Role of doped layers in the dephasing of two-dimensional electrons in quantum-well structures

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The temperature and gate voltage dependences of the phase breaking time are studied experimentally in GaAs/InGaAs heterostructures with a single quantum well. It is shown that appearance of states at the Fermi energy in the doped layers leads to a significant decrease of the phase breaking time of the carriers in the quantum well and to saturation of the phase breaking time at low temperature.

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Inelasticity of electron-electron interaction is the main mechanism of dephasing of the electron wave function in low-dimensional systems at low temperature. Whereas the theory predicts divergence of the phase breaking time τ_φ with decreasing temperature,[1] an unexpected saturation of τ_φ at low temperatures has been experimentally found in one- and two-dimensional structures.[2,3] These observations rekindle a particular interest in dephasing.

In order to perform transport experiments, a δ- or modulation-doped layer is arranged in semiconductor heterostructures. Usually the doped layer is spaced from the quantum well, all carriers leave the impurities and pass into the quantum well. In some cases a fraction of the carriers remain in the doped layer. As a rule, these carriers do not contribute to the dc conductivity because they are localized in fluctuations of long-range potential. In other words, the percolation threshold of doped layer is above the Fermi level. In this paper we demonstrate that the presence of the carriers and/or empty states in a doped layer at the Fermi energy can contribute to dephasing and its temperature dependence.

The main method of experimental determination of the phase breaking time is an analysis of the low-field negative magnetoresistance, resulting from destruction of the interference quantum correction to the conductivity. We have measured the negative magnetoresistance in single-well gated heterostructures GaAs/$In_xGa_{1-x}As$. The heterostructures were grown by metal-organic vapor-phase epitaxy on a semi-insulator GaAs substrate. They consist of a 0.5-mkm-thick undoped GaAs epilayer, a Sn δ layer, a 60-Å spacer of undoped GaAs, an 80-Å $In_{0.2}Ga_{0.8}As$ 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 then an Al gate electrode was deposited onto the cap layer by thermal evaporation. The measurements were performed in the temperature range 1.5–16 K at magnetic field B up to 6 T. The discrete at low-field measurements was 5×10^{-5} T. The electron density was found from the Hall effect and from the Shubnikov–de Haas oscillations. These values coincide with an accuracy of 5% over the entire gate-voltage range.

Varying the gate voltage V_g from $+1.0$ to -2.5 V we changed the electron density in quantum well from 8×10^{11} to 3.5×10^{11} cm^{-2} and the conductivity σ from 2.3×10^{-3} to 1.5×10^{-4} Ω^{-1}. The low-field magnetoconductivity $\Delta\sigma(B)=\rho_{xx}^{-1}(B)-\rho_{xx}^{-1}(0)$ for two gate voltages is shown in Fig. 1. To determine the phase breaking time we have used the standard procedure of fitting of the low-field magnetoconductivity to the Hikami expression[4]

$$\Delta\sigma(B)=\alpha G_0\left[\psi\left(\frac{1}{2}+\frac{\tau_p}{\tau_\varphi}\frac{B_{tr}}{B}\right)-\psi\left(\frac{1}{2}+\frac{B_{tr}}{B}\right)-\ln\left(\frac{\tau_p}{\tau_\varphi}\right)\right], \tag{1}$$

where $G_0=e^2/(2\pi^2\hbar)$, $B_{tr}=\hbar/(2el^2)$, l is the mean-free path, τ_p is the momentum relaxation time, $\psi(x)$ is the digamma function, and α is equal to unity. This expression was obtained within the diffusion approximation. Nevertheless, as shown in Ref. 5, with α less than unity it can be used for analysis of the experimental data even beyond the diffusion approximation, giving the value of τ_φ close to the true one. The results of the fitting carried out in two magnetic field ranges are presented in Fig. 1. One can see that the values of the fitting parameters somewhat depend on the magnetic-field range. However, the difference in τ_φ does not

