

Transition from Strong to Weak Localization in the Split-Off Impurity Band in Two-Dimensional p -GaAs/AlGaAs Structures

N. V. Agrinskaya*, V. I. Kozub, D. V. Poloskin, A. V. Chernyaev, and D. V. Shamshur

Ioffe Physicotechnical Institute, Russian Academy of Sciences, St. Petersburg, 194021 Russia

**e-mail: nina.agrins@mail.ioffe.ru*

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A crossover from strongly localized behavior to weak localization (SL–WL) was observed in two-dimensional modulation-doped GaAs/Al_{0.3}Ga_{0.7}As structures as the impurity concentration increased. In this case, it was observed that the low-temperature dependence of the conductivity changed its character (from exponential to logarithmic) and the magnetoresistance changed its sign (from linear negative to root positive). For 2D structures, it is shown that this transition proceeds in the impurity band separated from the valence band by the mobility gap, whereas the effective mass in the impurity band is larger than in the valence band. © 2004 MAIK “Nauka/Interperiodica”.

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1. INTRODUCTION

Both effects associated with disorder and effects of electron–electron interaction can play an important role in the vicinity of the metal–insulator (MI) transition in doped (both 3D and 2D) semiconductors. As for disorder effects, it is known that these lead to broadening of the impurity band and its subsequent coalescence with the conduction band. In this connection, it is often suggested that it is in the conduction band tail formed by disorder that the MI transition occurs. However, a number of magneto-optical and transport experiments at $n_c \leq n \leq 5n_c$ (where $n_c = (0.25/a)^3$ is the Mott estimate for the critical concentration for the metal–insulator transition) indicate that the transition to metallic conductivity proceeds in the split-off impurity zone [1, 2].

Strictly speaking, the above consideration relates to 3D. The scaling theory of localization predicts the absence of the metal–insulator transition in 2D, because all the states prove to be localized as the temperature tends to zero. Nevertheless, it is known that, in experiments performed with sufficiently clean structures [3], a transition from a dielectric to metallic behavior was observed as the electron concentration increased. The nature of this behavior has not been quite understood so far. Several mutually contradictory explanations have been proposed, including those associated with electron–electron interactions, with non-Fermi-liquid effects, and with simulations of the metallic behavior by temperature-dependent scattering [3, 4]. We incline to the latter suggestion and previously have proposed a model for the MI transition in 2D in which the observed behavior is explained by the coexistence of weakly localized states (fully described by the scaling theory of localization) and strongly localized states lying lower in energy [5]. It is suggested that the latter

states are not described by the scaling theory of localization and an analogue of the mobility edge can be introduced. In accordance with the scenario [6], the states localized in the vicinity of this mobility edge form a peak in the upper Hubbard band.

A transition from the regime of strong localization (SL) to the regime of weak localization (WL) or a SL–WL crossover was observed in contaminated or doped 2D structures as the carrier concentration increased [7, 8]. In this case, the question of whether the transition occurred in the tail of the allowed band or in the impurity band (separated from the conduction band) remained open.

In this work, we performed a corresponding study with respect to a particular system of a selectively doped structure of quantum wells that allow both single and double occupations of the localized states. Special attention was given to the character of the corresponding localized states. We observed a SL–WL crossover in 2D GaAs/Al_{0.3}Ga_{0.7}As structures. The series of investigations performed in this work allows the conclusion that this transition occurs in the impurity band separated from the valence band. The available experimental data are indicative not only of the existence of a minimum in the density of states between the impurity and conduction bands but also of the existence of the second mobility edge in the impurity band.

2. EXPERIMENTAL

The procedure of growing multilayer structures by molecular-beam epitaxy was described in our previous work [9]. The structures contained 10–20 GaAs quantum wells 10 or 15 nm thick separated by Al_{0.3}Ga_{0.7}As barriers 25 nm thick. In the investigated samples, the

