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Impurity band and magnetic-field-induced metal-insulator transition in a doped GaAs/Al$_x$Ga$_{1-x}$As superlattice

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A combination of infrared spectroscopy and magnetotransport is used to investigate the impurity band and the magnetic-field-induced metal-insulator transition in n-type GaAs/Al$_x$Ga$_{1-x}$As superlattices. The dropping of the Fermi level from the conduction band into the impurity band upon increasing magnetic field is observed in a sample doped to $n=4n_c$, where n_c is the critical density according to the Mott criterion. The metal-insulator transition takes place while the Fermi level is in the impurity band, with no qualitative change from the metallic to the insulating side. Due to the anisotropy of the superlattice band structure, the metal-insulator transition is shifted to higher magnetic field, when the magnetic field is tilted away from the growth axis towards the layer planes.

Doped semiconductors can become insulating or remain conducting at low temperature, dependent upon the doping concentration. When the doping concentration n is low, the energy spectrum consists of independent hydrogenic donor levels, and hopping between them can account for the transport, resulting in an activated conductivity. As n is increased, the donor wave functions overlap, and an impurity band is formed. At even higher n, screening of the free electrons becomes effective, and the impurity band merges with the conduction band. The crossover between insulating and conducting behavior, the metal-insulator transition (MIT), occurs at a critical density n_c which can be estimated by the Mott criterion $n_c^{1/3}a^*=0.25$ (a^* is the effective Bohr radius). A metal-insulator transition can also be induced by application of a large enough magnetic field to a metallic sample. In this case the magnetic field diminishes the extent of the wave functions, and leads to localization. The critical behavior in the vicinity of the MIT has been the subject of numerous experimental and theoretical studies.[1,2] Less attention has been paid to the shape of the density of states[3] and the position of the Fermi energy.[4]

Recently it has been shown that at the critical density the Fermi energy is in the impurity band, i.e., metallic conduction already takes place in the impurity band.[4] This was evidenced through far-infrared absorption experiments in n-type GaAs,[4] where the MIT was induced by a magnetic field. Also, the electron effective mass in the impurity band has been measured and found to be much larger than the GaAs conduction-band mass.[5] It was found that at densities $n>5n_c$, only the free-carrier response remains, and thus the impurity band has merged with the conduction band.[4]

Apart from studies of bulk semiconductors, considerable work has been done on low-dimensional systems,[6] especially to study the intimate relation between the quantum Hall effect and localization in two-dimensional electron systems.[7–9] Recently, such systems have also been studied by far-infrared spectroscopy.[10] Semiconductor superlattices, on the other hand, which represent anisotropic three-dimensional systems, have been investigated to a much lesser extent (most works concern theoretical and experimental studies[11,12] of weak localization). Superlattices exhibit several features different from bulk semiconductors. (1) The band structure is highly anisotropic and, depending on the parameters, could correspond to an effective dimensionality between two and three. (2) The impurity binding energy depends on the position of the impurity atom along the growth axis;[13] as a result, if the superlattice (SL) is homogeneously doped, an impurity band is formed even at low doping. (3) Fluctuations of potential heights and layer thicknesses provide a source of Anderson localization not present in bulk semiconductors.[11]

In this paper we present a study of the impurity band and the magnetic-field-induced metal-insulator transition in an n-type GaAs/Al$_x$Ga$_{1-x}$As superlattice, which is doped somewhat above the critical density for the MIT. Magnetotransport and infrared-absorption measurements give evidence that the MIT occurs in the impurity band, just as in the case for bulk GaAs. The critical magnetic field is shown to depend on the field orientation due to the anisotropic band structure.

The superlattice sample was grown by molecular-beam epitaxy on a semi-insulating (001) GaAs substrate. It consists of 500 periods of 75-Å GaAs wells and 25-Å Al$_{0.3}$Ga$_{0.7}$As barriers, and is homogeneously doped to $n=6\times10^{16}$ cm^{-3}, which is about four times higher than the Mott critical density (for bulk GaAs) of $n_c=1.5\times10^{16}$ cm^{-3}. The strong coupling between the wells due to the thin barriers leads to a (calculated) width of

