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TITLE: Nanostructures: Physics and Technology International Symposium [9th], St. Petersburg, Russia, June 18-22, 2001 Proceedings

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9th Int. Symp. "Nanostructures: Physics and Technology"
St Petersburg, Russia, June 18–22, 2001

Transition from several to one conductor channel induced by intersubband scattering in 2D weak localization

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Abstract. The theory of weak localization is presented for quasi-2D systems where several subbands of size quantization are occupied. The weak-localization correction to conductivity is shown to depend strongly on the level concentration ratio and intersubband scattering intensity. Specifically, at the comparable level occupations and equal relaxation times, the conductivity correction of the m-subband system decreases in m times when transiting from the isolated levels to the high-intensive intersubband scattering case.

A weak localization phenomenon is known to be an interference of waves propagating along the same paths in opposite directions [1]. Processes of phase and spin relaxation or magnetic field destroy the interference and therefore can make observable the weak localization effect. The brightest manifestation of the phenomenon is the anomalous behavior of resistance in classically weak magnetic fields, $\omega_c\tau \ll 1$. Here ω_c is the cyclotron frequency, and τ is the momentum relaxation time. Since the magnetic field destroys the coherence at distances comparable to magnetic length, l_B, this effect takes place when l_B is simultaneously equal to characteristic kinetic lengths.

In very low magnetic fields, the coherence is destructed at long trajectories, when the mean free path, l, is much less than l_B. This is so-called *diffusion* regime of weak localization, and the corresponding characteristic size is the dephasing length, l^{φ}. In higher fields, when $l_B \sim l$, short trajectories passing through several scatterers contribute to weak localization. This regime is called *non-diffusion*.

The anomalous magnetoresistance was widely investigated both theoretically and experimentally in bulk semiconductors and metals, thin films and ultra-quantum two-dimensional (2D) structures. A comparison of theory and experimental data in both diffusion and non-diffusion regimes allowed to determine the kinetic parameters such as times and lengths of elastic relaxation and dephasing.

Recently the magnetotransport investigations have been devoted to more complicated, so-called quasi-2D systems which are between three-dimensional and ultra-quantum two-dimensional ones. These structures are tunnel-coupled quantum wells, multivalley 2D semiconductors and quantum wells with two or several occupied levels of size quantization. Intersubband scattering taking place in these systems leads to effective averaging of the kinetic parameters corresponding to different levels and therefore can affect magnetotransport [2].

Quasi-2D systems are very attractive objects for study of weak localization because even rare intersubband transitions affect it strongly. Usually the intersubband scattering time, τ_{ij} $(i \neq j)$, exceeds enough the total momentum relaxation times in subbands, τ_i, therefore an influence of intersubband transitions on classical magnetotransport is insignificant. In opposite, the dependence of weak-localization correction to conductivity on magnetic field,

$\Delta\sigma(B)$, in the diffusion regime and its value in zero field, $\Delta\sigma(0)$, are determined by the dephasing time τ_i^φ exceeding τ_i. Therefore at τ_{ij} long with respect to τ_i but comparable to τ_i^φ intersubband scattering affects weak-localization correction strongly.

The aim of this communication is to present the theory of weak localization for multi-level 2D systems. We calculate the conductivity correction $\Delta\sigma(B)$ in the whole range of classically weak magnetic fields. To concentrate on the effect of intersubband transitions, scattering is assumed to be isotropic and a spin relaxation is neglected. Note, that $\Delta\sigma(B)$ in the frame of diffusion approximation was obtained in Ref. [3]

The main weak localization corrections to the conductivity appear in the first order in the parameter $(k_F l)^{-1}$ with respect to classical conductivity, where k_F is the Fermi wave vector. The corresponding expression has the form

$$\Delta\sigma = \Delta\sigma^{(a)} + \Delta\sigma^{(b)}\,, \tag{1}$$

where the terms are given by

$$\Delta\sigma^{(a)} = -\frac{e^2}{\pi^2\hbar}\sum_i \frac{l_i^2}{l_B^2}\tau_i \sum_{N=0}^{\infty} P_i(N)\, C_{ii}^{(3)}(N)\,, \tag{2}$$

$$\Delta\sigma^{(b)} = \frac{e^2}{\pi^2\hbar}\sum_{ij}\frac{l_i l_j}{l_B^2}\frac{\tau_i\tau_j}{\tau_{ij}}\sum_{N=0}^{\infty} Q_i(N)Q_j(N)\frac{1}{2}\left[C_{ij}^{(2)}(N) + C_{ji}^{(2)}(N+1)\right].$$

