Out-of-Plane Weak Localization in Two-Dimensional Electron Structures

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The paper presents experimental data on magnetotransport in highly disordered two-dimensional electron gas (2DEG) subsystems contained in GaAs and InP structures in a parallel magnetic field. To interpret the observed negative magnetoresistance we introduce a model of potential fluctuations and the idea of the destruction of out-of-plane weakly localized orbits by the magnetic field. We derive a simple formula for the magnetic field B_s characterizing this effect and find relations between the behavior of our system and other structures that also contain parallel 2DEG subsystems. [S0031-9007(98)05937-7]

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An important electronic quantum interference effect called weak localization (WL) has been counted since the late 1980s among well understood effects and has become a subject of rather extensive literature [1,2]. However, the diversity of its manifestation still evokes new waves of interest. Recently, the idea of WL has been used, e.g., for the explanation of electronic transport in narrow channels, dot arrays, and systems in the regime of quantum chaos [3–6]. Traditionally, the most striking, well established effect is the low temperature giant negative magnetoresistance observed in two-dimensional (2D) disordered structures with a variable range hopping regime in the perpendicular magnetic field [7–9]. On the contrary, sporadic analogous experiments with a magnetic field parallel to the 2D subsystem [10,11] gave evidence that this effect is not quite negligible in only the case where the structure contains two or more parallel 2D subsystems a tunneling distance apart. The theoretical treatment [12,13] has shown that the observed behavior of magnetoresistance is very likely due to the existence of weakly localized orbits incident with two adjacent 2D subsystems. It is a remarkable fact that this result has some common features with a quite recent [14,15] interpretation of the influence of the in-plane magnetic field on the electronic bilayer existing in wide quantum wells. To bring both these limiting cases together (i.e., insulating and conducting) the present Letter provides lacking experimental data on structures containing parallel 2D subsystems of electron concentrations from the range (10^{15}–10^{16} m^{-2}) where the metal-insulator transition in disordered 2D takes place [11]. The data obtained are interpreted using a model of potential fluctuations and the idea of the destruction of certain out-of-plane weakly localized orbits by parallel magnetic field. In further discussion the authors claim to show that just these states incident to different 2D subsystems and which are not, strictly speaking, two-dimensional may serve as a satisfying general model of states responsible for the interaction between two parallel 2DEG's regardless of types of scattering and transport regime.

The measurements were performed on semiconductor GaAs and/or InP based, metal-organic chemical-vapor deposition (MOCVD) grown multi-δ-layer structures. The two-dimensional subsystem consisted of ten parallel δ layers 100 nm apart. Every δ layer, i.e., the layer with doping confined to only a few atomic layers, contained silicon or sulfur induced shallow donors of planar concentrations per layer covering the range $(2-5) \times 10^{15}$ m^{-2}. The samples were shaped into the Hall-bar structures by means of wet etching and provided with AuGeNi based alloyed contacts. For the four-probe resistance measurements we used an Oxford Instruments AVS-47 bridge eliminating spurious signals due to thermopower and working with extremely low excitation signal levels. Temperature of the sample was controlled by a pumped He cryostat in the range 1.2–20 K. The constancy of temperature during the sweeps of magnetic field was ensured by setting constant He vapor pressure and/or constant heating power. Corresponding temperature was measured at zero magnetic field by means of calibrated carbon resistor. A magnetic field up to 8 T generated by a superconducting solenoid was applied in either parallel or perpendicular direction with respect to the multi-δ-layer subsystem. In the measurements in parallel magnetic field the current flow was always perpendicular to the magnetic vector. In order to provide more complete information about the structures under study a short presentation of some results only indirectly related to the subject of this paper is given in the following paragraph.

