

WEAK LOCALIZATION EFFECTS IN GaAs DOPING SUPERLATTICES

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The conductivity of an n-layer in a GaAs doping superlattice decreases logarithmically with temperature between about 25 K and 250 mK. The magnetoresistance in low fields is negative and varies logarithmically. The results are explained in terms of the theory of weak localization in two dimensions. The inelastic scattering time is determined from a fit of the magnetoresistance as a function of temperature and carrier density.

In recent years the concept of weak localization has proved to be very fruitful for an understanding of the electronic transport in a regime between complete localization and quasimetallic behaviour, especially in two-dimensional (2D) systems such as Si MOS, GaAs/AlGaAs heterostructures and in thin metallic films [1,2,6,7]. In the present paper we report the observation of weak localization effects in a new quasi 2D system, the GaAs doping superlattice. Such a structure consists of alternating periodic thin GaAs layers of n- and p-type doping. The electrons from the donors in the n-layer transfer to the acceptors in the p-layers and the resulting space charge leads to potential wells in the n-layers for the electrons and in the p-layers for the holes. Through selective contacting of the n- and p-layers, the potential difference between the layers can be changed externally. In this way the carrier density of the layers can be varied by injection or extraction of carriers. Up to now a number of different experiments [3,4] have confirmed the quasi 2D nature of the system predicted theoretically [5]. In many aspects this system, which essentially differs from the heterojunction GaAs/AlGaAs heterojunction system, seems to

be particularly well suited for studying localization phenomena, because there is a considerable amount of disorder due to the relatively high doping level, which is controllable during growth. Moreover, in one and the same sample the density of mobile carriers, which in this case are not spatially separated from the fixed impurities, and the space charge potential can be changed easily.

Three samples grown by molecular beam epitaxy (MBE) have been used for the present study, two multilayer structures with 10 alternating n- and p-layers (sample A: $N_D = 7 \times 10^{17} \text{ cm}^{-3}$, $N_A = 7.85 \times 10^{17} \text{ cm}^{-3}$, doping layer thickness $d = 90 \text{ nm}$; sample B: $N_D = 5.25 \times 10^{17} \text{ cm}^{-3}$, $N_A = 6.74 \times 10^{17} \text{ cm}^{-3}$, $d = 100 \text{ nm}$) and one single layer sample consisting of one n-layer sandwiched between two p-layers ($N_D = N_A = 7 \times 10^{17} \text{ cm}^{-3}$, $d_n = 90 \text{ nm}$, $d_p = 500 \text{ nm}$). For the analysis a multilayer sample is considered as 10 layers electrically connected in parallel. In fig. 1 the sheet conductivity of the n-layer is plotted as a function of temperature between 50 mK and 25 K for samples A and B. It shows a logarithmic behaviour over two orders of magnitude in T and saturates

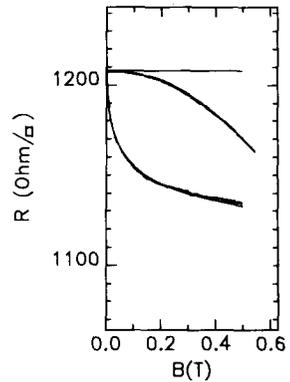
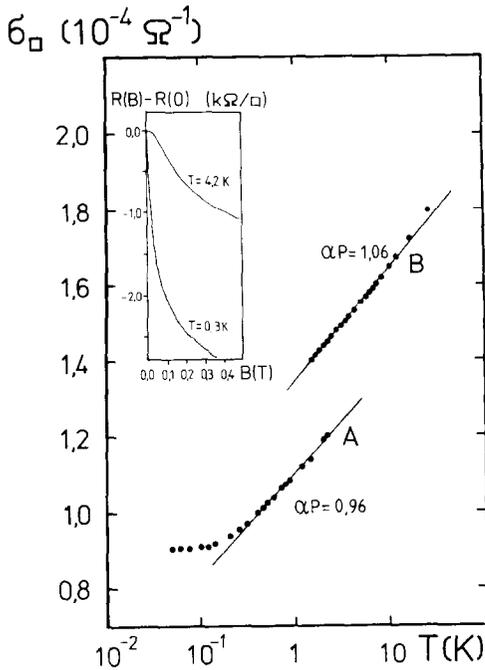


Fig. 1. Sheet conductivity versus T for two different samples with $U_{np} = 0$. The inset shows the magnetoresistance at $T = 4.2 \text{ K}$ and $T = 0.3 \text{ K}$ for sample A with $U_{np} = -0.5 \text{ V}$. The sheet resistances at $B = 0$ are 10087 Ohm and 12188 Ohm respectively.

Fig. 2. Magnetoresistance and fit for a single layer with B perpendicular and parallel to the layer plane. The temperature is $T = 1.5 \text{ K}$.

below about 150 mK. The slope of the straight lines connecting the data is $\alpha P = 1.0 \pm 0.1$ in agreement with the theory of weak localization (eq. (1)). This result seems to indicate that the weak localization mechanism rather than interaction effects is dominant at these T . However, at present one cannot rule out that interaction effects play a role especially at $B = 0$.

