Dephasing and interwell transitions in double quantum well heterostructures

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The interference quantum correction to the conductivity in the gated double quantum well AlxGa1−xAs/GaAs/AlxGa1−xAs structures is studied experimentally. The consistent analysis of the interference induced positive magnetococonductivity allows us to find the interwell transition time τ12 and the electron dephasing time τφ. It has been obtained that τ12 resonantly depends on the difference between the electron densities in the wells as predicted theoretically. The dephasing times have been determined under the conditions when one and both quantum wells are occupied. The surprising result is that the τφ value in the one well does not depend on the occupation of the other one.

I. INTRODUCTION

The quantum corrections to the conductivity of the two-dimensional (2D) electron gas with the single-valley parabolic energy spectrum is extensively investigated last three decades (see Refs. 1, 2 and references therein). A reasonably good agreement between experimental and theoretical results evident at relatively high conductivity, σ ≳ (10 − 15)G0, where G0 = e2/πℏ, attests adequate understanding of the role of the quantum interference and electron-electron (e-e) interaction in the transport properties of 2D systems. The quantum corrections in the double quantum well structures are studied significantly less.10−13 Specific features of the corrections in this case are governed by relationship between the following parameters: the transport times τ, the phase relaxation time τφ, and the interwell transition time τ12, the temperature length LT = D/T (where D is the diffusion coefficient), the interwell distance d, and the screening length r0, which is half the Bohr radius, r0 = aB/2. In the limiting cases such structures can look like a single quantum well structure (at τ12 ≪ τφ, 1/T) or a structure with two uncoupled wells (at τ12 ≫ τφ, 1/T and d ≫ r0). In the last case, the quantum corrections to the conductivity are simply the sum of the corrections of each well, however, the crossover to this case for the WL and interaction corrections may occur at different conditions.

The intermediate cases are more interesting and diversified. Concerning the interference correction, the gain of the interaction in a multiplet channel can be so significant that it can lead to the change of the sign of the temperature dependence of the conductivity from dielectric (dσ/dT > 0) to metalliclike (dσ/dT < 0) as it takes place in the 2D systems with double valley energy spectrum. The interference correction, even without interwell transitions (τ12 ≫ τφ), can differ from the case of non-interacting wells due to inelasticity of the e-e interaction of carriers in the different wells. This interaction can change the dephasing rate significantly. Just this effect in the gated double quantum well AlxGa1−xAs/GaAs/AlxGa1−xAs structures is studied in the present paper. Analyzing the interference induced positive magnetococonductivity we show that the interwell transition rate resonantly depends on the gate voltage. We also show that the dephasing rate is almost insensitive to the number of the wells occupied contrary to the theoretical expectations.

II. EXPERIMENTAL DETAILS

Two structures grown by the molecular beam epitaxy on a semiinsulating GaAs substrate were investigated. The first structure 3243 consists of 200 nm-thick undoped GaAs buffer layer, 50 nm undoped Al0.3Ga0.7As layer, two 8 nm GaAs quantum wells separated by 10 nm Al0.3Ga0.7As barrier, 70 nm Al0.3Ga0.7As undoped layer. The thickness of the GaAs cap layer is 130 nm. The main doping δ layer of Si is situated in the barrier center. Because the gate voltage in such a type of structures can effectively decrease the electron density only, an additional Si δ layer is located above the upper quantum well at distance of 18 nm from the well interface. The energy diagram of the structure 3243 is shown in Fig. 1. The second structure 3154 differs by the doping level and has lower electron density and mobility. Such structure design allows us to have the close mobilities in the wells at equal electron density that is very important for reliable determination of the phase relaxation time as will be discussed below. The samples were mesa etched into standard Hall bars and then an Al gate electrode was deposited by thermal evaporation onto the cap layer through a mask. All the measurements were carried out in the Ohmic regime using DC technique. The results obtained were mostly analogous and we will discuss more thoroughly the results obtained for the structure 3243.