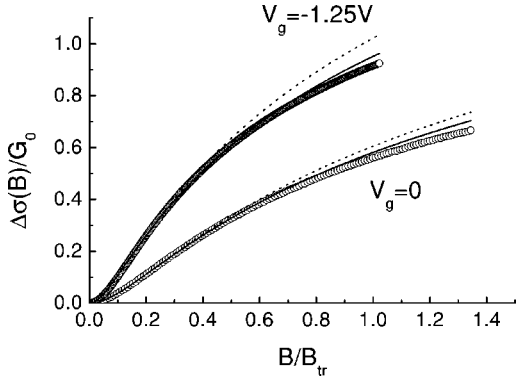

FIG. 1. Conductivity changes versus magnetic field at $T=4.2$ K for two gate voltages. Symbols are the experimental data. Curves are the results of best fit by Eq. (1), carried out over the ranges $0-0.25B_{tr}$ (dotted curves) and $0-0.5B_{tr}$ (solid curves). The fitting parameters for the curves from the top to bottom are: $\alpha=0.8$, $\tau_\varphi=0.87\times10^{-11}$ sec; $\alpha=0.70$, $\tau_\varphi=1.0\times10^{-11}$ sec; $\alpha=0.8$, $\tau_\varphi=0.73\times10^{-11}$ sec; $\alpha=0.68$, $\tau_\varphi=0.77\times10^{-11}$ sec. $B_{tr}=5\times10^{-3}$ T for $V_g=0$ V, $B_{tr}=1.5\times10^{-2}$ T for $V_g=-1.25$ V.

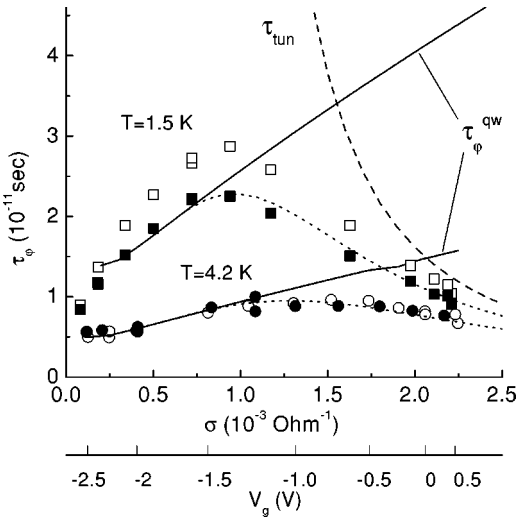

FIG. 2. Conductivity (gate voltage) dependences of τ_φ obtained by fitting of the experimental $\Delta\sigma$-versus-B curves by Eq. (1) in the magnetic-field range 0–$0.25B_{tr}$ (open symbols) and 0–$0.5B_{tr}$ (solid symbols) for two temperatures. Solid lines are the theoretical dependences given by Eq. (2). The τ_{tun}-versus-σ line is obtained as described in text. Dotted lines are $\tau_\varphi=[(\tau_\varphi^{qw})^{-1}+(\tau_{tun})^{-1}]^{-1}$.

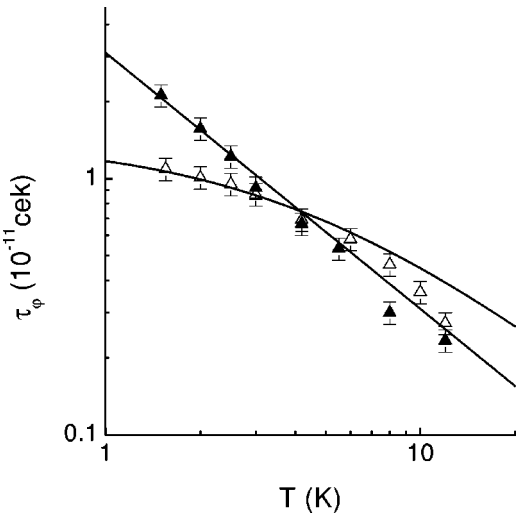

FIG. 3. The temperature dependences of τ_φ at $V_g=-1.8$ V, $\sigma=0.53\times10^{-3}$ Ω^{-3} (solid triangles) and $V_g=+0.5$ V, $\sigma=2.2\times10^{-3}$ Ω^{-3} (open triangles). The lines are results of calculation described in text with $\tau_{tun}=\infty$ for $V_g=-1.8$ V and $\tau_{tun}=1.4\times10^{-11}$ sec for $V_g=+0.5$ V.

exceed 20%. The value of α is lower than unity and lies within the interval $\alpha=0.6$–0.8. This is result of the fact that in the structure investigated the ratio τ_p/τ_φ is not low enough:[5] $\tau_p/\tau_\varphi\simeq0.014$–$0.1$.