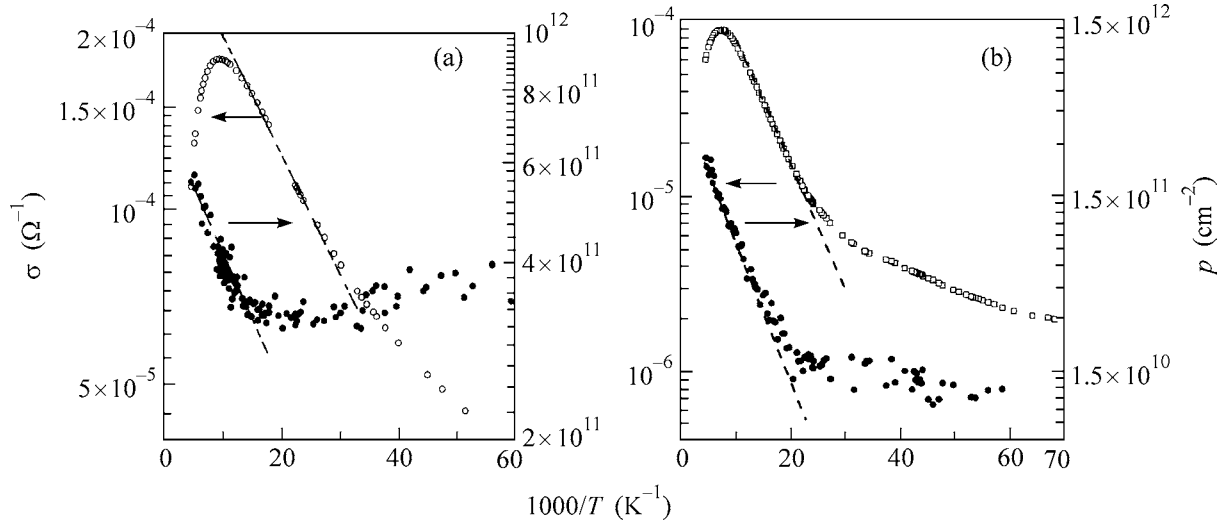


Fig. 1. Temperature dependences of the conductivity and the hole concentration: (a) for sample 1 (20 10-nm wells) with wells and barriers doped (the Be concentration is $6 \times 10^{17} \text{ cm}^{-3}$) and (b) for sample 2 (10 15-nm wells) with only wells doped (the Be concentration is 10^{18} cm^{-3}).

middle area of the quantum wells 5 nm thick was doped, and the $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ barriers in certain samples were doped as well (so that the middle area of the barriers 5 nm thick was doped). Beryllium was used as a p -type doping impurity. The impurity concentration was the same in both wells and barriers (the bulk concentration was varied from 5×10^{17} to $2 \times 10^{18} \text{ at/cm}^3$). The critical concentration for the bulk p -type GaAs is $2 \times 10^{18} \text{ cm}^{-3}$; that is, the above concentrations are of the same or somewhat lower order ($p_{300 \text{ K}} \leq p_c$). The temperature dependences of the conductivity and the hole concentration for two samples are presented in Fig. 1. Sample 1 contained A^+ centers, both wells (10 nm) and barriers were doped, and the bulk concentration of Be was $6 \times 10^{17} \text{ cm}^{-3}$. Sample 2 contained A^0 centers, only wells (15 nm) were doped, and the bulk concentration of Be was 10^{18} cm^{-3} .

At temperatures higher than 100 K, an activation behavior of the Hall coefficient was observed. The activation energy was 15–13 meV for sample 2 and 5–6 meV for sample 1. A maximum or a plateau in the temperature dependence of the Hall coefficient and a rather weak variation of the conductivity in the impurity band were observed at lower temperatures. The variation of the conductivity with temperature becomes considerably weaker as compared with the exponential dependence of the samples located on the insulating side of the junction, which was observed in our previous investigation [9]. The low-temperature conductivity in sample 1 decreases according to a logarithmic law with decreasing temperature (Fig. 2). The resistivity at a low temperature (0.4 K) is 3×10^4 – $6 \times 10^4 \text{ } \Omega$, which is somewhat higher than the quantum limit $R_0^{-1} = G_0 = e^2/h$. This fact can be associated with the difference of

the sample geometry from a purely square shape. Namely, the measurements were performed with the use of four point contacts at the vertices of the square sample, so that, in measuring the conductivity at the nearest contacts, the shape of the conducting region is not square to an extent of the ratio between the sizes of the contact and the sample.