III. RESULTS AND DISCUSSION

The shape of magnetococonductivity ∆σ(B) caused by suppression of the weak localization in the transverse
magnetic field $B \parallel n$, where $n$ is the normal to the structure plane, is widely varied in the double well structures. Really, even in the case of low interwell transition rate, $\tau_{12}$, when $\Delta \sigma(B)$ is barely the sum of the contributions from each well

$$\Delta \sigma(B) = \frac{\rho_{xx}(B) - \rho_{xx}(0)}{G_0} = \alpha_1 \mathcal{H}(\frac{\tau_{\phi 1}}{\tau_1} B / B_{tr 1}) + \alpha_2 \mathcal{H}(\frac{\tau_{\phi 2}}{\tau_2} B / B_{tr 2}),$$

(1)

it depends, as seen, on the large number of parameters: the two phase relaxation times, $\tau_{\phi 1}$ and $\tau_{\phi 2}$, the two transport times, $\tau_1$ and $\tau_2$, and two transport magnetic fields, $B_{tr 1} = h/4eD_1\tau_1$ and $B_{tr 2} = h/4eD_2\tau_2$. The remaining designations in Eq. (1) are the following:

$$\mathcal{H}(x) = \psi \left( \frac{1}{2} + \frac{1}{x} \right) + \ln x,$$

(2)

where $\psi(x)$ is a digamma function, $\alpha_1$ and $\alpha_2$ are prefactors, which appear due to not rigorous fulfilment of the diffusion approximation $\tau_i/\tau_{\phi i} \ll 1/2$ due to the magnetic field dependence of the dephasing time and the contributions of the second order corrections. Obviously it is impossible to find six parameters fitting the single smooth curve. Reliable obtaining of the phase relaxation time is possible only when the parameters of the wells $\tau_i$, $\tau_{\phi i}$, and $B_{tr i}$ are close to each other. Therefore, before to inspect interference induced low field magnetoconductivity let us analyze the transport in high magnetic field in more detail.

The magnetic field dependences of the Hall coefficient $R_H = \rho_{xy}/B$ and transverse resistivity $\rho_{xx}$ for the different gate voltages are presented in Fig. 2. First we analyze the Shubnikov-de Haas (SdH) oscillations. As seen the oscillations picture is rather complicated at some gate voltages that stems from the difference in the electron densities in the wells. The $V_g$ dependences of the $n_1$ and $n_2$ values obtained from the Fourier analysis are shown in Fig. 3(a) by circles. One can see that $n_1$ and $n_2$ linearly decrease with the $V_g$ decrease. Therewith, the decrease rate for one of the wells at $V_g \gtrsim -4$ V is about fifteen times larger than that for other one: $dn_1/dV_g \sim 2.8 \times 10^{11}$ cm$^{-2}$/V against $dn_1/dV_g \sim 2 \times 10^{10}$ cm$^{-2}$/V. Both values are in agreement with the results of simple estimations. The rate $dn_2/dV_g$ agrees well with the geometric capacity between the upper well and the gate electrode. The nonzero value of the rate for the lower well, $dn_1/dV_g$, results from the finite compressibility of the electron gas in the upper well. Simple estimation gives the decrease rate due to this effect about $2.3 \times 10^{10}$ cm$^{-2}$/V that is close to the experimental $dn_1/dV_g$ value in Fig. 2(a).

At $V_g \lesssim -4$ V, the upper well is fully depleted and no longer screens the gate electric field. Therefore $dn_2/dV_g$ is enhanced up to approximately $2.5 \times 10^{11}$ cm$^{-2}$/V, which agrees with the geometric capacity again. Thus, the analysis of the SdH oscillations shows that the structure comes to the balance, i.e., to the state when the electron densities in the wells become close to each other, at $V_g = -1.5 \pm 0.1$ V.