In perpendicular magnetic fields the low temperature longitudinal magnetoresistance R_{xx} reveals a sharp minimum at a magnetic field B_m accompanied by a plateau (inflection) in the Hall resistance at $R_{xy} \approx h/2e^2$ per layer, corresponding to the Landau level filling factor $\nu = 2$. It proves the fact that multi-δ-layer system behaves at helium temperatures as actually two dimensional and simultaneously provides a more accurate value of the electron concentration ($= \upsilon e B_m / h$) than that which can be deduced on the basis of technological data. Besides, at low perpendicular magnetic fields (~ 1 T) the giant negative magnetoresistance (20%–30%) is systematically observed. The existence of this effect which is usually ascribed to the destruction of weakly localized orbits by perpendicular magnetic field, as well as the observed linearity of the temperature dependence of the sheet conductance per layer $G^{\square}$ at zero magnetic field [16] (see the inset of Fig. 1), shows the primary importance of the coherence breaking of electron waves for the transport in these structures. The extent of space where interference phenomena can take place in principle is characterized by the phase coherence length L_φ. A reasonable estimate of this quantity reads [16]

$$L_\varphi = e^2/4\pi\varepsilon\varepsilon_0 k(T_0 + T), \qquad (1)$$

where $\varepsilon\varepsilon_0$ is the permittivity, k the Boltzmann constant, and T_0 the parameter characterizing the particular system. It should be noticed that for GaAs and InP based multi-δ-layers with interlayer distance $d = 100$ nm, the coherence length L_φ at helium temperatures (10^{-7}–10^{-6} m) is just sufficient to enable the interference of electron waves extending over the interlayer space. Another important effect observed in perpendicular as well as parallel fields applied to the multi-δ-layer is due to the so-called shrinkage of the wave functions in the high field limit where their diameter (~ 2 times Bohr radius) exceeds the magnetic length $\lambda = (\hbar/eB)^{1/2}$. According to theory [17] the dependence of $\log R_{xx}$ on the square of magnetic field should be linear in this case. An example of such a dependence is demonstrated in Fig. 1 where the magnetoresistance in parallel field is plotted in coordinates $\log R_{xx}$ vs B^2. In the figure two regions can easily be distinguished, namely, that corresponding to the linear part of the curve where the shrinkage dominates and the system is an insulator and that (below ~ 4.5 T) where the system has properties of highly disordered conductor. Just the behavior of the multi-δ-layer system in this range will be the subject of further discussion.

As an example Fig. 2 shows a set of magnetoresistance curves measured at various temperatures and corresponding to the parallel magnetic field up to 5 T. The common features of these curves may be described as follows. At very low fields (0–0.1 T) the resistance is almost constant (cf. Ref. [16]). Then the curves decrease by about 3%–5% till the magnetic field reaches a certain value B_s (~ 0.5 T in Fig. 2) where this decrease strongly diminishes. After that the symptoms of further oscillations are distinguishable before the high field exponential increase of magnetoresistance prevails. Such behavior can be described admitting that some universal oscillatory function scaling with characteristic parameter B_s is superimposed on the magnetoresistance curve due to the shrinkage effect.

For the interpretation of these results we have employed the following model of two-dimensional electron gas (2DEG) disordered by random potential fluctuations. The donors randomly distributed over the plane of δ layer, together with the acceptor background, introduce a strongly oscillating potential. The variation of the potential $\delta\psi$ can be estimated as [11]

$$\delta\psi = e\sqrt{N}/4\pi\varepsilon\varepsilon_0, \qquad (2)$$

where N is the donor planar concentration in the δ layer and $1/4\pi\varepsilon\varepsilon_0$ is the fundamental constant of electrostatics related to the host crystal. In the concentration range

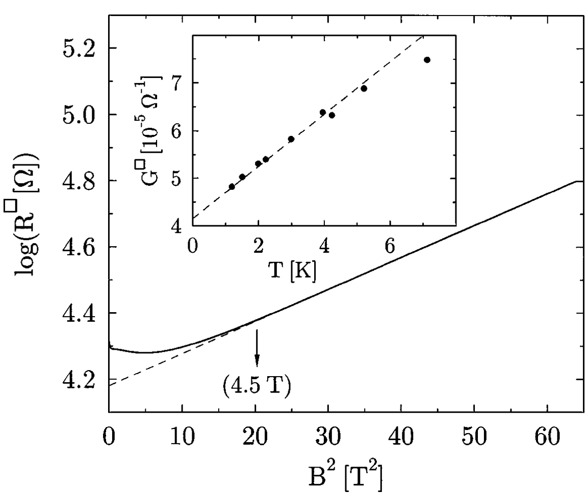

FIG. 1. The field dependence of the magnetoresistance of InP:Si based multi-δ-layer ($N = 2.5 \times 10^{15}$ m^{-2}) measured at 1.2 K and plotted at coordinates relevant to the shrinkage effect. Inset: The temperature dependence of the zero-field conductance of the same sample ($T_0 = 2.2$ K).