The saturation of the conductivity at low temperatures is not an experimental artifact. It has also been observed in Si MOS, and has been attributed to a ‘‘hot electron–finite size effect’’, which occurs when the energy relaxation length becomes comparable with the sample dimensions [6]. Although the characteristic length $L = \sqrt{D\tau_i}$, where D is the diffusion constant and τ_i the inelastic scattering time determined in the present work, is much smaller than the sample size (roughly $0.3 \times 1 \text{ mm}^2$), the inelastic scattering process responsible for the energy loss of the electrons may involve a much longer relaxation time, which is not known in this system. The inset in fig. 1 shows the magnetoresistance for two different temperatures in the low B regime. It varies logarithmically in agreement with theory and with experimental results obtained on other 2D systems [6,7]. In the following we determine the inelastic scattering time τ_i from a fit of the negative magnetoresistance. Theoretically the temperature and magnetic field dependence of the conductivity is given by [6]:

$$\sigma(T, H) = \sigma(T_0, 0) + \frac{\alpha P e^2}{2\pi^2 \hbar} \ln \frac{T}{T_0} + \frac{\alpha e^2}{2\pi^2 \hbar} \left[\psi\left(a + \frac{1}{2}\right) - \ln a \right], \quad (1)$$

where $a = \hbar/2eBl_e l_i$ and ψ is the di-gamma function. In principle, there is another magnetic field dependent term which accounts for the influence of the magnetic field on the interaction effects. We have incorporated this term, which depends on $\mu gB/kT$ and the screening parameter F , in our model calculation and found that the fit of the negative magnetoresistance is insensitive to the choice of the parameter F . This is due to the fact that the g -factor in GaAs is small and in the limit of very low T , where $\mu gB/kT$ becomes important, the conductivity and the magnetoresistance were found to saturate. The negative magnetoresistance given by eq. (1) should depend on the perpendicular component of the magnetic field only. This is confirmed by our experiment in the limit of very small magnetic fields. Fig. 2 shows the magnetoresistance for B perpendicular and parallel to the layer plane for the single layer sample. Also shown is a fit using eq. (1) with $\tau_i = 4.7 \times 10^{-11} \text{ s}$ and $\alpha = 0.9$. The other sample parameters ($E_F = 37 \text{ meV}$, $\mu = 2350 \text{ cm}^2/\text{V} \cdot \text{s}$) are known from measurements in higher fields [8]. A strong anisotropy is observed; however, there is also a negative component for B_{\parallel} , whereas eq. (1) yields a straight line as indicated. The negative component for B_{\parallel} is not due to misalignment, because the vanishing of the Hall voltage in a strong field was used to verify the parallel configuration. The interaction model would lead to a positive magnetoresistance and effects due to spin–orbit coupling are not

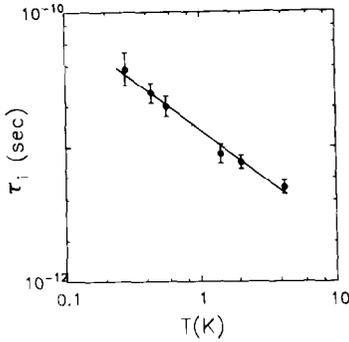


Fig. 3. Inelastic scattering time as determined from a fit of the negative magnetoresistance versus T .

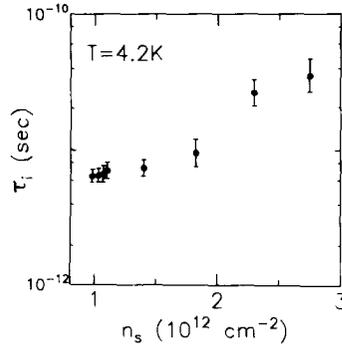


Fig. 4. Inelastic scattering time versus 2D carrier density at $T = 4.2$ K.

expected in this system. This additional magnetoresistance is found to be sample dependent and presumably indicates deviation from a strictly 2D behaviour [9].

From a fit of the negative magnetoresistance we have determined τ_i as a function of T for sample A in a range where the conductivity varies logarithmically and no saturation is observed (fig. 3). The line connecting the data points corresponds to $T^{-0.74}$. This dependence is somewhat weaker than predicted for electron-electron scattering and the experimental values found in the Si MOS system [6].

As already mentioned, the carrier density of the system can be changed by applying a U_{np} bias voltage. The inelastic scattering time as a function of the 2D carrier density is plotted in fig. 4 for $T = 4.2$ K, where n_s is taken from the Hall effect and Shubnikov-De Haas oscillations at high B [4]. The increase of τ_i with n_s may qualitatively be attributed to screening. The variation is much weaker than found in Si MOS. However, comparing these two systems one has to consider that here an increase in n_s is not directly correlated with an increase in the Fermi energy, but with a widening of the space charge potential and thus a reduction of the subband separation, which leads to the occupation of higher subbands. In the limit of high forward bias a transition occurs from 2D to 3D.

In summary, we have found that electrons in thin layers of GaAs produced by alternating n- and p-doping are weakly localized at low temperatures. The temperature dependence of the sheet conductivity and the negative magnetoresistance can be understood in terms of the existing theories. The results further substantiate the 2D behaviour of the system in the limit of low carrier density.

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