Effect of strong in-plane magnetic field on negative magnetoresistance in 2D at low perpendicular magnetic field

G. M. Minkov[1], O. E. Rut[1], A. V. Germanenko[1], A. A. Sherstobitov[1] and B. N. Zvonkov[2]

[1] *Institute of Physics and Applied Mathematics, Ural State University, Ekaterinburg 620083, Russia*

[2] *Physical-Technical Research Institute, University of Nizhni Novgorod, Nizhni Novgorod 603600, Russia*

The interference correction determines in the main the temperature and magnetic field dependences of the conductivity of weakly disordered two-dimensional systems. For an ideal two-dimensional system only the perpendicular magnetic field $B_\perp$ destroys the interference resulting in negative magnetoresistance, whereas the in-plane magnetic field $B_\parallel$ does not effect the interference correction. Therefore, application of the in-plane magnetic field should not change the magnetoresistance caused by the perpendicular field. In reality, an interface roughness of 2D structures not only gives rise to the negative magnetoresistance at in-plane magnetic field but changes the magnetoresistance in perpendicular field in the presence of in-plane field [1]. Thus, the study of the interference correction in the presence of in-plane magnetic field gives a possibility to find the parameters of interface roughness. Moreover, we show that the effect of in-plane magnetic field allows us to determine the role of doped layers in dephasing.

In the present work we experimentally study the gated GaAs/InGaAs/GaAs quantum well heterostructures which consist of 0.5 mkm-thick undoped GaAs epilayer, a Sn δ-layer, a 9 nm spacer of undoped GaAs, a 8 nm $In_{0.2}Ga_{0.8}As$ well, a 9 nm spacer of undoped GaAs, a Sn δ-layer, and a 300 nm cap layer of undoped GaAs. The Al gate electrode was thermally evaporated onto the cap layer. The electron density n and mobility μ at $V_g = 0$ were the following: $n = 9.5 \times 10^{15}$ m^{-2}, $\mu = 1.4$ m^2/Vs. The Hall effect and Shubnikov-de Haas oscillations show that at $V_g > -1$ V the states in δ-layers start to occupy. Just in this region the dephasing time τ_ϕ decreases with conductivity increase, contrary to theoretical prediction [2] (Fig. 1(d)). In the paper [3] we have shown that the discrepancy can be explained by the tunneling of electrons from the quantum well to the δ-doped layer.

Firstly, we consider the data for the case when this effect is negligible. As an example, the low-field magnetoresistance $\Delta\sigma(B_\perp)$ measured for different values of $B_\parallel$ for $V_g = -1.5$ V is shown in Fig. 1(a). Our analysis shows that these data are well described by the HLN formula [4] with some effective value of dephasing rate τ_{eff}^{-1} growing with $B_\parallel$ increase [see Fig. 1(b)]. Thus, application of the in-plane field increases the dephasing rate but does not otherwise alter the negative magnetoresistance line shape. Just such an effect of the in-plane magnetic field was predicted for short-range correlated roughness [1]. For this case $\tau_{eff}^{-1} = \tau_\phi^{-1} + \tau_\parallel^{-1}$, where

$$\frac{1}{\tau_\parallel} \simeq \frac{1}{\tau_p} \frac{\sqrt{\pi}}{4} \left(\frac{B_\parallel}{B_{tr}}\right)^2 \frac{\Delta^2 L}{l_p^3}\,. \qquad (1)$$

Here, τ_p is the momentum relaxation time, $B_{tr} = \hbar/(2el_p^2)$, l_p is the mean free path, Δ is the root-mean-square height fluctuations, and L is the distance over which the fluctuations are correlated. One can see from Fig. 1(b) that τ_p/τ_{eff} really increases linearly with $B_\parallel^2$ in full agreement with (1). The slope of this dependence gives the value of $\Delta^2 L \simeq 6$ nm^3. If L is set to be equal to $l_p \simeq 24$ nm one obtains $\Delta \simeq 0.5$ nm. We have carried out such an analysis for various gate voltages and plotted the V_g dependence of $\Delta^2 L$ in Fig. 1(c). One can see that