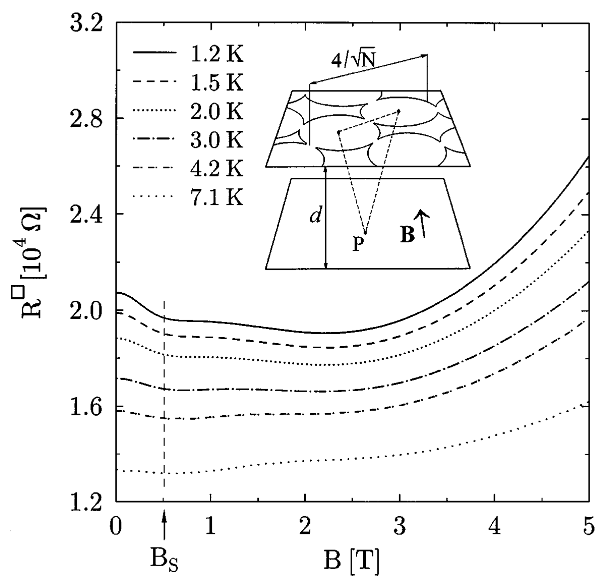

FIG. 2. Magnetoresistance curves measured at various temperatures corresponding to the same sample as in Fig. 1. Inset: Schematic illustration to the presented model.

between 10^{15}–10^{16} m^{-2} this variation amounts to a few mV. Size confinement of electrons to the area S, generating in 2DEG the same mean energy spacing as $e\delta\psi$, is given by the formula

$$S = 2\pi\hbar^2/me\delta\psi\,, \tag{3}$$

where m is the effective electron mass. A simple calculation gives evidence of the fact that the characteristic dimension (diameter) of such an area defined as $a = (4S/\pi)^{1/2}$ is practically the same as the mean distance between neighboring donors, i.e., $2/\sqrt{N}$ (for $N = 3 \times 10^{15}$ m^{-2}, it follows that $\delta\psi = 6.3 \times 10^{-3}$ V, $a = 3.8 \times 10^{-8}$ m, and $2/\sqrt{N} = 3.7 \times 10^{-8}$ m). We can thus imagine the highly disordered 2DEG in the δ layer as a sea divided into a system of randomly distributed shallow basins interconnected by tunnel junctions at the saddle points of the potential profile (cf. [18,19]). According to this model the transport along the δ layer will be provided by tunneling through the potential barriers at the saddle points separating adjacent basins. Moreover, according to the above estimates the typical basin having a diameter of $\sim 2/\sqrt{N}$ will contain on average one electron (see the inset of Fig. 2).

A recent analysis of the electronic transport in disordered 2DEG based on a similar model has shown that the magnetic field perpendicular to the δ layer should affect the tunnel probabilities through the saddle points changing the overlap of wave functions on both sides of the junctions [19]. Just this effect together with the interference (weak localization) effects gives rise to a giant negative magnetoresistance observed. Both these effects vanish in the parallel magnetic field provided that the electrons do not leave the plane of the δ layer. The experimental observation of the negative magnetoresistance in the parallel magnetic field may be, however, consistently explained by the assumption that some electrons are also scattered by the centers lying out of the particular δ layer and especially by those forming adjacent δ layers.