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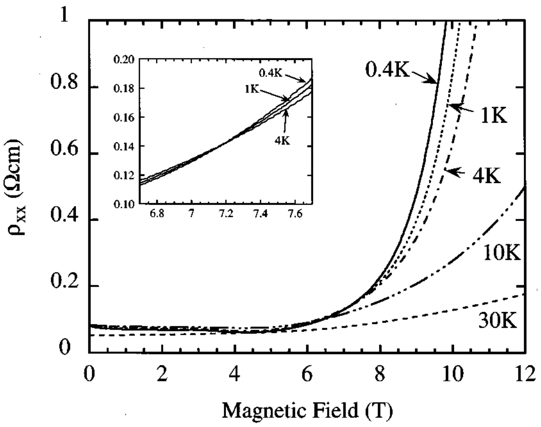

FIG. 1. The transverse magnetoresistivity ρ_{xx} is shown for different temperatures. The inset shows the common crossing point of resistivity curves.

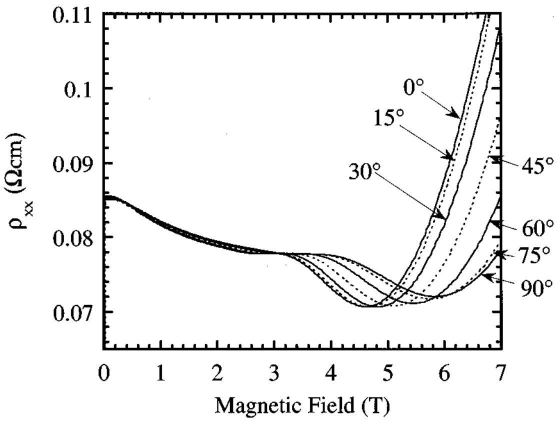

FIG. 2. The transverse magnetoresistivity ρ_{xx} is shown for different magnetic-field orientations with respect to the surface normal at a temperature of $T=4.2$ K.

the first miniband of 18 meV. The doping and the miniband widths are such that the Fermi energy at low temperature lies approximately in the middle of the first miniband. As a consequence, the samples behave three dimensionally, but are strongly anisotropic.

The electron concentration and mobility were determined from temperature-dependent Hall measurements. The mobility reaches a maximum of 6000 cm^2/V s at 100 K, and drops to about 1000 cm^2/V s at low temperature. Magnetotransport measurements were performed in standard Hall geometry with a 16-T superconducting magnet system using a variable temperature insert for temperatures down to 1.5 K or He^3 insert for temperatures down to 0.4 K.

Infrared-absorption measurements were performed with a Bruker IFS 113v rapid-scan Fourier-transform spectrometer. For the midinfrared measurements at $B=0$, the sample was mounted in a liquid-helium flow cryostat, where the temperature could be varied between 5 and 300 K. In order to achieve an active polarization for the intersubband absorption (electric field perpendicular to the layers), the sample was prepared in a multipass waveguide geometry.[14] For the far-infrared (FIR) magnetoabsorption measurements the spectrometer was connected to the magnet system via a lightpipe. In these measurements, the magnetic field was oriented perpendicular to the superlattice layers. The sample transmission was detected by a Si bolometer operated at 2.2 K and mounted below the magnet.

Figure 1 shows the transverse magnetoresistivity ρ_{xx} in a magnetic field perpendicular to the layers for different temperatures between 0.4 and 30 K. A last minimum ($\nu=2$) in the Shubnikov–de Haas (SdH) oscillations occurs at 4.5 T, followed by a steep increase of the resistance. Note that the resistance curves for all temperatures $T<$ 4.2 K exhibit a common crossing point at $B=7.2$ T (inset of Fig. 1). The resistance above this critical field increases consistently on lowering the temperature. Such a common crossing point in the resistance curves can apply as a criterion for the critical field of the magnetic-field-induced MIT.[9] However, the conductivity σ_{xx}, as calculated from ρ_{xx} and ρ_{xy}, extrapolates to zero for $T\rightarrow 0$ only for magnetic fields above 10 T (not shown). This latter criterion has usually been employed in most recent work on the magnetic-field-induced MIT.[2,4] Possibly the lowest achievable temperature within our experiments of 0.4 K is still too high to perform such an extrapolation accurately. Yet this ambiguity is not relevant for the implications made below. The Hall resistivity (not shown) does not exhibit any special feature, except a superlinear rise above 7 T.

