (for a review, see [1], and references therein). In our system, a fix point occurs in ρ_{xy}, while ρ_{xx} increases for increasing temperature over the entire magnetic field range. A scaling analysis around the fix point in ρ_{xy} reveals a scaling exponent of $\kappa = 0.22 \pm 0.02$, in good agreement with exponents found in standard spin-degenerate quantum Hall systems [22]. These transitions can also be observed in samples with a lower density of InAs dots, where a fix point is also observed in ρ_{xx}. This is in tune with the fact that these samples always display insulating behavior at

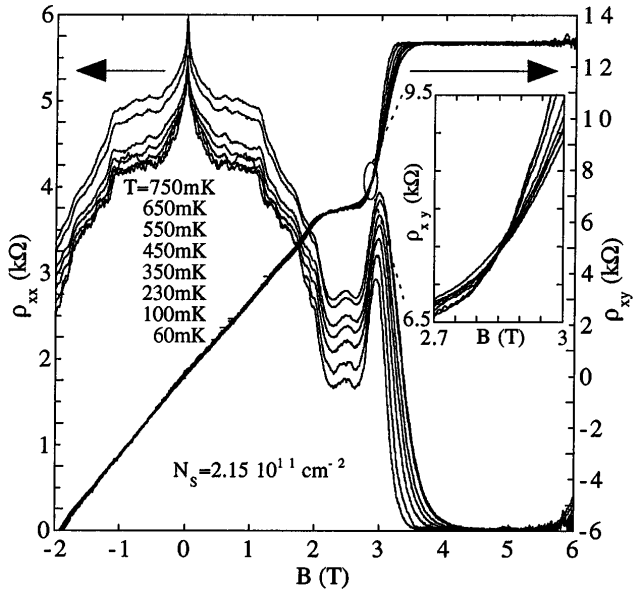

FIG. 3. Longitudinal and Hall resistance for various temperatures as a function of $B_\perp$ in the metallic regime. No insulator to quantum Hall liquid transition in ρ_{xx} is observed. ρ_{xy}, however, does show a fix point at $B_\perp = 2.85$ T (inset).

$B_\perp = 0$ and crossing points at finite magnetic fields are therefore possible.

To conclude, our experimental data clearly indicate the occurrence of a metal-insulator transition at zero magnetic field in a disordered two-dimensional electron gas in a Ga[Al]As heterostructure. Scaling theory has been applied to both the temperature dependence and the electric field dependence. While electric field scaling works well, temperature scaling is poor since the fix point in temperature is poorly defined. We have estimated the scaling exponents for our sample to $z = 1.4 \pm 1.0$ and $\nu = 1.9 \pm 0.9$, in agreement with the current framework of scaling theory and percolation theory. We speculate that it is the special kind of disorder potential in our samples that possibly modifies the ratio between the electron-electron interaction energy and the kinetic energy and thus drives this transition. In that sense the metal-insulator transition in two-dimensional systems remains a research topic that is far from being understood and requires more experimental as well as theoretical work.

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