Anisotropy of the conductivity in $\delta$-doped multilayers

Th. Ihn $^{a,\ast}$, C. Gauer $^b$, F. Koch $^a$, J.P. Kotthaus $^b$

$^a$ Physik Department E16, Technische Universität München, James-Franck-Strasse, D-85748 Garching, Germany
$^b$ Sektion Physik, Ludwig-Maximilians Universität, D-80539 München, Germany

Received 21 June 1995; accepted for publication 21 September 1995

Abstract

We have investigated three Si $\delta$-doped multilayer structures with sheet-doping concentrations around $N_D = 5 \times 10^{11} \text{cm}^{-2}$ and sheet distances of 17, 40 and 100 nm. Cyclotron resonance measurements and far-infrared spectroscopy in a multiple reflection geometry allow the determination of the effective masses and the scattering times normal and parallel to the doping planes. While the scattering time was found to be isotropic, the effective mass exhibited a strong anisotropy with $m_\perp < m_\parallel$. The measurements are supported by a self-consistent calculation of the subband structure of the samples.

A number of evenly spaced $\delta$-doped planes in a MBE-grown GaAs matrix can be considered to be a periodical doping structure in the growth direction. Many authors have reported measurements of the electronic properties of such multilayers which probed the motion of carriers parallel to the doping planes [1–4]. The usual description of a single metallic $\delta$-doped layer considers it as translationally invariant within the doping plane. In multilayers an additional translation symmetry in the third dimension is introduced. A displacement by a multiple of the sheet distance $d$ leaves the system unchanged (ignoring boundaries). In the limit of $d \approx N_D^{-1/2}$ ($N_D$ is the sheet-doping concentration) we have a three-dimensional system, whereas the case of $d \gg N_D^{-1/2}$ represents a system with fully decoupled parallel two-dimensional electron gases. The conductivity measured in the growth direction is expected to be different from that measured in the plane. The conductivity is determined by the number density of the charge carriers contributing to the transport, their effective masses and the scattering times. We measured the anisotropy of the two latter quantities by comparing the in-plane cyclotron resonance with the plasmonic excitations normal to the $\delta$-layers. All measurements were performed with a Fourier-transform spectrometer at $T = 4.2 \text{ K}$.

The samples investigated typically contained 10 silicon $\delta$-doped layers with a sheet-doping concentration of about $N_D = 5 \times 10^{11} \text{ cm}^{-2}$ embedded in a GaAs matrix. The main difference between the three samples is the separation of the doped planes, which is $d = 100 \text{ nm (sample A)}$, $40 \text{ nm (sample B)}$ and $17 \text{ nm (sample C)}$. The samples have been grown at a temperature of 520°C. It was demonstrated in Ref. [3] that the $\delta$-layers are clearly resolved even in sample C in spite of the small
layer separation. Further details about the sample growth and transport properties can be found in Ref. [3].

Fig. 1 shows the calculated self-consistent potential, the energy levels and the density of states (DOS) in the three samples. Resonant subband-states of neighbouring sheets interact more strongly for smaller $d$ and when the states are higher in energy and, hence, more extended. This interaction leads to a level repulsion of the subbands which results in the minibands labelled $E_0$ and $E_1$ indicated by the hatched areas in Fig. 1. In sample A this interaction is not strong enough to widen the minibands significantly, whereas in sample C the level repulsion is so strong, that the subband character of individual wells is completely destroyed and the energy dispersion in the $z$-direction is given by $E(k) = \hbar^2 k^2 / 2m_\perp$ with $m_\perp = m^*$, the GaAs effective mass. Sample B with a sheet spacing between that of samples A and C has two occupied minibands like sample A. While the $E_0$-miniband states are hardly split, the $E_1$-miniband states can be described by a parabolic dispersion in the $z$-direction similar to the states in sample C. The effective mass $m_\perp = 0.45m^*$ is, however, significantly smaller than the GaAs conduction band mass $m^*$. This important result, which can be understood as a consequence of the "electrons in a weak periodic potential" situation, raises the question, whether this effective mass of the electrons in the $E_1$-miniband can be measured in an experiment.