In this regime of weak localization, the conductivity of a two-dimensional system with regard for quantum corrections can be written as [3]

$$\sigma \approx \frac{e^2}{h} \left(k_F l - \ln \frac{L_\phi(T)}{l} \right), \quad (1)$$

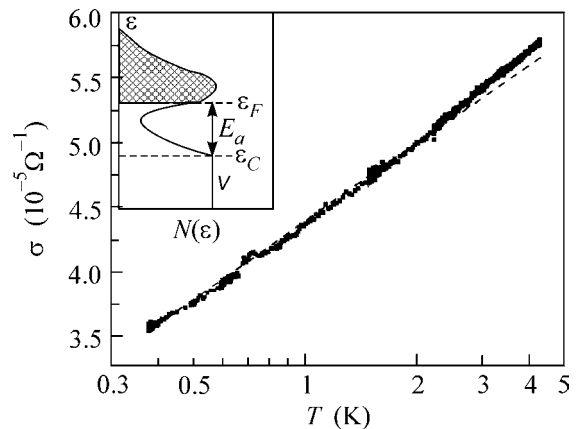


Fig. 2. Temperature dependences of the low-temperature conductivity for sample 1. The inset shows the density of states for sample 1, where ϵ_F , ϵ_C , and E_a are the position of the Fermi level in the impurity band, the mobility edge in the valence band, and the high-temperature activation energy, respectively.

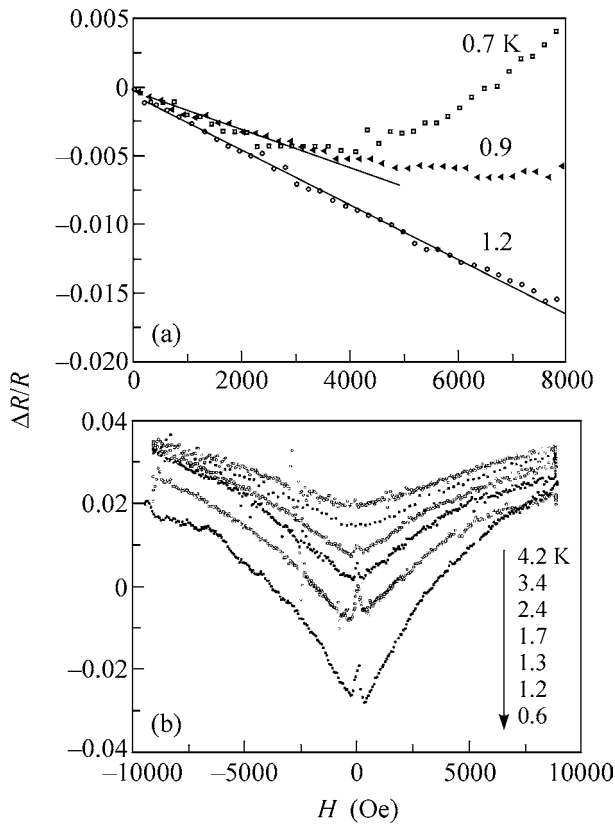


Fig. 3. MR at various temperatures for samples with A^+ centers: (a) for a sample in the regime of strong localization [9], the resistance at $T = 0.6$ K is $R = 3 \times 10^6 \Omega$; (b) for sample 1 in the regime of weak localization, the resistance at $T = 0.4$ K is $R = 3 \times 10^4 \Omega$.

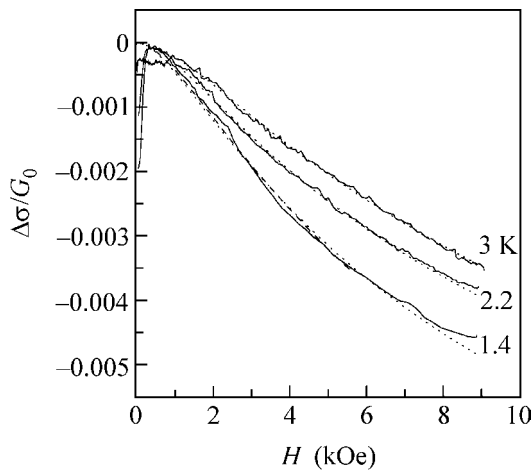


Fig. 4. Comparison of experimental MR curves for sample 1 with the theory [10]. The solid curves correspond to the experiment; the dotted curves correspond to the calculation at the following fitting parameters: $\tau_s = 3.1 \times 10^{-12}$ s (independent of temperature); dephasing time $\tau_\phi = 4.8 \times 10^{-11}$ s (3 K), 6.3×10^{-11} s (2.2 K), and 7×10^{-11} s (1.4 K).

where L_ϕ is the dephasing length, which equals $L_\phi = (D\varepsilon_F\tau/T)^{1/2}$ for the case of diffusion electron–electron collisions; k_F and ε_F are the Fermi vector and energy; and D , l , and τ are the diffusion coefficient, the mean free path length, and the momentum relaxation time, respectively.