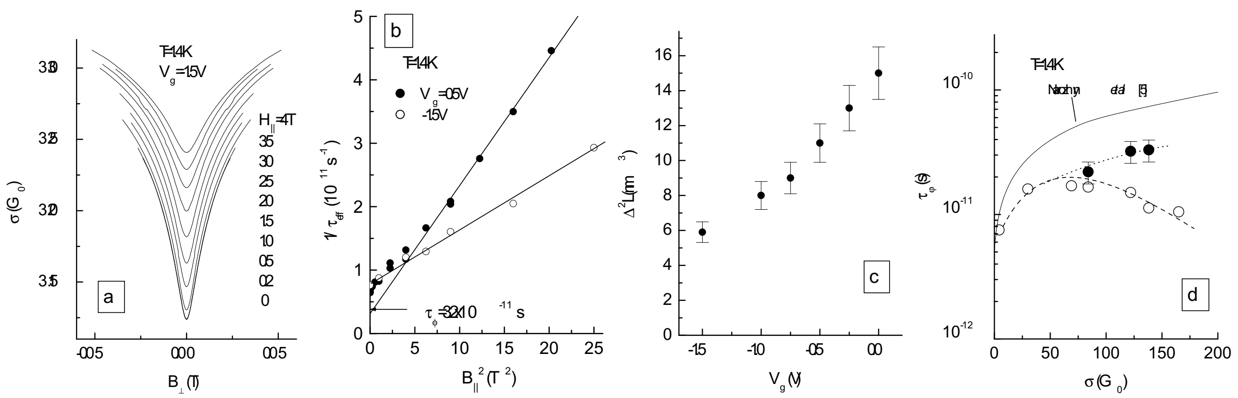

Figure 1: (a) The $\Delta\sigma$-versus-$B_\perp$ dependences measured for different in-plane magnetic fields; (b) The ratio τ_p/τ_{eff} as a function of $B_\parallel$ for $V_g = -1.5$ V ($B_{tr} = 0.21$ T) and -0.5 V ($B_{tr} = 0.022$ T); (c) The parameter of interface roughness $\Delta^2 L$ as a function of the gate voltage; (d) The τ_ϕ-versus-σ dependence. Open circles are obtained from the fit of the $\Delta\sigma$-versus-$B_\perp$ plot at $B_\parallel = 0$, solid circles are the extrapolation points from the panel (b), solid line is theory [5], other lines are provided as a guide for the eye.

$\Delta^2 L$ decreases with decreasing gate voltage. The following model can explain this observation. The inner interface lying in the depth of the structure has smaller roughness than that lying closer to the cap layer. With decrease of the gate voltage the wave function is kept close gainst the inner interface that in its turn leads to reduction of the role of the more rough outer interface. The larger roughness of the outer interface seems to be natural for the quantum well heterostructures studied because it is grown on strained InGaAs layer.

Next, we analyze the parallel-magnetic-field dependence of the dephasing rate for $V_g > -1$ V ($\sigma > 70\,G_0$). The τ_{eff}-versus-$B_\parallel$ dependence for this case is presented in Fig. 1(b). A pronounced deviation from a quadratic dependence is evident. An extrapolation of the experimental data to $B_\parallel = 0$ gives the dephasing rate smaller than that obtained from the negative magnetoresistance at $B_\parallel = 0$. Such a deviation is observed at those conductivity values at which the deviation of τ_ϕ down from the theoretical value occurs [see Fig. 1(d)]. The last was attributed in [4] with the tunneling of electrons from the quantum well to the states in doped layer which appear at the Fermi energy at these gate voltages. For this mechanism the $1/\tau_\phi$-versus-$B_\parallel^2$ dependence becomes clear. The in-plane magnetic field shrinks the wave functions in growth direction of the structure and, thus, reduces the role of the tunneling. Therefore, an extrapolation of the $1/\tau_\phi$-versus-$B_\parallel^2$ plot from strong magnetic fields to $B_\parallel = 0$ should give the dephasing rate without contribution of tunneling. Indeed, the values of τ_ϕ obtained in such a way are close to the theoretical dependence [5] within whole conductivity range as it is seen from Fig. 1(d).

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