Figure 2 shows the conductivity dependence of τ_φ for two temperatures. One can see that the τ_φ-versus-σ plot exhibits the maximum: τ_φ increases with increasing conductivity while $\sigma<10^{-3}$ Ω^{-1} and decreases at higher σ values. Qualitatively this behavior is independent of the fitting range. The maximum is more pronounced at lower temperature.

Nonmonotonic conductivity dependence of τ_φ is in conflict with the theoretical prediction. In two-dimensional (2D) systems the main phase breaking mechanism at low temperature is inelasticity of the electron-electron interaction and the phase breaking time has to increase monotonically with σ:[1]

$$\tau_\varphi^{th}=\frac{\hbar}{kT}\frac{\sigma}{2\pi G_0}\left[\ln\left(\frac{\sigma}{2\pi G_0}\right)\right]^{-1}. \tag{2}$$

As is seen from Fig. 2 the conductivity dependence of τ_φ is close to the theoretical one only when $\sigma<(1.0$–$1.2)\times10^{-3}$ Ω^{-1}, but significantly deviates for higher σ. In addition, the increase of σ leads to changing in the temperature dependence of τ_φ (see Fig. 3). When $\sigma=(0.2$–$1.2)\times10^{-3}$ Ω^{-1}, the temperature dependence of τ_φ is close to T^{-1} predicted theoretically. At higher σ, the τ_φ-versus-T plot shows the saturation at low temperature.

To interpret the experimental temperature and conductivity dependences of τ_φ, let us first analyze the variation of electron density in the quantum well n with the gate voltage [see Fig. 4(a)]. The total electron density n_t in a gated structure has to be given by the simple expression $n_t(V_g)=n(0)+V_gC/|e|$, where C is the gate-2D channel capacity per centimeter squared. The straight line in Fig. 4(a) represents this dependence obtained with $n(0)$ as a fitting parameter and $C=\varepsilon/(4\pi d)$, where $d=3000$ Å is the cap-layer thickness, $\varepsilon=12.5$. One can see that over the range of V_g from -2.5 to -0.5 V the experimental data are close to the calculated dependence, whereas at $V_g>-0.5$ V the electron density in the quantum well is less than the total density n_t.

Such a behavior can be understood from inspection of Fig. 5, which presents the energy diagram of the structure investigated for two gate voltages. Self-consistent calculation shows that at $V_g<-0.5$ V there are only the states located in the quantum well (upper panels). At $V_g>-0.5$ V the states located in the δ layer appear (lower panels). However, it should be borne in mind that the strong potential fluctuations in the δ layer leads to formation of the tail in density of these states. At low electron density in the δ layer, when the Fermi level lies within the tail, the electrons are localized in potential fluctuations and thus do not contribute to the struc-

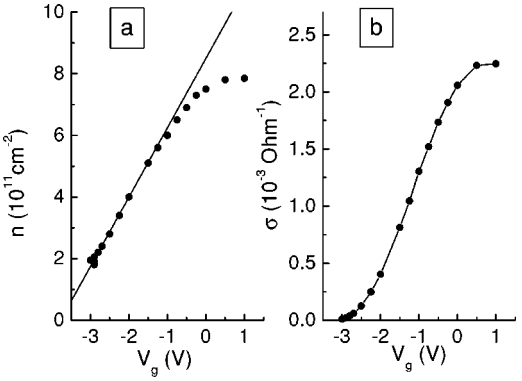

FIG. 4. The experimental gate voltage dependences of the electron density in quantum-well (a) and structure conductivity (b) at $T=4.2$ K (symbols). The straight line in (a) is the calculated total electron density with $n(0)=8.4\times10^{11}$ cm^{-2}.