We have employed both cyclotron resonance and magnetotransport measurements in order to obtain information about the in-plane transport properties of the three samples. The results of the self-consistent calculation are in excellent agreement with the magnetotransport data [3]. In the cyclotron resonance measurements we observe two modes of different linewidths in both sample A and sample B, in accordance with the two occupied minibands of different mobilities. In sample C, however, only one very broad resonance is identified similar to a three-dimensional sample. The in-plane cyclotron effective mass of the $E_1$-miniband extracted from the data according to $m_{\text{CR}} = eB/\Delta E_{\text{res}}$, where $B$ is the magnetic field and $\Delta E_{\text{res}}$ the resonance energy, is about 0.062$m_0$, e.g. lower than the expected value of 0.067$m_0$. This decreased effective mass due to a resonance energy increased relative to $\hbar\omega_0$ is a result of the strong potential fluctuations in the $\delta$-doping planes [5,6].

In order to obtain information about transport properties normal to the doping planes we measured the transmission of the samples in the multiple reflection geometry shown in the inset of Fig. 2. The metal film evaporated on top of the multilayer leads to a parallel component of the electric field vector which is small compared to the normal component in the near-field. This geometry therefore allows an optimal excitation of electrons in the growth direction of the crystal. We used a magnetic field parallel to the doping planes (see Fig. 2) in order to obtain the reference measurements necessary in Fourier transform spectroscopy. The diamagnetic shift of the minibands, which in first order perturbation theory is given by $\Delta E_{\text{dia}} = e^2 B^2 <z^2>/2m_0^*$, leads to the depopulation of the $E_1$-miniband at sufficiently high mag-
In sample B, however, the width of the $E_1$-miniband is about 5 meV (see Fig. 1). In contrast to the observed interminiband plasmon in sample A it should therefore be possible to detect an intraminiband plasmon in this $E_1$-miniband. The participating one-electron states are above the barriers which separate neighbouring layers and thus the electron motion is mainly confined by the potential barriers at the top and bottom of the multilayer rather than by the inter-layer barriers. Quantum mechanically, a simplified picture of the electronic potential for electrons in the $E_1$-miniband would be a large well (with extension over all layers) with a weakly modulated pseudo-potential accounting for the orthogonality of the states. The total density of states of all the levels constituting this “miniband” sums up to a shape that is well described by a $E^{1/2}$-behaviour as for a three-dimensional density of states (see Fig. 1), containing the “miniband-mass” $m_\perp$. We therefore expected to find an intraminiband plasmon with energy close to the three dimensional plasma energy

$$\omega_p^2 = \frac{n_e e^2}{\varepsilon_0 m_\perp},$$

where $n_e$ denotes the electron concentration, $m^*$ is the GaAs conduction-band mass relevant for the in-plane motion and $m_\perp$ is the effective mass relevant for the motion normal to the doping planes. The Fermi energy in this sample is determined to be $E_F = 5$ meV from the calculation and from Shubnikov–de Haas measurements parallel to the doping planes [3]. The plasmon frequency is thus estimated from Eq. (1) to be $\omega_p = 8.25$ meV. Fig. 3 shows the measured resonance. The resonance position is in excellent agreement with the estimated value, confirming the value of the calculated effective mass $m_\perp$.

The width of the plasmon resonance is determined by the momentum decay of the plasmon. It is caused by scattering of the electrons which constitute the plasmon at the potential fluctuations of the $\delta$-layers. This allows us to determine a scattering time $\tau_\perp$ normal to the doping planes from the line-width of the plasma resonance. The Lorentz-fit (in this case not obtained from an RPA
In conclusion, we have measured the transport properties normal to the doping planes of δ-doped multilayers in a far-infrared experiment. The samples exhibit no significant anisotropy in the scattering times parallel and perpendicular to the doped layers. However, a strong anisotropy in the \( E_1 \)-miniband effective masses relevant for the motion in the two directions was calculated and proven experimentally for sample B, where we found \( m_\parallel = 0.45m^* \) for the \( E_1 \)-miniband.

References