In Fig. 2 the transverse magnetoresistance ρ_{xx} at $T=4.2$ K is shown for different magnetic-field orientations with respect to the layers. As the angle between the magnetic-field orientation and the surface normal is changed from 0° (field perpendicular to the layers) to 90° (field parallel to the layers), the last SdH minimum is shifted to higher fields. This reflects the fact that the effective mass[15] and the density of states (DOS) along the growth direction are larger than in the layer planes, i.e., the Fermi surface is anisotropic.[16] As a consequence not only the SdH minimum, but also the magnetic-field-induced MIT is shifted to higher fields for B parallel to the layers. In this configuration the common crossing point of the resistance curves occurs at 10.2 T and the conductivity extrapolates to zero only for $B>13$ T (not shown).

In order to obtain information about the position of the Fermi level and on the interplay between the conduction and impurity bands, infrared-absorption measurements were performed (with B perpendicular to the layers). Using this technique, the position of the Fermi energy relative to the impurity and conduction bands can be deduced by monitoring the relative strength of impurity and conduction-band transitions. In previous work on bulk GaAs,[4] the $1s$-$2p_+$ and $1s$-$2p_0$ and cyclotron-resonance absorptions were analyzed at finite magnetic fields, and the $1s$-$2p$ and free-carrier absorption at $B=0$. At low magnetic fields, however, it becomes difficult to distinguish a free-carrier Drude or cyclotron-resonance absorption from the impurity absorption, which in Faraday geometry consists of a superposition of the $1s$-$2p_-$ and $2p_+$ transitions. This is due to the line broadening (a few meV) in doped samples, and is especially true in homogeneously doped superlattices, where the transition energy depends on the impurity position.[13] Yet in superlattices one can use the interminiband transition and the $1s$-$2p_0$ transition instead, which both occur at much higher energies,[14] in the midinfrared spectral region (depending on the layer widths of the

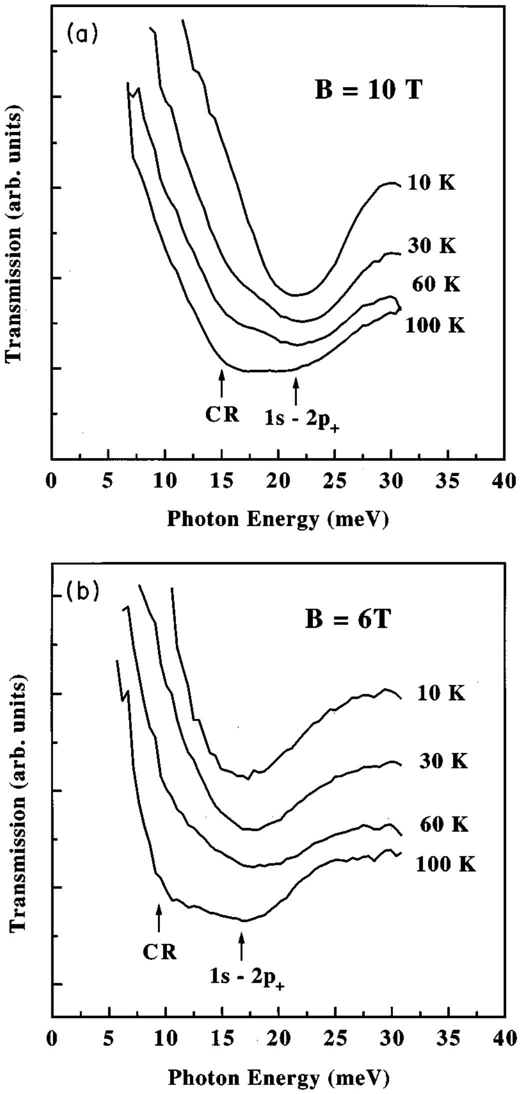

FIG. 3. Far-infrared magnetotransmission spectra are shown for different temperatures as indicated and a magnetic field of (a) 10 T and (b) 6 T. The different curves are shifted vertically for clarity.

superlattice) and can be easily distinguished from each other.[14] Midinfrared-absorption measurements on the present sample (at $B=0$) have been reported in Ref. 14. There it has been shown that at low temperature the absorption spectrum consists of the $1s$-$2p_0$ transition and a feature due to the miniband critical point at $k_z=0$. From this observation the clear conclusion can be drawn *that, at* $B=0$ *and the present electron concentration of* $n=4n_0$*, the impurity band still exists and the Fermi energy is located in the miniband.*