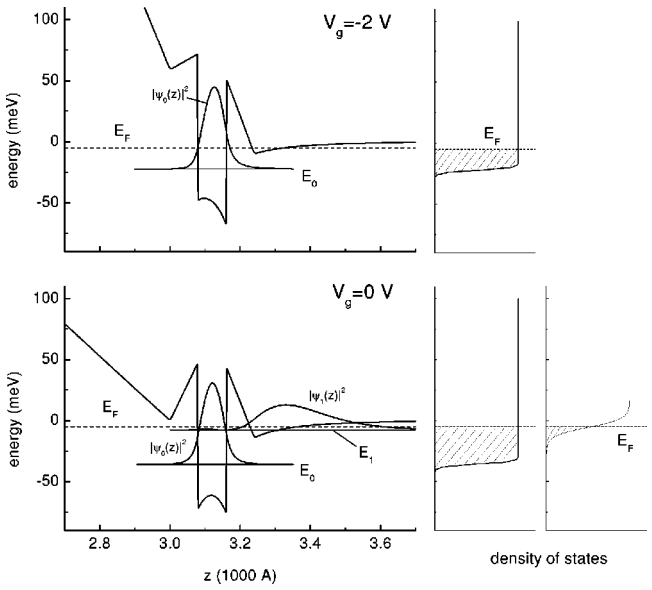

FIG. 5. The calculated energy diagram (left panels) and sketch for density of electron states (other panels) for the structure investigated at two gate voltages: $V_g=-2.0$ and 0 V. The energy levels of size quantization E_i and corresponding wave functions squared $|\Psi_i(z)|^2$ are presented also. The distance z is measured from the gate. The height of the Schottky barrier was taken to be equal to 700 meV ($V_g=0$).

ture conductivity. The absence of both magnetic-field dependence of the Hall coefficient and positive magnetoresistance in a wide range of magnetic field shows that this situation occurs in our structures while $(n_t-n)<10^{11}$ cm^{-2}.

Now we are in position to put together the gate voltage dependences of the phase breaking time and those of the electron density in the δ layer. Figure 6 shows the ratio $\tau_\varphi^{th}/\tau_\varphi$ as a function of V_g, where $\tau_\varphi^{th}(V_g)$ has been found from Eq. (2) with the use of experimental σ-versus-V_g dependence presented in Fig. 4(b). It is clearly seen that the experimental values of τ_φ are close to theoretical ones, i.e., $\tau_\varphi^{th}/\tau_\varphi \simeq 1$, when there are no electrons in the δ layer ($V_g<-0.5$ V), and become to be significantly less when carriers appear therein ($V_g>-0.5$ V). Thus an additional mechanism of phase breaking for electrons in the quantum well arises when the δ layer is being populated.

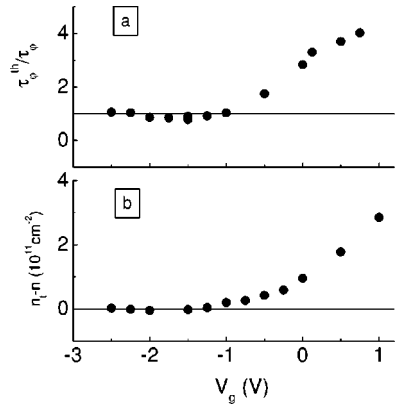

FIG. 6. The gate voltage dependences of the ratio $\tau_\varphi^{th}/\tau_\varphi$ for $T=1.5$ K (a) and difference between the total electron density and density of electrons in the quantum well (b).

