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Magnetic-field-induced metal-nonmetal transition in GaAs-$Ga_{1-x}Al_xAs$ heterostructures

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The metal-nonmetal transition in GaAs-$Ga_{1-x}Al_xAs$ heterostructures has been investigated using electrical conductivity and Hall measurements in the presence of a magnetic field and hydrostatic pressure. The binding energy of a magnetodonor, composed of donor atoms and electrons separated from each other by a spacer, has been measured as a function of magnetic field for different surface densities controlled by the pressure. A simple model is presented which accounts qualitatively for the observed effects.

Properties of impurities in quasi-two-dimensional structures have lately become the subject of numerous investigations because of their interesting physical properties as well as their important applications. As in other cases of "man-made" quantum structures, the geometry of a given situation is decisive for its behavior. Until the present, the most frequently investigated cases were those of impurities in the quantum well, either at its center or at the edge.[1-6] This is a situation in which an impurity atom is constrained from the outside, i.e., the electron is kept closer to the impurity center than it would be according to its "natural" behavior. In modulation-doped structures with a spacer, a different situation is possible, in which the impurity atom is constrained from the inside, i.e., the electron is kept farther from the impurity center than it would be according to its behavior without constraint.

It is well known from investigations on bulk semiconductors that the presence of an external magnetic field shrinks the atomic orbit and enhances the binding energy of the impurity atom.[7] This results in a magnetic freezeout of conduction electrons on the impurity level.[8,9] The effect represents a magnetic-field-induced metal-nonmetal transition.[10] Magneto-optical investigations of impurities in quantum wells show that, in this case also, the presence of a magnetic field enhances the impurity energy.[11,12]

In this Rapid Communication we report on transport investigations of two-dimensional (2D) structures in which the impurity atom and the electron are separated from each other by a spacer. The effect of an external magnetic field and of hydrostatic pressure on impurity behavior is examined.

In order to reach the ultraquantum limit with available magnetic fields, it is necessary to deal with a 2D electron gas of sufficiently low density. In this case only, the lowest Landau level is occupied. In our experiments such a condition was realized by applying hydrostatic pressure. It has been shown[13] that one can diminish the surface electron density n_s in GaAs-$Ga_{1-x}Al_xAs$ heterostructures by the effect of pressure on the Si donor in $Ga_{1-x}Al_xAs$. This deep-lying level, located in the energy gap of $Ga_{1-x}Al_xAs$, shifts rapidly downward with respect to the conduction-band minimum. As a consequence, donor deionization takes place and n_s is reduced. At temperatures lower than 100 K the deep-lying level is characterized by metastable occupation.[14] Because of lattice relaxation effects, the surface density can be slightly modified for a given pressure, depending on the speed of cooling of the sample. At sufficiently high pressures one can reduce n_s to values lower than 5×10^{10} cm^{-2}, even for highly doped samples.

The structures studied consisted of an undoped GaAs layer and an undoped $Ga_{1-x}Al_xAs$ spacer (with thickness varying between 60 and 250 Å), and a Si-doped $Ga_{1-x}Al_xAs$ layer, grown by molecular-beam epitaxy or metal-organic chemical-vapor-deposition techniques. The Hall coefficient and the transverse magnetoresistance were measured for two current and magnetic field directions in the temperature range 1.5–4.2 K. Magnetic field intensities up to 18 T were used. In the experiments care was taken to stay within the Ohmic regime by keeping the electric field low enough to avoid impact ionization effects.

In Table I, the sample characteristics at 4.2 K (with and without pressure) are presented. The values of n_s and of the mobility are the Hall values, measured at low magnetic field ($B=0.5$ T). In the high-magnetic-field range, when the condition $\mu B>1$ is valid, n_s is determined from the σ_{xy} component of the conductivity tensor. One has[10,15]

$$n_s=\frac{1}{e}\frac{R_HB^2}{\rho_\perp^2+R_H^2B^2} . \qquad (1)$$

Typical dependences of $\rho_\perp$ and R_H on magnetic field at 4.2 K and of n_s on magnetic field and on temperature are, respectively, shown in Figs. 1 and 2. It is seen that above a critical field B_c the surface electron density n_s is thermally activated (magnetic freezeout). This allows us to determine the critical value n_{sc}, corresponding to the transition between metallic and nonmetallic types of conduction. Both quantities B_c and n_{sc} are reported in Table I. The pressure applied to samples 1, 2, and 4 has been chosen in such a way as to obtain approximately the same critical density of $n_{sc}\simeq6\times10^{10}$ cm^{-2}.