Next we proceed to analyze the *far-infrared* magnetoabsorption measurements. Figure 3 shows FIR transmission spectra at different temperatures, for a magnetic field of $B=10$ T (a) and $B=6$ T (b). The spectra were obtained by ratioing the transmission at finite magnetic field to the transmission at $B=0$. This procedure causes the rise of the spectra at low frequency, which is due to the free-carrier absorption at $B=0$. Note that at 10 T the electron system is in the vicinity of the metal-insulator transition, whereas 6 T is a field definitely below the MIT. At low temperature ($T=10$ K) the spectra both at 6 and 10 T show a single absorption line, which can be identified with the $1s$-$2p_+$ donor transition. Only upon increasing the temperature the spectra evolve into doublets, the second line being the cyclotron-resonance absorption. This interpretation is confirmed by variational calculations of the donor transition energies for donors located in the center of the wells and the barriers. Figure 4 shows the measured peak positions together with the calculated ones. The measured peak positions of the donor absorption lie between the values for well-centered and barrier-centered donors. This is perfectly reasonable for this homogeneously doped SL, where the two donor contributions cannot be resolved due to the large line broadening. At low magnetic fields, the experimental points approach the theoretical value for the well donors; this can be an artifact due to the contribution of the free-carrier absorption in the $B=0$ spectra used for normalization. The theoretical position of the cyclotron resonance is indicated by the solid line (for an effective mass of $m^*=0.067m_0$). For magnetic fields lower than 5 T, no unambiguous assignment for the absorption was possible due to the broad free-carrier absorption. Nevertheless there is again a clear conclusion which can be drawn from the present data: *At a magnetic field below the MIT, i.e., at* $B=6$ *T, the Fermi level at low temperature is already in the impurity band and remains there for higher magnetic fields and through the metal-insulator transition.* Consequently, the magnetic-field-induced MIT in a GaAs/Al$_x$Ga$_{1-x}$As superlattice occurs in the impurity band, similar to the observations for bulk GaAs. Together with the data from the midinfrared measurements at $B=0$, we can come up with the following scenario: For a density of $n=4n_c$ the Fermi level is in the conduction band at $B=0$. Upon applying a magnetic field the Fermi level drops into the impurity band, well before the occurrence of the MIT. The MIT occurs while the Fermi level is in the impurity band, and results in no qualitative change in the FIR absorption spectra. Hence with increasing magnetic field we obtain a transition from a conduction-band metal to an impurity-band metal and further to a Mott-Anderson insulator.

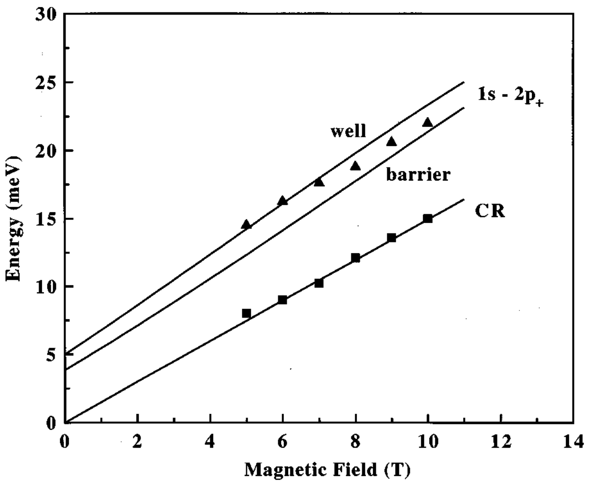

FIG. 4. The peak positions of the cyclotron resonance and impurity absorptions are plotted vs the magnetic field. The symbols represent the measurements, the lines result from a calculation of the positions of the cyclotron resonance and the impurity absorption, the latter for well and barrier donors.

In summary, using a combination of infrared absorption and magnetotranport measurements, we have shown that the magnetic-field-induced metal-insulator transition in GaAs/$\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ superlattices occurs in the impurity band, similar to bulk GaAs. As a consequence of the anisotropic superlattice band structure the MIT occurs at higher magnetic field in the orientation when B is parallel to the layers.

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