Low-field negative magnetoresistance in double-layer structures

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The weak-localization correction to the conductivity in coupled double-layer structures is studied both experimentally and theoretically. Statistics of closed paths have been obtained from the analysis of the magnetic field and temperature dependencies of negative magnetoresistance for the magnetic field perpendicular and parallel to the structure plane. The comparison of experimental data with the results of a computer simulation of carrier motion over two two-dimensional layers with scattering shows that interlayer transitions play a decisive role in the weak localization.

I. INTRODUCTION

Transitions between two-dimensional (2D) layers is one of the fundamental features of double-layer structures. They change the quantum corrections to the conductivity, especially in a magnetic field parallel to the layers.

It is well known[1] that the interference of electron waves scattered along closed trajectories in opposite directions (time-reversed paths) produces a negative quantum correction to the conductivity known as the weak-localization correction. An external magnetic field **B** gives the phase difference between pairs of time-reversed paths which is proportional to the area enclosed and thus destroys the interference and results in negative magnetoresistance.

In case of a single 2D layer the influence of a magnetic field is strongly anisotropic because all the paths lie in one plane. The magnetoresistance is maximal for $\mathbf{B}\parallel\mathbf{n}$, where **n** is the normal to 2D layer. When a magnetic field lies in the 2D layer plane, $\mathbf{B}\perp\mathbf{n}$, it does not destroy the interference, and the negative magnetoresistance is absent in this magnetic-field orientation.[2,3]

In coupled double-layer structures, the tunneling between layers gives rise to the closed paths for which an electron starts from one layer, goes to another, and then returns to the first layer. For these paths the phase shift is nonzero for any magnetic-field orientation and hence the negative magnetoresistance should appear for $\mathbf{B}\perp\mathbf{n}$ as well.

The magnetic-field dependence of the negative magnetoresistance is determined by the statistics of closed paths, namely, by the distribution function of an enclosed area, and the area dependence of the average length of closed paths.[4,5] These statistic dependencies have been studied in single 2D-layer structures by the analysis of negative magnetoresistance measured at $\mathbf{B}\parallel\mathbf{n}$.[5,6]

There is a number of papers devoted to the weak-localization phenomenon in double-layer and multilayer structures where interlayer transitions play a crucial role.[7–11] In Ref. 12 the closely related problem concerning the role of intersubband transitions in weak localization is theoretically studied for the case of quasi-two dimensional structures with several subbands occupied.

In this paper we present the results of experimental investigations of the negative magnetoresistance in a double-layer GaAs/$In_xGa_{1-x}As$ structure for different magnetic-field orientations. We obtain the area distribution functions and area dependencies of the average lengths of the closed paths using the approach developed in Refs. 5 and 6. These functions are compared with those obtained from the computer simulation of carrier motion when the interlayer transitions are accounted for. Close agreement shows that just the interlayer transitions determine the negative magnetoresistance in coupled double-layer structures.

II. EXPERIMENT

A. Details

The double-well heterostructure GaAs/$In_xGa_{1-x}As$ was grown by metal-organic vapor-phase epitaxy on a semi-insulator GaAs substrate. The heterostructure consists of a 0.5-μm-thick undoped GaAs epilayer, a Si δ layer, a 75-Å spacer of undoped GaAs, a 100-Å $In_{0.08}Ga_{0.92}As$ well, a 100-Å barrier of undoped GaAs, a 100-Å $In_{0.08}Ga_{0.92}As$ well, a 75-Å spacer of undoped GaAs, a Si δ layer, and a 1000-Å cap layer of undoped GaAs. The samples were mesa etched into standard Hall bridges. The measurements were performed in the temperature range 1.5–4.2 K at low magnetic field up to 0.4 T with discrete 10^{-4} T for two orientations: the magnetic field was perpendicular $(\mathbf{B}\parallel\mathbf{z})$ and parallel $(\mathbf{B}\parallel\mathbf{x})$ to the structure plane (see the inset in Fig. 1). Additional high-field measurements were also made to characterize the structure. It has been found that in the structure investigated the conductivity is determined by the electrons in the wells. Their densities have been determined from the Fourier analysis of the Shubnikov–de Haas oscillations and are $4.5\times10^{11}\,\mathrm{cm}^{-2}$ and $5.5\times10^{11}\,\mathrm{cm}^{-2}$. The Hall mobility was about $\mu\simeq4200\,\mathrm{cm}^2/(\mathrm{V}\times\mathrm{sec})$.