As described above, to obtain $\tau_{\phi}$ reliably, it is very important, besides the electron densities in the wells, to have the close values of the transport magnetic fields, i.e., the close values of the mobility. We used different ways to determine the mobilities. First we analyzed the monotonic run of the $\rho_{xx}$ vs $B$ and $R_H$ vs $B$ curves within the framework of the model of the classical transport by two types of carriers. An example of such the data processing is shown in Fig. 3(b) and Fig. 3(c). The values of the electron densities in the wells obtained by this method [presented in Fig. 3(a) by triangles] agree well with the that found from the SdH oscillations. Unfortunately, this method gives good results in the case when the mobilities differ noticeably. For the structure 3243 it happens at $V_g \simeq -(0 \ldots 0.5)$ V and $V_g \simeq -(3 \ldots 3.5)$ V [see Fig. 3(d)]. By assuming that $\mu_1$ and $\mu_2$ depend on the gate voltage monotonically,
one obtains that the mobilities differ not so strongly in the balance: \( \mu_1 \approx \mu_2 = (1.5 \pm 0.1) \times 10^4 \text{ cm}^2/\text{Vs} \) at \( V_g = -1.5 \text{ V} \).

Another way to insure that the mobilities in the wells are close in the magnitude at the balance is the detailed analysis of the SdH oscillations [see Fig. 3]. If one neglects the tunneling splitting, \( \Delta_{SAS} \), as compared with the broadening due to scattering, \( \hbar/\tau_g \), the conductivity tensor for the structure can be represented as the sum of that for each well:

\[
\sigma_j(B, V_g) = \sigma_j^{(1)}(B, V_g) + \sigma_j^{(2)}(B, V_g), \quad j = xx, xy.
\]

For our case the estimation gives \( \Delta_{SAS} \approx 0.1 \text{ meV} \), that is much less than \( \hbar/\tau_g \approx 5 \text{ meV} \) found from the \( B \) dependence of the SdH oscillations amplitude. So, such the approach seems reasonable. For the case of \( \mu_1 = \mu_2 \) in the balance: \( \sigma_j^{(1)}(B, V_g^b) = \sigma_j^{(2)}(B, V_g^b) = \sigma_j(B, V_g^b)/2 \).

Since the electron density and mobility in the lower well are practically independent of \( V_g \) near the balance [see Fig. 3(d)], the components \( \sigma_j^{(2)} \) for the upper well can be extracted as

\[
\sigma_j^{(2)}(B, V_g) = \sigma_j(B, V_g) - \frac{1}{2} \sigma_j(B, V_g^b).
\]

The components in the right hand side of Eq. (1) were found from the measured resistivity components \( \rho_{xx} \) and \( \rho_{xy} \). After obtaining \( \sigma_j^{(2)} \) and \( \sigma_j^{(3)} \) we have calculated \( \rho_j^{(2)} \) and plotted it in Fig. 3(b). Therewith, to remove the monotonic component, the \( \rho_{xx} \) vs \( B \) curves were differentiated. One can see that: (i) the oscillations extracted consist of one period; (ii) the \( n_2 \) vs \( V_g \) dependence found from the Fourier analysis is linear [see insert in Fig. 3(a)]; (iii) its slope is close to that found within whole \( V_g \) range; (iv) the oscillations amplitude is practically independent of \( V_g \) while \( V_g = -(1.7 \ldots 1.3) \text{ V} \). Such the behavior can be observed only when the mobilities in the wells at the balance, \( V_g = -1.5 \text{ V} \), are close to each other.

Now we are ready to discuss quantitatively the low field negative magnetoresistance caused by suppression of the weak localization. The magnetic field dependences of \( \Delta \sigma(B) \) at temperature 1.35 K for different gate voltages are presented in Fig. 5(a). At first sight all the curves are the same in the shape and no peculiarity in the balance at \( V_g = -1.5 \text{ V} \) is observed. This, indeed, should be when the interwell transition rate is low, \( 1/\tau_{12} \ll 1/\tau_\phi \), and \( \Delta \sigma(B) \) is the sum of the contributions from each well.