TABLE I. Sample characteristics, critical magnetic fields, and surface electron densities for metal-nonmetal transition in GaAs-$Ga_{1-x}Al_xAs$ heterostructures at different hydrostatic pressures. The last column gives the value of the Mottlike criterion for the metal-nonmetal transition.

Sample	x	Spacer thickness (Å)	$P=0$ n_s (10^{10} cm^{-2})	$T=4.2$ K μ (10^4 cm^2/V s)	Hydrostatic pressure $T=4.2$ K p (kbar)	n_s (10^{10} cm^{-2})	μ (10^4 cm^2/V s)	B_c (T)	n_{sc} (10^{10} cm^{-2})	Fig. 5	$\sqrt{n_{sc}}L_c$
1	0.3	60	52	7.5	13.3	8.5	0.95	6	6		0.26
2	0.25	150	24	12.9	8.8	6.2	2.55	5	5.9	*a*	0.28
					8.8	5.7	2.36	4.2	5.6	*b*	0.29
					8.8	5.1	1.84	3	5	*c*	0.33
					8.8	4.9	1.73	2.8	4.8	*d*	0.34
3	0.27	250	20.8	5.2	5.9	12.5	2.0	10	11		0.27
4	0.3	250	35	41.9	13	6.5	6.82	8	6.5		0.23

A thermally activated density can be described as $n_s = n_0 \times \exp(-E_a/kT)$, where E_a is the activation energy. Figure 2 shows a linear dependence of ln (n_s) vs $1/T$. Thus, n_0 is temperature independent and the activation energy E_a can be directly determined from the slopes of the curves.

The activation energies determined for samples 1, 2, and 3 are presented in Fig. 3. For samples 3 and 4, the activation energies were detectable at higher magnetic field only, and they remained so small at available fields that the determination of E_a is only qualitative. Figure 3 shows that the magnetic field dependences of the activation energies are distinctly different for different samples, in spite of the fact that the critical densities n_{sc} are almost the same. This suggests that the observed localization effect should not be ascribed to the Wigner condensation of a dilute 2D gas, which, in the case of similar electron densities, would lead to the same activation energy value. On the other hand, if the observed decrease of n_s is due to localization of the electrons in GaAs on the donors in $Ga_{1-x}Al_xAs$, the $E_a(B)$ variation should strongly depend on the thickness of the spacer. This is, in fact, what is observed: the activation energy decreases with increasing spacer thickness (cf. Fig. 3). This is further confirmed by the experiments of Mendez, Heiblum, Chang, and Esaki[16] with a large spacer thickness of 520 Å and comparable surface electron density n_s, in which no temperature-activated process was observed even at high magnetic fields.