One of such mechanisms can be associated with tunneling. Indeed, appearance of electrons in the δ layer means arising of empty states at the Fermi energy therein, and, as sequence, tunneling of electrons between the quantum well and the δ layer. In this case, an electron moving over closed paths (just they determine the interference quantum correction) spend some time within the δ layer. Due to low value of local conductivity in the δ layer, the electron fast loses the phase memory therein. (Strictly speaking, the phase breaking mechanisms in doped layers, where electrons occupy the states in the tail of density of states, are the subject of additional study, but it seems no wonder that dephasing in these layers occurs faster than in quantum well.) If the phase breaking time in the δ layer is much shorter than both the tunneling time τ_{tun} and the phase breaking time in the quantum well τ_φ^{qw}, the effective phase breaking time will be given by the simple expression

$$\frac{1}{\tau_\varphi}=\frac{1}{\tau_\varphi^{qw}}+\frac{1}{\tau_{tun}}. \tag{3}$$

Let us analyze our experimental results from this point of view. We can find the gate voltage dependence of τ_{tun} and thus the conductivity one from Eq. (3) using τ_φ^{qw} calculated from Eq. (2) and the experimental values of τ_φ for $T=1.5$ K. The results presented by a dashed line in Fig. 2 were obtained with τ_φ determined from the fitting within the magnetic field range $0-0.5B_{tr}$. It is seen that τ_{tun} sharply decreases when the conductivity increases. Such a behavior is transparent. The tunneling rate is proportional to the tunneling probability summed over the all final states with the same energy and thus to the density of final states. In our case the final states are the states in the tail of the density of states of the δ layer, therefore their density at the Fermi energy increases when V_g increases (see Fig. 5). In addition, the barrier transparency increases as well. Both effects lead to a sharp decrease of τ_{tun} with V_g.

Since the tunneling is a temperature-independent process, Eq. (3) with the τ_{tun}-versus-V_g dependence found above has to describe the experimental gate voltage dependence of τ_φ for any temperatures. Really, as is seen from Fig. 2, the results for $T=4.2$ K are very close to the calculated curve.

The tunneling has to change the temperature dependence of τ_φ also. Because τ_φ^{qw} increases with the temperature decrease as T^{-1}, the effective phase breaking time has to saturate at low temperature. In Fig. 3 the temperature dependences of τ_φ found from Eq. (3) with τ_φ^{qw} calculated from Eq. (2) and τ_{tun} determined above are presented. Good agreement between the calculated and experimental results shows that this model naturally describes the low-temperature saturation of τ_φ.

To realize whether the tunneling is important in our structures, it is necessary to calculate the tunneling time. Its value is strongly determined not only by the z component of the wave functions $\Psi(z)$ (Fig. 5), but by the mechanisms chang-

ing the in-plane quasimomentum $k_\parallel$ at the tunneling. They are interaction with impurity potential, roughness of the quantum well boundaries, and so on. Therefore it is a complicated problem to find the realistic value of τ_{tun}. It is easy to estimate τ_{tun} in two opposite cases. If $k_\parallel$ is conserved, there is no tunneling because the states in the quantum well and the δ layer with a given energy have different $k_\parallel$. In the opposite case, when $k_\parallel$ is not conserved completely, the estimations give τ_{tun} at about 2×10^{-13} sec at $V_g=0$. Thus the rough estimation shows that the tunneling can really be efficient in the structure investigated.

Thus, taking into consideration the electron tunneling between the quantum well and the δ layer, we have explained both the gate voltage and temperature dependences of phase breaking time.

Another possible mechanism of the phase breaking for the systems where carriers occur not only in the quantum well is their interaction with carriers in the doped layer. Inelasticity of this interaction can be of importance. High efficiency of such interaction can be the result of the exciting of local plasmon modes in δ layers, for example. We are not aware of papers where the inelasticity of the interaction between electrons in the quantum well and in the doped layer was taken into account.

It is worth noting that the δ- or modulation-doped layers are arranged in all the heterostructures suitable for transport measurements, to create the carriers in the quantum well. Two mechanisms discussed above differently depend on the parameters of heterostructures, first of all, on the spacer width and band offset. The role of the tunneling can be dominant in structures with thin enough spacer, whereas the inelasticity of Coulomb interaction with carriers in the doped layer can be more efficient in structures with a thick spacer. These mechanisms can be important for the phase breaking, even though the doped layers do not contribute to the conductivity.

In conclusion, the study of weak localization in gated structures shows that appearance of carriers in the doped layer leads to a decrease of the phase breaking time and a change in the conductivity and temperature dependences of τ_φ.

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