Closeness of the mobilities in the balance means closeness of transport fields, \( B_{tr1} = B_{tr2} = B_{tr} \) so that \( \Delta \sigma(B) \) should be described by Eq. (2), which in this case reduces to the following

\[
\Delta \sigma(B) = \alpha G_0 H \left( \frac{\tau_\phi}{\tau} \frac{B}{B_{tr}} \right),
\]

where \( \alpha = 2 \). Therefore, let us start analysis from \( V_g = -1.5 \text{ V} \). The result of the best fit within magnetic field range \( (0 - 0.3)B_{tr} \) for \( T = 1.35 \text{ K} \) is shown in Fig. 5(b). It is evident that Eq. (5) perfectly fits the data.
with prefactor which value is really about two. The temperature dependences of the fitting parameters $\tau_\phi$ and $\alpha$ are presented in Fig. 4. It is seen that the $T$ dependence of $\tau_\phi$ is close to $1/T$ (some deviation will be discussed below). Slight decrease of the prefactor with the growing temperature is sequence of the lack of the diffusion regime due to the decrease of the $\tau_\phi$ to $\tau$ ratio\textsuperscript{14} from 85 at $T = 1.35$ K to 30 at $T = 4.2$ K.

Let us now analyze the data in the vicinity of $V_g = -1.5$ V. Strictly speaking, the use of Eq. (5) is not fully correct because $B_{tr}$ and $\tau_\phi/\tau$ are different in the wells. Nevertheless, before to discuss the workability of Eq. (5) for obtaining of $\tau_\phi$ experimentally, let us consider the results of such treatment. The gate voltage dependence of $\tau_\phi$ presented in Fig. 7(a) by the diamonds exhibits the sharp minimum at $V_g = -1.5$ V. To understand whether or not this minimum results from the approximation used, we have simulated experimental situation. We have calculated the magnetoresistance using Eq. (1) with the values of $n_i$ and $\mu_i$ given in Fig. 3. The phase relaxation times have been calculated according to Ref. 17. Then, these curves have been fitted by Eq. (5) in the same manner as it has been done with the data. It turns out that Eq. (5) well fits the calculated curves. Therewith, the fitting parameter $\tau_\phi$ monotonically changes with the changing gate voltage and its value is close to $(\tau_{\phi 1} + \tau_{\phi 2})/2$ with an accuracy of 5\% in the range of the parameters corresponding to $V_g = -(1.3 \ldots 1.7)$ V. This means that the minimum in Fig. 7 is not sequence of the fitting procedure.

It stands to reason that the minimum results from the interwell transitions neglected in Eq. (5). Theoretically, their role in the positive magnetoconductivity was considered in Refs. 10 and 11. However attempts to use the expressions from these papers for the data fit have failed. The values of $\tau_\phi$ and $\tau_{12}$ are obtained with very large uncertainty. This is because the shape of the magnetoconductivity curve in actual case is mainly controlled by some combination of $\tau_\phi$ and $\tau_{12}$ but not by $\tau_\phi$ and $\tau_{12}$ individually. It becomes clear when considering the parabolic (at $B \to 0$) and logarithmic (at $B \gg B_{tr}/\tau_\phi$) asymptotics of Eq. (24) in Ref. 11 at $\tau_{12} > 2\tau_\phi$. They coincide with corresponding asymptotics, which one can extract from Eq. (5) by using $\alpha = 2$ and $\tau_{12} = (1/\tau_\phi + 1/\tau_{12})^{-1}$ instead of $\tau_\phi$. So, the sum $1/\tau_\phi + 1/\tau_{12}$, but not the rates $1/\tau_\phi$ and $1/\tau_{12}$ separately are experimentally obtained when the interwell transitions are relatively rare.

According to Ref. 11 the interwell transition rate resonantly depends on the difference between the Fermi energies in the wells:

$$\frac{1}{\tau_{12}} = \frac{1}{\tau_{12}^0} 1 + \left[ (E_{Fb} - E_{Fb})/\hbar \right]^2,$$  \hspace{1cm} (6)

where $1/\tau_{12}^0$ is the rate in the balance and $E_{Fb} = \pi \hbar^2 n_i/m$ is the Fermi energy in $i$-th well. Taking into account the fact that $n_1$ is practically independent of $V_g$, one obtains the following expression