The magnetic-field dependencies of in-plane magnetoconductance

$$\Delta\sigma(B)=\sigma(B)-\sigma(0)=1/\rho(B)-1/\rho(0) \qquad (1)$$

at the magnetic field perpendicular $[\Delta\sigma(B_z)]$ and parallel $[\Delta\sigma(B_x)]$ to the structure plane are presented in Fig. 1. One can see that the negative magnetoresistance is observed for

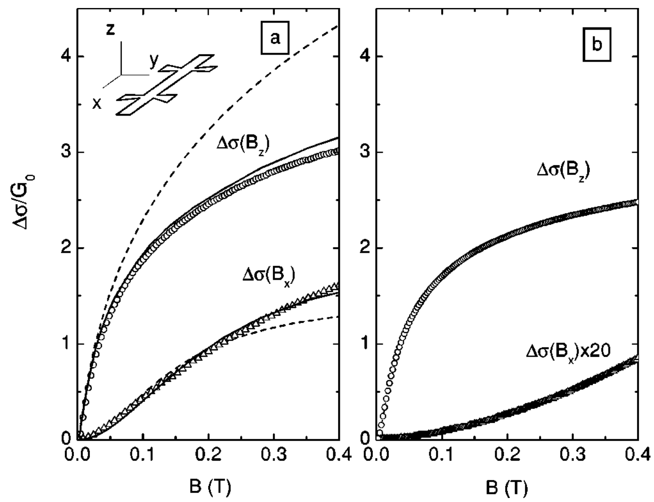

FIG. 1. Magnetic-field dependencies of $\Delta\sigma/G_0$ for different magnetic-field orientations for $T=4.2$ (a), 1.5 K (b). Symbols are the experimental data, solid curves are the simulation results. Dashed curves are the results of calculations carried out according to Ref. 20. The inset in (a) shows a system of coordinates.

both magnetic-field orientations and, in contrast to the case of single-layer structures, the effects are comparable in magnitude. An analysis of the behavior of the conductivity in a wide range of temperatures ($1.5<T<20$ K) and magnetic fields ($B<6$ T) shows that at $B<0.4$–0.5 T the main contribution to the negative magnetoresistance comes from the interference correction.

B. Basis of data processing

It is known that the weak-localization effect can be understood on the quasiclassical level as a manifestation of quantum-mechanical interference.[13–15] According to this approach the weak-localization correction to the conductivity $\delta\sigma$ is proportional to the quasiprobability[16] density $\mathcal{W}$ that an electron returns to the vicinity of starting point

$$\delta\sigma\propto\mathcal{W}. \tag{2}$$

In the presence of a magnetic field, which gives the phase difference between time-reversed closed paths

$$\Delta\varphi=\frac{2\pi}{\Phi_0}\oint d\mathbf{l}\,\mathbf{A}=\frac{2\pi}{\Phi_0}\int d\mathbf{S}\,\mathbf{B}, \tag{3}$$

where $\mathbf{A}$ is a vector potential, Φ_0 is quantum of magnetic flux, and $\mathcal{W}$ is expressed through the area distribution function of closed paths as follows:

$$\mathcal{W}=\int_{-\infty}^{\infty}dS\,W(S)\exp\left(-\frac{\overline{L}(S)}{l_\varphi}\right)\cos\left(\frac{2\pi BS}{\Phi_0}\right). \tag{4}$$

Here, S is defined as

$$S=\int d\mathbf{S}\frac{\mathbf{B}}{B}, \tag{5}$$

$W(S)dS$ is the probability density of return with S from the interval $(S,S+dS)$, $\overline{L}(S)$ has a meaning of average length calculated by the appropriate manner [see Eq. (6) in Ref. 5] for the closed paths with $S=(S,S+dS)$, $l_\varphi=v_F\tau_\varphi$, v_F is the Fermi velocity, and τ_φ is the phase-breaking time. Note that the exponential factor in Eq. (4) takes into account interference destruction due to inelastic scattering processes.

