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Anisotropy of the conductivity in δ-doped multilayers

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Abstract

We have investigated three Si δ-doped multilayer structures with sheet-doping concentrations around $N_D = 5 \times 10^{11} cm^{-2}$ 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 δ-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 δ-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 δ-layers. All measurements were performed with a Fourier-transform spectrometer at $T = 4.2$ K.

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

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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 $E(k)=\hbar^2k^2/2m_\perp$ 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

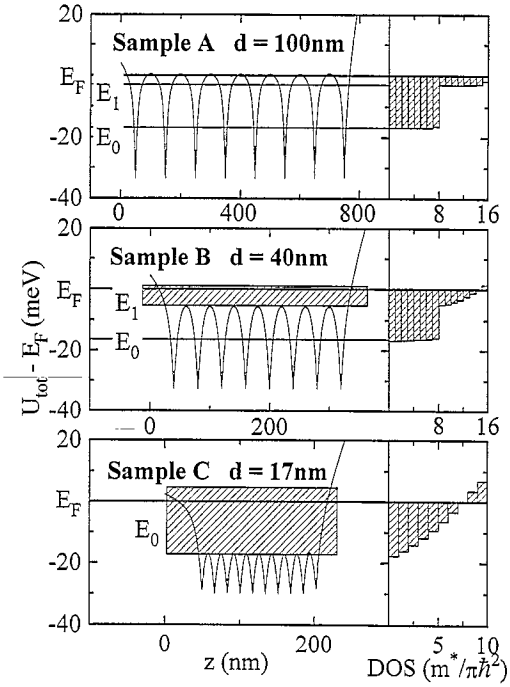

Fig. 1. Self-consistent potential and electron density at $T=1.3$ K for the three samples. (a) Sample A with $d=100$ nm and $N_D=5.6\times10^{11}$ cm^{-2}. (b) Sample B with $d=40$ nm and $N_D=5.4\times10^{11}$ cm-2. (c) Sample C with $d=17$ nm and $N_D=4.3\times10^{11}$ cm^{-2}.

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 $m_{CR}=eB/E_{res}$, where B is the magnetic field and E_{res} the resonance energy, is about $0.062m_0$, e.g. lower than the expected value of $0.067m_0$. This decreased effective mass due to a resonance energy increased relative to $\hbar\omega_c$ is a result of the strong potential fluctuations in the δ-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 $\Delta E_{dia}=e^2B^2<z^2>/(2m^*)$, leads to the depopulation of the E_1-miniband at sufficiently high mag-

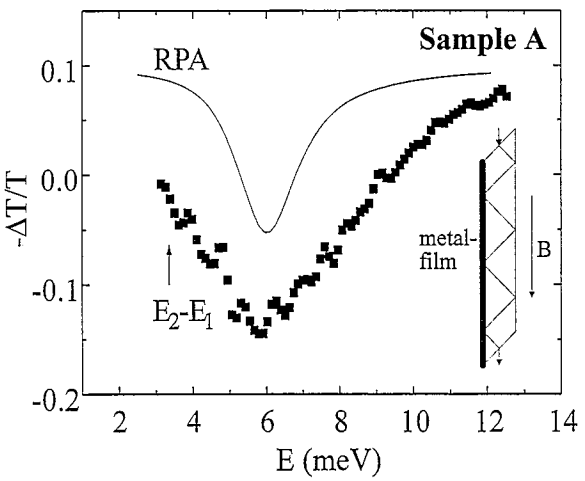

Fig. 2. Interminiband resonance in sample A. The arrow indicates the position of the $E_1 \rightarrow E_2$ transition estimated without the depolarisation shift. The result of an RPA-calculation is shown as a solid line. The inset shows the geometry of the setup.

netic fields enabling us to switch the excitations in this miniband on and off. With this arrangement we can explore plasmonic excitations in the E_1-miniband normal to the doping planes of the multilayer structure.

Fig. 2 shows the results of the measurements for sample A. The resonance at about 6 meV is attributed to the $E_1 \rightarrow E_2$ interminiband transition. The self-consistent calculation gives a separation of 3 meV between the E_1- and the E_2-minibands (The E_2-miniband is not shown in Fig. 1.). The discrepancy to the measured value is caused by a strong depolarisation shift of the transition. To confirm this interpretation we performed a calculation of the $E_1 \rightarrow E_2$ resonance in the random phase approximation (RPA) using the wave functions and energy-spectrum from the self-consistent calculation [7]. The solid line in Fig. 2 shows the result for a calculation in which a broadening of the resonance was achieved by introducing a scattering time of 1.3 ps which is not too far from the experimental value of 0.45 ps obtained from the resonance linewidth. There is an excellent agreement between the measured and the calculated resonance energy confirming that the individual δ-layers are decoupled, as expected for $d \gg N_D^{-1/2}$, and that it is actually the depolarisation-shifted $E_1 \rightarrow E_2$ transition that is observed.

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 pseudopotential 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

$$\omega_p^2 = \frac{n_s e^2}{\epsilon \epsilon_0 m_\perp}, \tag{1}$$

where n_s 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 $E_p = 8.25$ 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 δ-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

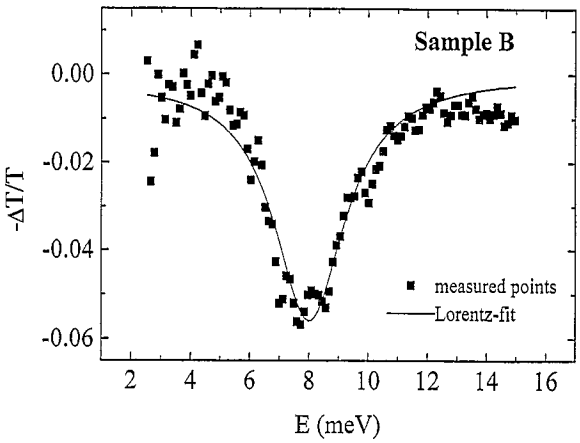

Fig. 3. Plasma-resonance of electrons in the first miniband in sample B. The solid line is a Lorentz-fit with the resonance position at $E_{res} = 8$ meV.

calculation) of the resonance (see Fig. 3) gives a plasmon lifetime of $\tau_\perp = 0.46$ ps, which agrees with the in-plane value determined from Hall-measurements [3] and cyclotron resonance measurements. Similar agreement was found for sample C.

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 $m_\perp = 0.45m^*$ for the E_1-miniband.

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