$$\frac{1}{\tau_{12}} = \frac{1}{\tau_{12}^0} \left[ 1 + \left( \frac{\pi \hbar^2 n_i}{m (V_g - V_g^b)} \right)^2 \right]^{-1},$$  \hspace{1cm} (7)

which can be directly applied to describe the data. Experimentally, the rate $1/\tau_{12}$ near the balance can be found as the difference between $1/\tau_\phi^0$ and $1/\tau_\phi$, if one supposes that the interwell transitions do not contribute to $\tau_\phi^0$ at $V_g = -1.8$ V and $V_g = -1.2$ V, and $1/\tau_\phi$ linearly depends on $V_g$ between these gate voltages as shown.

![Figure 5](image_url)  \hspace{1cm} ![Figure 6](image_url)

**FIG. 5.** (Color online) (a) The interference induced positive magnetoconductivity for different gate voltages near the balance. For clarity, the curves are shifted in the vertical direction. (b) The magnetoconductivity measured at $V_g = -1.5$ V for two orientations of the magnetic field. Solid lines are the data, the dashed line is the the best fit by Eq. (5) with the parameters $\alpha = 1.9$, $\tau_\phi/\tau = 85$. $T = 1.35$ K for all the cases, $B_{tr} = 8.4$ mT.

**FIG. 6.** (Color online) The temperature dependences of $\tau_\phi$ (a) and $\alpha$ (b) found from the fit of the magnetoconductivity curves by Eq. (5). Solid symbols are obtained at $V_g = -1.5$ V when the structure is in the balance. Open symbols correspond to $V_g = -3.7$ V when the conductivity over the upper well is negligible. The solid and dashed lines are the functions $6 \times 10^{-11}/T$ and $(T/6.4 \times 10^{-11} + 1/2 \times 10^{-10})^{-1}$, respectively.
on the temperature and $\tau$ approximately three times larger, explanations can be independently estimated from the in-plane symbols and the dashed curve in Fig. 6(b).

The gate voltage dependence of the transition rate for structure 3243. Symbols are the experimental data, the line is calculated from Eq. (7) with $m = 0.067 m_o$, $d n / d V_g = 2.8 \times 10^{11} \text{cm}^{-2} / V$, $\tau_{12} = 1.7 \times 10^{-10} \text{s}$, and $\tau = 5.5 \times 10^{-13} \text{s}$.

The results are presented in Fig. 8(c) by the circles. As seen the experimental $V_g$ dependence of $1 / \tau_{12}$ is really close to the theoretical one calculated from Eq. (7) with $\tau = 5.5 \times 10^{-13} \text{s}$ found from the mobility value at $V = V_g$ and $\tau_{12} = 1.7 \times 10^{-10} \text{s}$.

Thus, we obtain from the above analysis that the dephasing time $\tau_\phi$ in the balance is about $5 \times 10^{-11} \text{s}$ at $T = 1.35 \text{ K}$, whereas the interwell transition time is approximately three times larger, $\tau_{12} \simeq 1.7 \times 10^{-10} \text{s}$. The fact that $\tau_\phi$ is the combination of $\tau_0$ inversely dependent on the temperature and $\tau_{12}$, which is independent of the temperature, explains the tendency to saturation of the $\tau_\phi$ dependence taking into account the presence of the second well according to Eq. (8).

The same measurements were carried out on the structure 3154. The balance in this structure occurs at $V_g = -2 \text{ V}$, at the lower electron density, $n \simeq 4.5 \times 10^{11} \text{cm}^{-2}$, and lower mobility, $\mu \simeq 6500 \text{ cm}^{2} / \text{Vs}$. The results differ by two issues. The value of $\tau_\phi$ is less than that for the structure 3243. It seems natural because the conventional theory predicts that $\tau_\phi \propto \sigma / \ln (\sigma / G_0)$. The second point is that the noticeable minimum at the balance is not observed [see Fig. 8(a)]. It is explained by the relatively low interwell transition rate, which is estimated as being about two times lower than that in the structure 3243 and more than six times lower than $1 / \tau_\phi$ at lowest temperature.