In 2D systems all the trajectories lay in one plane; therefore, only the normal component of the magnetic field changes $\mathcal{W}$ so that the negative magnetoresistance is absent for $\mathbf{B}\perp\mathbf{n}$. In double-layer structures, the interlayer transitions lead to the closed paths, which are long enough, and have a nonzero value of S with respect to any orientation. Thus the negative magnetoresistance should exist even in the case when a field $\mathbf{B}$ is applied parallel to the layers.

Using this approach (for more detail see Sec. II of Ref. 5) one can write the expression for conductivity of a weakly coupled double-layer structure with identical layers as follows:

$$\sigma(B_i)=\sigma_0+\delta\sigma(B_i)$$
$$=\sigma_0-4\pi l^2G_0\int_{-\infty}^{\infty}dS_i\left\{W(S_i)\exp\left(-\frac{\overline{L}(S_i)}{l_\varphi}\right)\right.$$
$$\left.\times\cos\left(\frac{2\pi B_iS_i}{\Phi_0}\right)\right\}, \tag{6}$$

where $i=x$, z indicates the magnetic-field orientation, $\mathbf{B}=(B_x,0,0)$ or $\mathbf{B}=(0,0,B_z)$, respectively, σ_0 is the classical Drude conductivity, $G_0=e^2/(2\pi^2\hbar)$, $l=v_F\tau$, and τ is the momentum relaxation time.

One can see from Eq. (6) that the Fourier transform of $\delta\sigma(B_i)/G_0$

$$\Phi(S_i,l_\varphi)\equiv\int_{-\infty}^{\infty}\frac{dB_i}{\Phi_0}\frac{\delta\sigma(B_i)}{G_0}\cos\left(\frac{2\pi B_iS_i}{\Phi_0}\right) \tag{7}$$

is determined by the statistic characteristics of closed paths $W(S_i)$ and $\overline{L}(S_i)$,

$$\Phi(S_i,l_\varphi)=4\pi l^2W(S_i)\exp\left(-\frac{\overline{L}(S_i)}{l_\varphi}\right). \tag{8}$$

Thus, analyzing the temperature behavior of the Fourier transforms of the experimental curves $\delta\sigma(B_i)$ one can obtain the area-distribution function $W(S_i)$ and dependence $\overline{L}(S_i)$ for real samples. As is seen from Eq. (8) the value of $4\pi l^2W(S_i)$ is given by extrapolation of the Φ-versus-T curve to $T=0$ because l_φ tends to infinity when T tends to zero.[17] The ratio $\overline{L}(S_i)/l_\varphi$ for given S_i can be then obtained as $\ln[4\pi l^2W(S_i)]-\ln[\Phi(S_i,l_\varphi)]$.

C. Results of data processing

Let us now turn to the analysis of our experimental data. The value $\Delta\sigma(B)=\sigma(B)-\sigma(0)$, not $\delta\sigma(B)$, is experimentally measured. It is clear from Eqs. (1) and (6) that $\delta\sigma(B)=\sigma(0)-\sigma_0+\Delta\sigma(B)$. To obtain $\delta\sigma(B)$, we assume that the Drude conductivity σ_0 is equal to the conductivity at $T=20$ K, when the quantum corrections are small. Notice that the final results are not sensitive to the value of σ_0 practically. Obtaining the distribution function $W(S_x)$ from the experimental $\delta\sigma(B_z)$ dependencies for the structure investi-