In addition to the dependence $\sigma(T)$, differences in the behavior of the magnetoresistance (MR) in the region of low temperatures may be evidence in favor of the manifestation of the SL–WL crossover. We showed previously [9] that insulating samples are characterized by the existence of a linear negative interference MR. As the temperature decreases, this negative MR is suppressed by the quadratic positive MR associated with the fact that the localization radius decreases in a magnetic field (Fig. 3a). In the samples occurring in the regime of weak localization, the MR proves to be positive in the temperature range (0.6–3) K and depends on the magnetic field approximately as $H^{0.5}$ (Fig. 3b). This can be associated with the manifestation of weak antilocalization given spin–orbit interaction. Figure 4 presents a comparison of experimental data and the calculated dependences $\sigma(H)$ obtained from the corresponding theoretical models [10]. It is evident that good agreement with the theory is observed for the entire region of magnetic fields and temperatures at the following fitting parameters: spin relaxation time $\tau_s = 3.1 \times 10^{-12}$ s (independent of temperature) and dephasing time $\tau_\phi = 4.8 \times 10^{-11}$ s (3 K), 6.3×10^{-11} s (2.2 K), and 7×10^{-11} s (1.4 K). The fact that weak antilocalization is observed up to fields of 1 T is associated with very small values of the parameter $k_F l$ corresponding to the vicinity of the SL–WL transition. A negative MR peak is evident in the region of very low fields and low temperatures. The temperature at which this peak starts to emerge correlates with the superconducting transition temperature for the indium contact. Note, however, that the suppression of the superconducting state by a magnetic field leads to an increase in the system conductivity (rather than resistivity, as might be expected from the simplest considerations). We hope to investigate this phenomenon more comprehensively in a subsequent work.

3. DISCUSSION

The SL–WL transition in GaAs/AlGaAs structures was observed experimentally in [7]. The transition occurred as the carrier concentration was varied with the use of a gate. It was manifested as a change in the temperature dependence from an activation form to a logarithmic form. An analogous behavior was also observed in ultrathin Cu/Ge, Ag/Ge, and Au/Ge films as the concentration of the noble metals was varied [8]. In the SL–WL transition, the MR sign changed from negative to positive. In this case, the low-temperature conductivity was close to $G_0 = e^2/h$.

Our GaAs/Al_{0.3}Ga_{0.7}As structures with wells whose center is heavily doped are distinct from clean structures studied previously [3], because the localized states in these structures are determined by the dopant and their parameters are known. In particular, it is known that, as the doping level increases, an impurity band forms. This band determines the specific features of transport phenomena at low temperatures. In the two-dimensional case, the lower and, especially, upper Hubbard bands are located lower in energy than those for bulk materials. As the impurity concentration increases, an SL–WL transition occurs in the split-off impurity band and the concept of the Hubbard energy loses its meaning for delocalized states. Moreover, even for the localized states that are close in energy to the delocalized ones, the Hubbard energy is very small so that these states also prove to be doubly occupied [5, 6]. The logarithmic temperature dependence of the conductivity and the transition from the negative (interference) to positive (associated with weak antilocalization) magnetoresistance serve as evidence for the onset of the WL regime.

The set of studies performed in this work allows the conclusion that the SL–WL crossover indicated above occurs in the impurity band separated from the valence band (see the inset in Fig. 2). Actually, as is evident in Fig. 1, a pronounced exponential growth of the conductivity is observed with increasing temperature at temperatures higher than 30 K (with an activation energy of 6 and 13 meV for samples 1 and 2, respectively). At somewhat higher temperatures, the Hall concentration also exhibits an exponential growth. This behavior can be explained by the contribution from two bands with metallic conduction (namely, the lower one originating from the impurity band, and the upper, from the valence band) in combination with the suggestion that the mobility in the valence band is appreciably higher than the mobility in the impurity band. The minimum in the Hall concentration $n = e/cR$ at temperatures of about 50 K is explained by a combination of contributions from two bands indicated above (see, for example, [11]). Actually, the Hall coefficient R for the two-band model is expressed through partial mobilities μ and concentrations n as

$$R = (e/c) \frac{\mu_1^2 p_1 + \mu_2^2 p_2}{(\mu_1 p_1 + \mu_2)^2}, \quad (2)$$

so that, when $\mu_1 \gg \mu_2$ in the region of concentrations $(\mu_2/\mu_1)p_2 > p_1 > (\mu_2/\mu_1)^2 p_2$, we have $R \approx (e/c)(p_1 \mu_1^2)(p_2^2 \mu_2^2)$. Hence, R reaches a maximum at $p_1 \sim p_2(\mu_2/\mu_1)$.

