The role of doped layers in dephasing of 2D electrons in quantum well structures

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Abstract. The temperature and gate voltage dependencies of the phase breaking time is studied experimentally in the structures with quantum well based on GaAs/InGaAs. There is shown that arising of the states at the Fermi energy in the doped layers (Sn δ layer in our case) leads to significant decreasing of the phase breaking time and to weakness its temperature dependence.

The inelastic of the electron-electron interaction is the main phase breaking mechanism in low dimensional structures at low temperature. This mechanism predicts divergence of phase breaking time (τφ) with decreasing temperature. But unexpected saturation of τφ at low temperatures was revealed in recent years in one and two dimensional structures [1, 2]. It is one of reason of the particular interest to the possible additional dephasing mechanisms in such structures.

The analysis of the low field negative magnetoresistance, resulting from destruction of the interference correction to the conductivity, is the main method of determination of the phase breaking time. We report the results of detailed studying of the negative magnetoresistance in gated structures based on GaAs/InGaAs. The heterostructures investigated consist of 0.5 μm-thik undoped GaAs epilayer, a Sn δ-layer, a 60 Å spacer of undoped GaAs, a 80 Å In0.2Ga0.8As well, a 60 Å spacer of undoped GaAs, a Sn δ-layer, and a 3000 Å cap layer of undoped GaAs. The samples were mesa etched into standard Hall bridges and Al gate was thermally evaporated over the cap layer. The gate voltage dependencies of the electron density, conductivity and Hall mobility are presented in Fig. 1 for one of the structures. The low field magnetoresistance for some voltage are shown in Fig. 2. The magnetic field dependencies of Δσ(B) at B < 1 - 0.5Btr, where Btr = hc/2e1l2, l is mean free path, are well described by the standard Hikami expression [3]:

\[ \Delta \sigma (b) = \alpha G_0 \left[ \psi \left( \frac{1}{2} + \frac{\tau_p}{\tau_\phi} b \right) - \psi \left( \frac{1}{2} + \frac{1}{b} \right) - \ln \frac{\tau_p}{\tau_\phi} \right], \]

where \( G_0 = e^2/(2\pi^2 h) \), b is magnetic field measured in units of \( B_{tr} \), \( \tau_p \) is momentum relaxation time, and \( \alpha = 1 \) in the diffusion approximation. In [3] we showed that (1) well describes Δσ(B) beyond the diffusion approximation also, but with \( \alpha < 1 \). Thus, one can determine \( \alpha \) and \( \tau_\phi \) as fitting parameters, comparing the experimental Δσ(B) dependence with (1). Note that values of \( \alpha \) and \( \tau_\phi \) determined by this way depend on fitting magnetic field range and in Fig. 3 the conductivity dependencies of \( \tau_\phi \) as determined from the different fitting range are presented.
Fig. 1. The gate voltage dependencies of the conductivity (a), electron density (b), and Hall mobility (c) at \( T = 4.2 \) K. The straight line in (b) is the theoretical total density of the electrons.

Fig. 2. Negative magnitoresistance at \( T = 4.2 \) K for two gate voltages. Curves are the theoretical dependencies according to (1) with parameters obtained by the fitting in magnetic field range \( 0 - 0.25B_{tr} \) (open symbols) and \( 0 - 0.5B_{tr} \) (solid symbols) for \( T = 4.2 \) K (circles) and \( T = 1.5 \) K (squares). Curves are the theoretical dependencies given by (2).

When inelasticity of electron-electron interaction is main phase breaking mechanism, \( \tau_\psi \) depends on conductivity and temperature only and for 2D case

\[
\tau_\psi = \frac{\hbar}{kT} \frac{\sigma}{2\pi G_0} \frac{1}{\ln \left( \frac{\sigma}{2\pi G_0} \right)}.
\]  

As is seen from Fig. 3 the conductivity dependence of \( \tau_\psi \) is close to the theoretical one when \( \sigma \) varies in the range \((0.2 - 1.2) \times 10^{-3} \Omega^{-1}\), but significant deviation is evident for larger \( \sigma \). The temperature dependencies of \( \tau_\psi \) are presented in Fig. 4 for some gate voltage and one can see that \( \tau_\psi \) deviates from \( 1/T \) dependence just for \( \sigma > 1 \times 10^{-3} \Omega^{-1} \).

To interpret these temperature and conductivity dependencies of \( \tau_\psi \) let us analyze the variation of density of electron in quantum well \( n \) (exactly this value is determined from the Hall effect and Shubnikov–de Haas oscillation) with gate voltage (see Fig. 1). The
Fig. 4. Gate voltage dependencies of the ratio \( \frac{\tau_{\text{theor}}}{\tau_{\Phi}} \) (a) for \( T = 4.2 \) K (circles) and \( T = 1.5 \) K (squares). The difference between the total electron density and density of 2D electron in the quantum well as function of \( V_g \) (b).

Fig. 5. Temperature dependencies of \( \tau_{\Phi} \) at \( V_g = -1.8 \) V (squares) and \( V_g = +0.5 \) V (circles). The line is the \( 1/T \) dependence.

variation of the total electron density \( n_t \) with \( V_g \) has to be described by the simple expression

\[
n_t(V_g) = n(0) + V_g C/e,
\]

where \( C \) is the gate-2D channel capacity per centimeter squared (straight line in Fig. 1(a)). One can see that in the range of \( V_g \) from \(-1\) to \(-3\) V the experimental data are close to this dependence, but at \( V_g > -1 \) V the electron density in the quantum well is less than the total density of the electrons \( n_t \). It means that at \( V_g > -1 \) V the fraction of the electrons \( (n_t - n) \) occupies the states in \( \delta \)-layers. From Fig. 4, where the gate voltage dependence of \( (n_t - n) \) and ratio \( \tau_{\Phi}/\tau_{\text{theor}} \) are presented, one can see that \( \tau_{\Phi}/\tau_{\text{theor}} \) deviates from unity when the electrons arise in \( \delta \)-layers. Thus, appearance of the states in \( \delta \)-layer at the Fermi energy, and, consequently, the arising of the tunneling of the electrons between quantum well and \( \delta \)-layer leads to decreasing \( \tau_{\Phi} \). This interdependence is clear when the phase breaking time of an electron in \( \delta \)-layer is significantly shorter than that in quantum well. The phase breaking mechanisms in the doped layers, where electrons occupy the states in the tail of density states, are the subject of additional study, but it seems no wonder that dephasing in this layers occurs faster than in quantum well.

In conclusion, the \( \delta \)- or modulation doped layers are arranged in heterostructures to create the carriers in quantum well or near the hetero-junction. When the states at the Fermi energy appear in the doped layers, the tunneling of the carriers between quantum well and doped layers arises. This process can lead to significant decreasing of the phase breaking time of the carriers in quantum well.

Acknowledgment

This work was supported in part by the RFBR through Grants No. 00-02-16215 and No. 01-02-17003, the Program University of Russia through Grants No. 990409 and No. 990425, and the CRDF through Award No. REC-005.

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