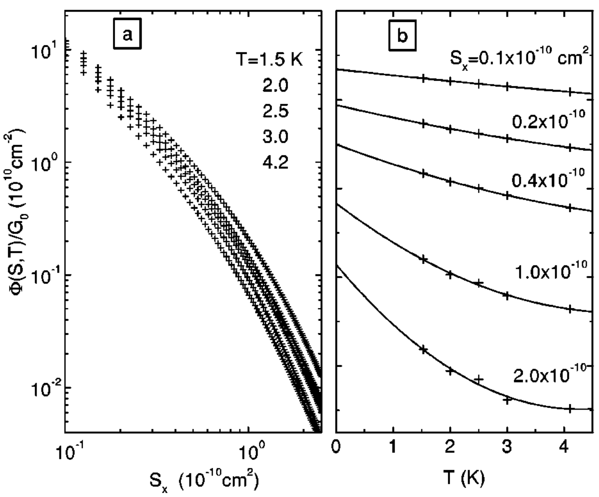

FIG. 2. Area (a) and temperature (b) dependencies of the Fourier transforms of $\delta\sigma(B_x)$. Curves in (b) show the extrapolation of $\Phi(S,T)$ to $T=0$.

gated is illustrated by Fig. 2. In the left panel the Fourier transforms of $\delta\sigma(B_x)$ measured at different temperatures are presented. The right panel shows how the Φ-vs-T data have been extrapolated to $T=0$. The area-distribution function $W(S_z)$ has been obtained from the analysis of $\delta\sigma(B_z)$ curves in a similar way.

The results of data processing described are presented in Fig. 3(a). As is seen the $4\pi l^2 W(S_z)$ dependence is close to $(2S_z)^{-1}$ for $S\simeq(0.3\text{–}5)\times10^{-10}\,\text{cm}^2$. The analogous behavior of the area distribution function was obtained for a single 2D layer in Ref. 6. The behavior of $W(S_x)$ significantly differs from that of $W(S_z)$. In particular, the $W(S_x)$ curve shows a much steeper decline for $S>0.8\times10^{-10}\,\text{cm}^2$. Another feature of the statistics of the closed paths in the double-layer structure is the fact that for given S the values of $\overline{L}(S_x)$ are significantly larger than $\overline{L}(S_z)$ [Fig. 3(b)].

Qualitatively these peculiarities of the statistics of closed paths in double-layer structures can be understood if one considers how trajectories with large enough length, $L \gg l/t$, look. They are isotropically smeared over the xy plane for the distance $\sim\sqrt{Ll}$; their extended area in this plane is $s_z\sim Ll$. In the yz plane they have size $\sim\sqrt{Ll}$ in the y direction and Z_0 (where Z_0 is the interlayer distance) in the z direction. So, the extended area in the yz plane is $s_x \sim Z_0\sqrt{Ll}$. Thus, closed trajectories have significantly larger s_z than s_x, and the s_z/s_x ratio increases with increasing s. It is clear that the qualitative behavior of S_z and S_x is analogous. Therefore, for $S_x=S_z$ the inequality $W(S_z)>W(S_x)$ is valid. The average length of the trajectories $\overline{L}(S_x)$ therewith is greater than $\overline{L}(S_z)$.

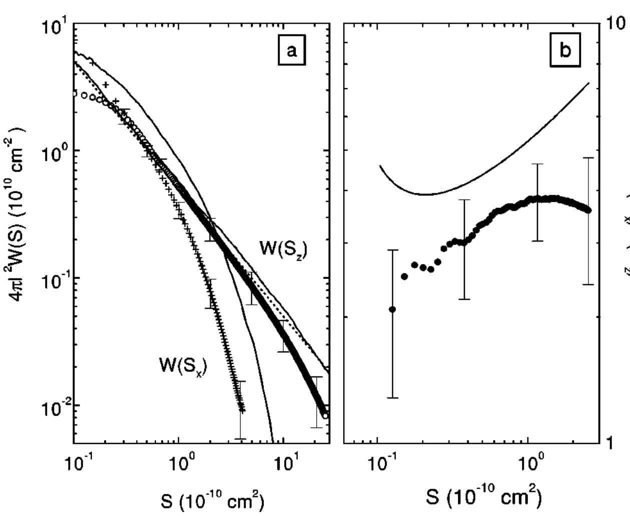

FIG. 3. The area-distribution functions of closed paths (a) and the area dependence of the $\overline{L}(S_x)/\overline{L}(S_z)$ ratio at $T=1.5\,\text{K}$ (b). The symbols are the experimental data, the solid curves are the results of simulation with $t=0.1$, and the dotted curve is $(2S)^{-1}$ dependence.