In order to get a qualitative insight into the observed

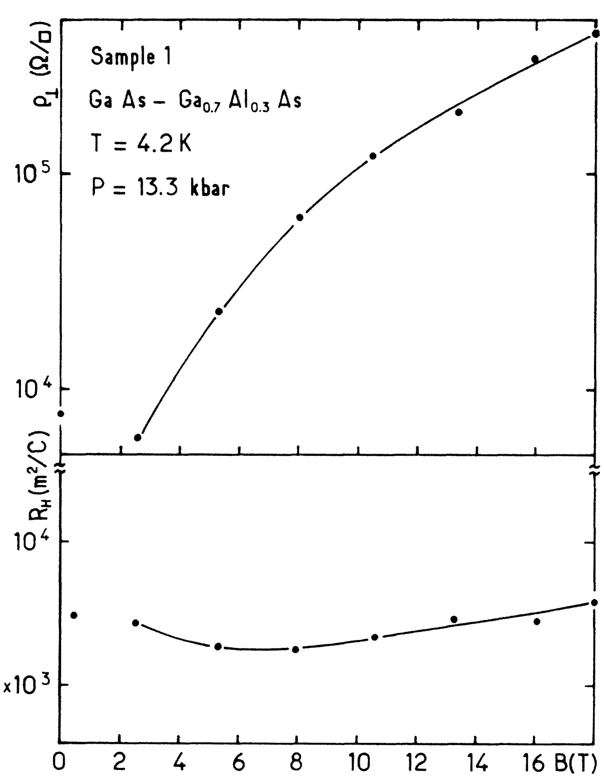

FIG. 1. Magnetic field dependence of the Hall coefficient R_H and of the transverse magnetoresistivity $\rho_\perp$ for sample 1 at 4.2 K and under pressure of 13.3 kbar.

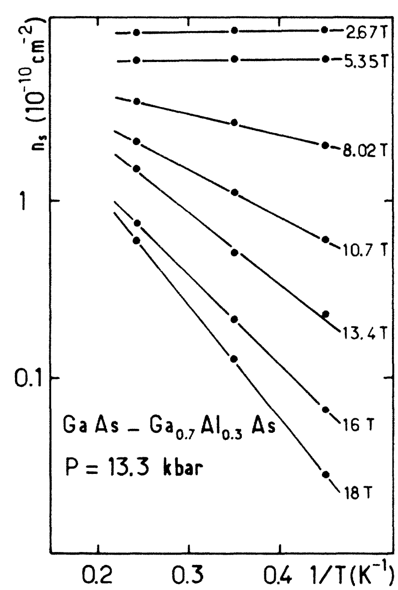

FIG. 2. Temperature dependence of the surface electron density for different magnetic fields. Sample 1 under pressure of 13.3 kbar.

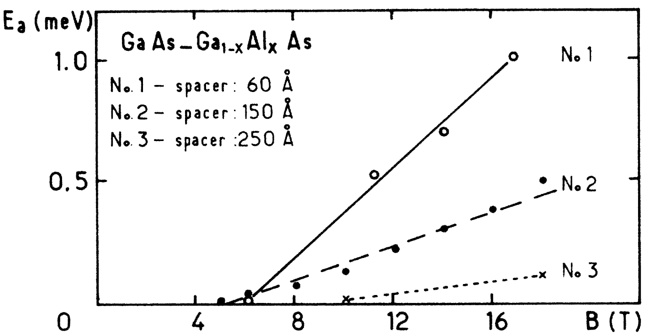

FIG. 3. Activation energies E_a of magnetodonors (the inversion electron is separated from the donor atom by a spacer) for samples 1, 2, and 3 vs magnetic field.

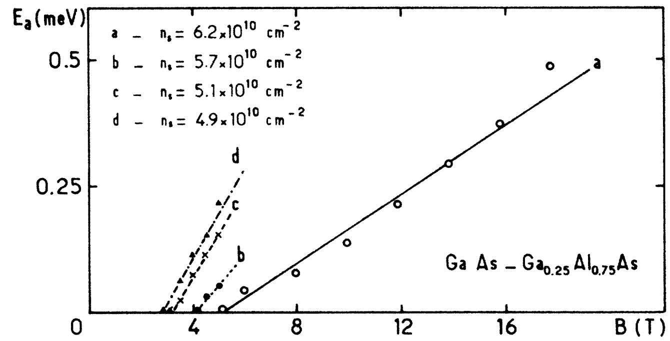

FIG. 5. Magnetodonor activation energies E_a for sample 2 (under pressure of 8.8 kbar) vs magnetic fields. The dashed lines are drawn to guide the eye. Different $E_a(B)$ dependences correspond to various n_s values, obtained by different speeds of cooling the sample (cf. Table I).