Here τ_{ij} $(i \neq j)$ and τ_{ii} are inter- and intrasubband scattering times, l_i and l_i^φ are the mean free path and the dephasing length in the i-th subband, e is the electron charge, $P_i(N)$ and $Q_i(N)$ are defined by

$$P_i(N) = \frac{l_B}{l_i}\int_0^\infty dx\, \exp\left[-x\frac{l_B}{l_i}\left(1+\frac{l_i}{l_i^\varphi}\right) - \frac{x^2}{2}\right] L_N(x^2)\,, \tag{3}$$

$$Q_i(N) = \frac{l_B}{l_i}\frac{1}{\sqrt{N+1}}\int_0^\infty dx\, x\, \exp\left[-x\frac{l_B}{l_i}\left(1+\frac{l_i}{l_i^\varphi}\right) - \frac{x^2}{2}\right] L_N^1(x^2)\,,$$

with L_N and L_N^1 being the Laguerre polinomials. The Cooperons $C^{(2)}$ and $C^{(3)}$ are determined from the following system of linear equations

$$\sum_k \left(\delta_{ik} - \frac{\tau_k}{\tau_{ik}}P_k(N)\right) C_{kj}^{(2)}(N) = \sum_k \frac{\tau_k}{\tau_{ik}\tau_{kj}} P_k(N)\,, \tag{4}$$

$$C_{ij}^{(3)}(N) = C_{ij}^{(2)}(N) - \sum_k \frac{\tau_k}{\tau_{ik}\tau_{kj}} P_k(N)\,.$$

The expressions (2) describe the weak-localization correction to conductivity in the whole range of classically weak magnetic field.

Figure 1 presents the dependence of $\Delta\sigma$ on magnetic field for the system with two size-quantized levels at various intersubband scattering rates and different level occupations. We assume here that the total relaxation times in the subbands coincide, $\tau_1 = \tau_2$, and the dephasing times are also identical and equal to $10\tau_1$. The solid, dashed and dotted curves

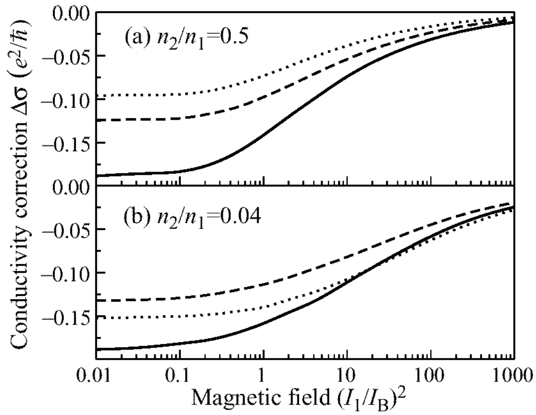

Fig. 1. The dependence of weak localization correction to the conductivity at different level occupations and various intersubband scattering times, $\tau_1/\tau_{12} = 0$ (solid curves), $\tau_1/\tau_{12} = 0.5$ (dashed curves), and $\tau_1/\tau_{12} = 0.1$ (dotted ones).

correspond to the cases of isolated levels, $\tau_{12} \gg \tau_1^\varphi \gg \tau_1$, relatively rare intersubband transitions, $\tau_{12} \sim \tau_1^\varphi \gg \tau_1$, and intensive intersubband scattering, $\tau_{12} \sim \tau_1 \ll \tau_1^\varphi$, respectively.

At the comparable level concentrations (Fig. 1a), $l_1 \sim l_2$, intersubband scattering decreases the absolute value of the conductivity correction, $|\Delta\sigma|$, with respect to the isolated level case (solid curve). Rare intersubband transitions (dashed curve) change $|\Delta\sigma|$ rather in low magnetic fields corresponding to the diffusion regime. The reason is that weak intersubband scattering acts as an additional dephasing and therefore leads to reduction of the effective dephasing time that determines the behavior of $\Delta\sigma$ in the diffusion regime. Frequent intersubband transitions (dotted curve) decrease $|\Delta\sigma|$ in the whole range of classically weak magnetic fields.

Moreover, one can say the increasing of the intersubband scattering intensity causes the transition from two-level into one-level system. Indeed, in the absence of intersubband scattering, two independent levels exist. In the case of intensive intersubband scattering, $\tau_{12} \sim \tau_1$, the level division does not take place. There is only one subband effectively with average kinetic parameters. Since the total and dephasing subband times are chosen to be identical respectively, $\tau_1 = \tau_2$, $\tau_1^\varphi = \tau_2^\varphi$, the average parameters of the 'effective subband' coincide with those of separate subbands at the comparable level occupations, $n_1 \approx n_2$. The one-level weak localization correction to conductivity is independent of the level occupation. Therefore at $n_1 \approx n_2$ the magnitude of $|\Delta\sigma|$ for intensive intersubband scattering is approximately half as much as for isolated subband system. This difference for a factor of 2 can be seen between solid and dotted curves in Fig. 1(a).

In the case of different level concentrations (Fig. 1(b)) the quantum conductivity correction depends on the intersubband scattering intensity in complicated manner. However at arbitrary concentration ratio, rare intersubband transitions do decrease $|\Delta\sigma|$ in the diffusion regime because, as mentioned above, the role of weak intersubband scattering is restricted to an additional dephasing.

In conclusion, the theory of weak localization has been presented for multilevel 2D systems.

Acknowledgements

This work is supported by the Russian Foundation for Basic Research: 00-02-17011 and 00-02-16894, and by the Russian State Programme "Physics of Solid State Nanostructures".

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