As was shown in Ref. 5 the area-distribution function of closed paths, the area dependence of the average length of closed paths, and weak-localization magnetoresistance can be obtained by computer simulation of a carrier motion over a 2D plane.

III. COMPUTER SIMULATION

The model double-layer system is conceived as two identical plains with randomly distributed scattering centers with a given total cross section. Every plane is represented as a lattice $M\times M$ with lattice parameter a. The scatterers are placed in a part of the lattice sites with the use of a random number generator. We assume that a particle moves with a constant velocity along straight lines which happen to be terminated by collisions with the scatterers. After every collision the particle has two possibilities: it passes from one plane to another with a probability t and moves over the second plane or it remains in the plane with probability $(1-t)$, changing the motion direction only. If the trajectory of the particle passes near the start point at the distance less than $d/2$ (where d is a prescribed value, which is small enough), it is perceived as being closed. The algebraic areas S_z and S_x are calculated as

$$S_z=\sum_{j=1}^{N-1}\frac{y_{j+1}+y_j}{2}(x_{j+1}-x_j)+\frac{y_N+y_1}{2}(x_N-x_1), \quad (9)$$

$$S_x=\sum_{j=1}^{N-1}\frac{y_{j+1}+y_j}{2}(z_{j+1}-z_j)+\frac{y_N+y_1}{2}(z_N-z_1), \quad (10)$$

where N is the number of collisions for a given trajectory, x_j, y_j, z_j stand for coordinates of jth collision, z_j takes the value 0 or Z_0. Otherwise the simulation details are analogous to those described in Ref. 5 for the case of single 2D-layer system.

All the results presented here have been obtained using the parameters: lattice dimension is 6800×6800; the number of starts, I_s, is 10^6; the total number of scatterers is about 1.6×10^5; the scattering cross section is $7a$; $d=1a$; $Z_0=18a$. The value of the mean free path computed for such a system is about $43a$. If we suppose the value of a is equal to 11 Å, this model double-layer system corresponds to the heterostructure investigated. Namely, the mean free path is equal to the value of $l\simeq480$ Å, and the value of Z_0 is close to the distance between the centers of the quantum wells, 200 Å.

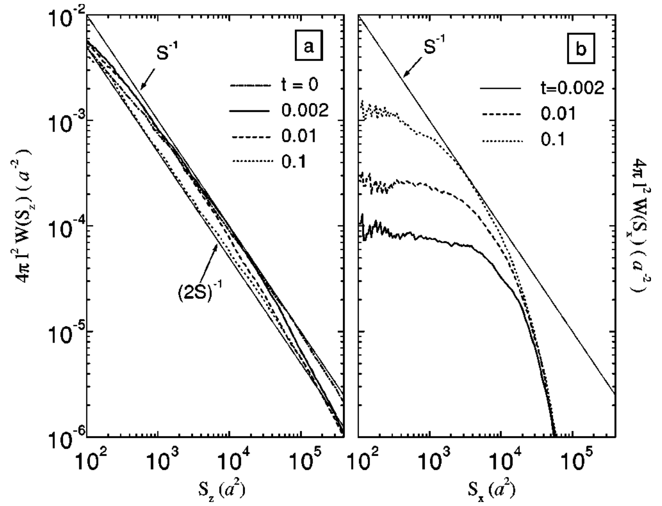

FIG. 4. Area-distribution functions $W(S_z)$ (a) and $W(S_x)$ (b) as they have been obtained from the simulation procedure with different t values.

The area distribution functions obtained as the result of simulation with different interlayer transition probabilities are presented in Fig. 4. Let us discuss at first the behavior of $W(S_z)$ [Fig. 4(a)]. For $t=0$, the $4\pi l^2 W(S_z)$ curve corresponds to the area-distribution function for a single layer. For large S this curve goes close to the S^{-1} dependence, which corresponds to the ideal 2D system in the diffusion regime.[5] The deviation, which is evident for $S_z < 10^3\, a^2$, is just due to the transition to the ballistic regime. It is obviously that for sufficiently large values of t, the probability of return to the start point has to be twice as small as that for $t=0$. As is seen from Fig. 4(a) even the value $t=0.1$ is large enough in this sense: the corresponding curve is close to the $(2S)^{-1}$ dependence practically in whole area range. This is because the long trajectories with a large number of passes between layers give significant contribution to $W(S_z)$ starting from small areas, $S_z > 0.1 l^2$. For the intermediate value of t ($t=0.002$, 0.01) the area-distribution function is close to the S^{-1} function for small areas and tends to the $(2S)^{-1}$ dependence for large ones.