metal-nonmetal transition, we consider a donor atom at a distance d from the GaAs-$Ga_{1-x}Al_xAs$ interface and assume for simplicity that electrons in GaAs are perfectly 2D. If d is smaller than the effective radius λ of the donor wave function, a semiclassical picture of the situation may be used (cf. Fig. 4). Since the 2D electron may not penetrate into $Ga_{1-x}Al_xAs$, in the bound donor state its wave function is given approximately by a disk, resulting from the cross section of the sphere of radius λ with the interface plane. It has been shown, by variational calculation, that the donor binding energy E_a^0 in this case is a small fraction of the bulk effective Rydberg Ry*, and its effective radius λ is much larger than a_B^* ($a_B^* \simeq 100$ Å for GaAs).[17] It is well known from the bulk investigations that in the presence of a magnetic field the donor wave function has a cigar shape, and its dimensions decrease with increasing magnetic field.[7] It is seen from Fig. 4 that the intersection of the magnetodonor wave function with the interface now gives a smaller disk, so that the electron is on an average closer to the donor atom than in the case of $B=0$. As a result, the Coulomb binding energy is enhanced by the presence of a magnetic field. This results in a magnetic freezeout, which we observe experimentally. It is also clear that at high fields the binding energy of such a magnetodonor should be much smaller than that in the bulk, since in the latter case the electron is on an average much closer to the donor atom. This is, in fact, the case: For $B=17$ T we measure, for sample 1, $E_a \simeq 1$ meV, whereas for the bulk magnetodonor in GaAs at the same field one calculates $E_d \simeq 12.5$ meV.[7] The above reasoning is qualitatively valid also for $\lambda < d$, although in this case one may not use the semiclassical picture.

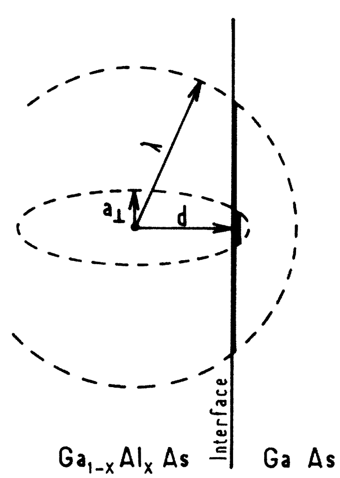

FIG. 4. Semiclassical model for the inversion electron in GaAs interacting with the Si donor atom in the doped layer of GaAlAs: d is the thickness of the spacer, λ the effective radius of the donor wave function at $B=0$, and $a_\perp$ the transverse radius of the orbit of the 3D electron bound to a donor at $B\neq 0$. Thick lines indicate interactions of the donor wave functions with the interface for $B=0$ and $B\neq 0$, respectively.

A metal-nonmetal Mott-type transition is usually associated with an overlap of the impurity wave functions. At high magnetic fields the 3D electron bound to the donor moves on the orbit, whose transverse radius, $a_\perp \simeq L = (\hbar/eB)^{1/2}$ (cf. Ref. 7). As follows from Fig. 4, one expects that the surface electron moves on the orbit with the same radius $a_\perp$. On the other hand, the average distance between surface electrons for the critical density is $n_{sc}^{-1/2}$. Thus, the overlap condition for the Mott transition is approximately given by $2L_c \simeq n_{sc}^{-1/2}$, i.e., $n_{sc}^{1/2}L_c \simeq 0.5$. As follows from Table I, we find, in fact, that the product $n_{sc}^{1/2}(\hbar/eB_c)^{1/2}$ is close to that value. It should be noted that at critical fields B_c one does reach the high-field limit: $\gamma = \hbar\omega_c/2E_a^0 >> 1$, where E_a^0 is the donor binding energy at $B=0$. In Fig. 5 we show the activation energy of magnetodonors in sample 2, measured at the same hydrostatic pressure $P=8.8$ kbar, for which the surface density n_s has been varied by changing the speed of cooling (cf. Table I). Since in this case one deals with the same spacer width, it is seen that the activation energy increases with decreasing n_s.

We also believe that the screening of the donor potentials by surface electrons plays an important role in the metal-nonmetal transition. As n_s decreases, the screening becomes weaker and the magnetodonor binding energy increases. This is what we observe, in agreement with the reasoning presented above. However, with decreasing n_s the donors functions overlap less, and the donor level becomes sharper, which also leads to an enhancement of the donor binding energy. The present experiments do not allow us to differentiate between these two effects.

It follows from our results that in GaAs-$Ga_{1-x}Al_xAs$

heterostructures with not too wide spacers, the Coulomb interaction between donor atoms in $Ga_{1-x}Al_xAs$ and inversion electrons in GaAs, is of an essential importance and it may not be neglected in the investigations of the quasi-two-dimensional electron gas.

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