Thus, the observed behavior, from our point of view, indicates that the delocalized states manifested experimentally are located rather deep in the impurity band, whereas the states in a certain energy band located closer to the conduction band bottom are localized.

Experimental estimates of the activation energy testify that the above band is rather broad.

Because the spectrum of delocalized wave functions in the impurity band can differ from the corresponding spectrum in the valence band, it is of interest to evaluate the effective mass of holes in the impurity band. Note that carriers at low temperatures are entirely concentrated in the impurity band and are degenerate. The relation of the Fermi energy with the concentration can be expressed as

$$\varepsilon_F = p\pi\hbar^2/m. \quad (3)$$

To estimate m , we will use the circumstance that the transport relaxation time τ at comparatively high temperatures is determined by temperature, whereas it is determined by the Fermi energy in the limit of low temperatures. Assuming that, in both cases, we deal with scattering by charged impurities and $\tau \propto \varepsilon$ (see, for example, [12]), it may be concluded that the ratio of the mobilities at $T = 50$ K in the valence band to the mobility in the impurity band is

$$\frac{\mu_{ib}(T \rightarrow 0)}{\mu_b(T = 50 \text{ K})} \sim \frac{\varepsilon_F m_b}{50 \text{ K} m_{ib}}. \quad (4)$$

Unfortunately, the two-band character of the Hall effect prevents the mobility in the valence band from being estimated directly. Therefore, we will estimate it indirectly using the following estimate for the concentration p_b in the valence band: $p_b(50 \text{ K}) \sim p_{i,b}(T = 0)e^{-E_a/T}(m_b/m_{i,b})$, where E_a is the activation energy. Hence, it follows that

$$\frac{\mu_{ib}(T \rightarrow 0)}{\mu_b(T = 50 \text{ K})} \sim \frac{\sigma_{ib}(T \rightarrow 0)e^{-E_a/T} m_b}{\sigma_b(T = 50 \text{ K}) m_{ib}}.$$

Using the above estimates and taking into account that the contributions to the conductivities at $T = 50$ K from both bands are approximately equal (which follows from the minimum of the Hall concentration), we finally find that $m_{ib} \sim 10^{-27}$ g. Because $m_b \sim 0.3 \times 10^{-27}$ g, the mass in the impurity band is approximately three times larger than in the valence band. It is evident that the above estimate is rather crude; however, both the activation dependence of the conductivity and the behavior of the Hall concentration point to a notable difference between the mobilities in the conduction and impurity bands, which is indicative of corresponding differences in the effective mass. Note that an electron mass substantially exceeding (by a factor of 5) the mass in the conduction band was observed in 3D GaAs [2] at impurity concentrations close to critical. This mass was assigned to the metallic phase in the impurity band.

Note that, up to this point, we discussed results obtained for samples in which both wells and barriers were doped. Correspondingly, transport in the impurity band and in the hopping regime was conducted through doubly occupied states of the upper Hubbard band. The

localization radius of a state in the upper Hubbard band exceeds the localization radius of an isolated acceptor by a factor of approximately 3 even at low impurity concentrations [9]. It is due to this circumstance that the regime of weak localization is observed at impurity concentrations substantially lower than those corresponding to the Mott criterion for the lower Hubbard band.

The samples in which only wells were doped (in which only the lower Hubbard band is filled in equilibrium) also exhibited a crossover from strong to weak localization, though, at a markedly higher doping level. In this case, a weak logarithmic temperature dependence of the resistivity and a positive magnetoresistance associated with antilocalization were observed at $T < 10$ K. The results for one such sample in the region of high temperatures are presented in Fig. 1b. It is seen that the activation behavior of both the conductivity and the Hall concentration in this sample is even more pronounced than in the sample with the filling of the upper Hubbard band. This is due to a considerably higher ionization energy. However, a quantitative analysis of the results for such samples reveals certain discrepancies with the simple model assuming equal contributions from all quantum wells. In our opinion, this can be attributed either to the nonuniformity of the samples or to the fact that individual wells differ in their doping levels. Then, weak localization in one of the wells occurs under conditions when the other ones still reside in the limit of strong localization. Such a behavior can be caused precisely by the high doping level of the corresponding samples.

In summary, it may be stated that we observed a crossover from strong to weak localization in two-dimensional modulation-doped GaAs/Al_{0.3}Ga_{0.7}As structures with increasing dopant concentration. The character of the temperature dependences of the conductivity and the Hall concentration of carriers allows

the conclusion that the crossover occurs in the impurity band separated from the valence band.

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