The behavior of $W(S_x)$ contrasts with that of $W(S_z)$ [Fig. 4(b)]. At small S_x, $W(S_x)$ depends only weakly on S_x, whereas at large S_x it decreases sharply when S_x increases. The sensitivity of $W(S_x)$ to the interlayer transition probability depends on the S_x value. For small S_x values, when the area-distribution function is mainly determined by short closed paths with a small number of interlayer transitions, the value of $W(S_x)$ considerably increases with increasing t. For large S_x, i.e., for paths with a large number of interlayer transitions, $W(S_x)$ weakly depends on the transition probability.

Here we demonstrate how the magnetoresistance of our model 2D system changes with the changing of the interlayer transition probability. The theoretical $\delta\sigma(B_i)$ dependencies have been calculated by summing over the contributions of every closed path to the conductivity in accordance with following expression:[5]

$$\frac{\delta\sigma(B_i)}{G_0} = \frac{4\pi l}{I_s d} \sum_k \cos\left(\frac{2\pi B_i S_k}{\Phi_0}\right) \exp\left(-\frac{l_k}{l_\varphi}\right), \qquad (11)$$

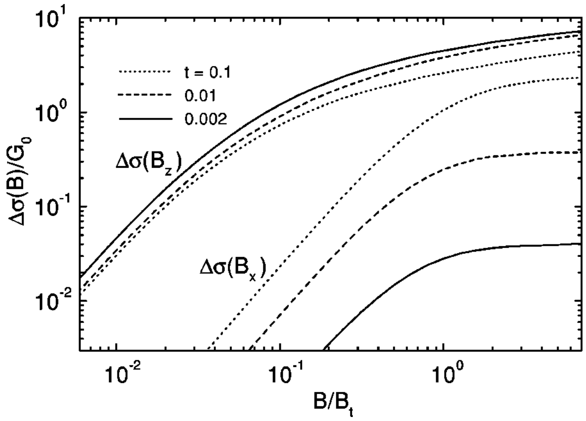

FIG. 5. Calculated magnetic-field dependencies of $\Delta\sigma$ for the different interlayer transition probability, $l/l\varphi = 0.01$.

where l_k is the length of the kth closed path. The results of the calculation are presented in Fig. 5, where $\Delta\sigma(B_i) = \delta\sigma(B_i) - \delta\sigma(0)$ is plotted against B/B_t, $B_t = \hbar c/(2el^2)$. As is seen the changes in magnetic-field dependencies of negative magnetoresistance with a change of the interlayer transition probability reflect the variation of area-distribution functions. Indeed, $\Delta\sigma(B_z)$ depends on t slightly: maximal change is less than two times for decreasing t up to zero, whereas $\Delta\sigma(B_x)$ changes drastically. It decreases about 100 times, when the value of t decreases from 0.1 to 0.002.

IV. DISCUSSION

Now we are in a position to compare the calculated area distributions with experimental data. One can see from Figs. 3(a) and 4 that the behavior of calculated and experimental $W(S_z)$ and $W(S_x)$ dependencies is close qualitatively. As mentioned above, $W(S_x)$ depends on interlayer transition probability significantly stronger than $W(S_z)$. Therefore we have estimated the transition probability comparing the calculated and experimental $W(S_x)$ curves. The most accordance has been obtained with $t \simeq 0.1$ [see Fig. 3(a)]. As seen from the figure, with this value of t the calculated $W(S_z)$ dependence describes the experimental data well.