As mentioned above, the dephasing time $\tau_\phi$ should mainly depend on the conductivity, at least for the single well structure. The open symbols in Fig. 8(a) are the data obtained for both structures for the case when the magnetic field dependence of $\tau_\phi$, the contributions of the second order corrections, and the finiteness of the $\tau_\phi$ to
The role of the isospin channel in the dephasing rate. To our knowledge the contribution of the multiplet (with respect to spin and well isospin) channel in the dephasing rate. At first glance the last seems very strange because the distance between the wells is about screening length so that the interaction between the carriers located in the different wells should not be significantly less than that for carriers in the one well. On the other hand, the inelastic interaction of an electron with electrons in the other well is not sole effect influencing the dephasing rate. Another effect is an additional screening of the interaction between the electrons in the one well by the carriers located in the other one. The former effect should lead to the $\tau_\phi$ decrease, while the second one to its increase. Theoretical calculations, which take into account both these effects, give the following expression for the dephasing time in a double layer system:

$$\frac{\tau^{(1)}_\phi}{\tau_\phi} = \left[ 1 - \frac{\ln T\tau_\phi}{\ln T\tau^{(1)}_\phi} \right] \left( \frac{3d + 2}{2d + 2} \right), \quad (8)$$

where $\tau^{(1)}_\phi$ denotes the dephasing time of a single layer, $d$ is the distance between the layers, and $\kappa = 1/r_0$. Using the distance between the centers of the wells, 18 nm, as the $d$ value and $r_0 = 5$ nm, we obtain approximately 25 percent increase of $\tau_\phi$ at $T = 1.35$ K, which should occur according to Eq. (8) when the upper quantum well starts to be occupied [see lines in Figs. 8(b) and 8(c)]. It may appear that this change is not sufficiently large to be fixed experimentally. However, as evident from Fig. 7(a) we reliably recognize the 20 percent resonant dip in the $\tau^{*}_\phi$ vs $V_0$ dependence resulting from the interwell transitions, but observe no change in $\tau_\phi$ of the lower well when occupying the upper one out of resonance (see symbols in Fig. 8). It should be noted that Eq. (8) takes into account the interaction appearing in the singlet channel only. So, the possible reason for disagreement between the experimental data and calculation results is the neglecting of the contribution of the multiplet (with respect to spin and well isospin) channel in the dephasing rate. To our knowledge the role of the $e-e$ interaction in the multiplet channel in the dephasing in the double quantum well structures has not been studied yet in the literature.

Before concluding the paper, let us note that our results are in contradiction with those obtained in Ref. 12. In the structures with the relatively high interwell transition rate, the authors observe the anomalous $\sigma$ dependence of the dephasing time, $\tau_\phi \sim \sigma^{-1}$. This observation is inconsistent not only with the data in Fig. 8 but with the Fermi-liquid model, which predicts $\tau_\phi \sim \sigma$. The possible reason is that the authors used the expression obtained in Ref. 11 for the case of identical wells, whereas the noticeable classical positive magnetoresistance observed at all the gate voltages fairly indicates that the mobilities in the wells are different.

IV. CONCLUSION

We have studied the interference quantum correction in the gated double quantum well $Al_xGa_{1-x}As/GaAs/Al_xGa_{1-x}As$ heterostructures. Analyzing the positive magnetoconductivity we have obtained the interwell transition rate and the phase relaxation rate under the conditions when one and two quantum wells are occupied. It has been found that the interwell transition rate resonantly depends on the difference between the electron densities in the wells in accordance with the theoretical estimate. The central point of the paper, however, is that the dephasing rate in the lower quantum well is independent of whether the upper quantum well contributes to the conductivity or not. This observation is inconsistent with the results of simplest theory, which takes into account the inelasticity of the $e-e$ interaction in the singlet channel only, and predicts the increase of the dephasing time in double layer structures as compared with the single layer case. The further experimental and theoretical investigations are needed to find the answer to the question of whether the interaction in the multiplet channel or some other mechanism is responsible for such the feature of the dephasing processes in double quantum well structures.

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