Let us turn now to magnetic-field dependencies of negative magnetoresistance. To calculate $\Delta\sigma(B_i)$, in addition to the interlayer transition probability it is necessary to know the phase-breaking length. Using the value of $t=0.1$ estimated above, we have found that the best agreement between theoretical and experimental $\Delta\sigma(B_i)$ dependencies is obtained with $l_\varphi \simeq 3.4$ and 1.4 μm for $T=1.5$ and 4.2 K, respectively. The $\Delta\sigma(B_z)$ and $\Delta\sigma(B_x)$ dependencies calculated with these l_φ values practically coincide with those measured experimentally (see Fig. 1). It should be noted that for these values of l_φ some differ from those obtained by fitting of the $\Delta\sigma(B_z)$ curves to the Hikami expression:[18] the fit gives $l_\varphi \simeq 4.8$ and 1.7 μm for $T=1.5$ and 4.2 K, respectively. The reason for this difference is that the Hikami formula was obtained for a single 2D layer, and it is not suitable for the analysis of negative magnetoresistance in coupled double-layers structures.

Finally, knowing the values of t and l_φ we are able to compare the calculated and experimental area dependencies of $\overline{L}(S_x)$ to $\overline{L}(S_z)$ ratio [Fig. 3(b)]. It is seen that the experimental ratio is significantly larger than unity as well as a calculated one.

It should be noted that some quantitative inconsistency between calculated and experimental curves $W(S_x)$ and $\overline{L}(S_x)/\overline{L}(S_z)$ is evident (Fig. 3). We believe this is a result of crudity of the model used. In particular, we supposed the identity of both 2D layers in the numerical calculation.

Let us briefly discuss the limits of validity of our approach. In the first place, the conditions $k_F l \gg 1$, where k_F is the Fermi wave vector, must be fulfilled. It is common for all theories of the weak localization. Since we neglect the spin effects, this approach is valid when the spin relaxation time is much greater than the phase-breaking time.[19] We have also supposed that an electron does not escape the layer moving through the interference region. This means that the condition $t \ll 1$ should be fulfilled. For the case of an in-plane magnetic field we have assumed that the asymmetry of wave functions and/or the scattering potential (see Ref. 2) gives a significantly lesser contribution to the negative magnetoresistance than the interlayer transitions. At last we have assumed that the interlayer transition probability is independent of the magnetic field. Thus an in-plane magnetic field must be low enough to change the electron wave functions.

After this paper has been prepared for publication, the paper by Raichev and Vasilopoulos on the theory of weak localization in double quantum wells is appeared.[20] Let us apply this theory to our case. Using the formulas derived in Ref. 20, we have calculated $\Delta\sigma(B_i)$ dependencies for our structure. These dependencies are represented in Fig. 1 by dashed curves. As is clearly seen, theory developed in Ref. 20 describes our experimental results only in low magnetic fields. The reason is that the calculations in Ref. 20 were carried out in the framework of the diffusion approximation. It means that two conditions are met. The first condition is $\tau \ll \tau_\varphi$. For the structure investigated $\tau/\tau_\varphi = 0.014 - 0.035$ for different temperatures, and this condition may be considered as fulfilled. According to the second condition, the magnetic field has to be low enough: $B \ll B_t$ when $\mathbf{B}\|\mathbf{z}$, or $B \ll B_t l/Z_0$ when $\mathbf{B}\|\mathbf{x}$. In our case $B_t \simeq 0.14$ T, $l/Z_0 \simeq 2.5$ and hence the diffusion approximation is applicable when $B \ll 0.14$ or 0.35 T, depending on the magnetic-field orientation. It is in this range of the magnetic field that the results of Ref. 20 are close to our experimental data.

Our calculations are valid beyond the diffusion approximation and therefore they better describe the experimental results in the whole magnetic field range, where the weak-localization correction to the conductivity is dominant.

V. CONCLUSION

We have investigated the weak-localization negative magnetoresistance in double-layer heterostructures for different magnetic-field orientations. Area-distribution functions and area dependencies of average lengths of closed paths have been extracted from the analysis of temperature and magnetic-field dependencies of magnetoresistance. In order to interpret the experimental results, we have investigated the statistics of closed paths and negative magnetoresistance using the computer simulation of the carrier motion with scattering over two 2D layers. Analysis of experimental and theoretical results unambiguously shows that in a parallel magnetic field the negative magnetoresistance in double-layer structures is determined by interlayer transitions.

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