Let us assume that during the transport along the δ layer the electron shifts over a distance $\sim 2/\sqrt{N}$ from one basin to another and simultaneously is scattered by a center P lying somewhere in a neighboring parallel δ layer (see the inset of Fig. 2). The alternative paths enabling weak localization constitute a triangular loop whose orthogonal projection onto the plane perpendicular to the vector B has an area which is independent of the position of the point P but depends on the angle α between the vector B and the direction of the electron shift in the plane of the δ layer. By averaging the projected area $\sim(d/\sqrt{N})\sin\alpha$ over the randomly distributed angle α we obtain the average area of the triangular loop orthogonal to the magnetic field as $\sim 2d/\pi\sqrt{N}$. Comparing this area with the square of magnetic length λ^2, i.e., with the area which is at a given magnetic field just sufficient to completely destroy the phase coherence of the electron moving on its periphery, we obtain the formula

$$B_s = \pi\hbar\sqrt{N}/2ed\,, \tag{4}$$

defining the magnetic field B_s at which the constructive interference on the triangular loops of described type is fully suppressed or, in other words, where the negative magnetoresistance reaches its ultimate value. In order to test its validity, formula (4) was compared with experimental data obtained on various multi-δ-layer systems. For this purpose the field B_s was determined graphically as the first point on the magnetoresistance curve at which the decrease of magnetoresistance stops and was plotted versus $\sqrt{N}/d$ (see Fig. 3). While the graphical method of the determination of B_s inevitably brings about a rather large error (15%), the coincidence of experimental data with formula (4) is astonishingly good. This fact strongly supports our opinion that despite the simplifying approach used, the interpretation of the negative magnetoresistance as a consequence of the destruction of out-of-plane weakly localized orbits by a magnetic field parallel to δ layers is essentially correct.

To generalize the discussion, let us examine the structure of Eq. (4) in more detail. Using dimensional analysis [20], this equation may be obtained very easily in the form of dimensionless monomial,

$$\hbar\sqrt{N}/eBd = \text{const.} \tag{5}$$

Obviously, the ensemble of universal constants and variables, namely, e, $\hbar$, N, d, and B, is relevant to a rather wider class of physical situations, and the constant in (5) defining the scaling properties of the solution of any particular problem cannot be, in general, determined without reference to a suitable physical model. To illustrate this circumstance let us apply our approach to a slightly different problem already solved by more sophisticated methods, namely, to the influence of parallel magnetic field on the two-dimensional bilayer electronic system existing

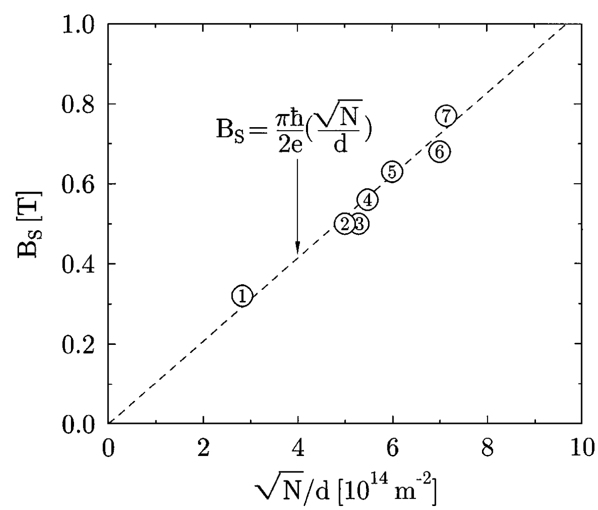

FIG. 3. Experimental test of formula (4) using the data taken from the present study and the literature. 1—Ref. [10]; 3—GaAs:Si; 2—InP:Si; 4—Ref. [21]; 5, 7—InP:S; 6—GaAs:S.

in wide quantum wells with remote doping [15]. In this structure the electrons condensing in the vicinity of both sides of quantum well give rise to two parallel 2DEG's, each of which has an effective concentration of $\sim N/2$. The absence of a strongly fluctuating potential in the remotely doped quantum well has two consequences. First, the characteristic length for planar electronic transport is no longer the size of potential fluctuations but the most probable distance between electrons, i.e., $\sim 1/\sqrt{2\pi(N/2)}$, measuring the distance between succeeding scattering events. Second, the moving electrons attain more freedom in comparison with those in δ layers, because the potential profile does not put further constraints on their motion, which makes the averaging procedure with respect to the angle α superfluous. Then in close analogy with the derivation of (4), we obtain immediately the following expression:

$$B_s' = 2\hbar\sqrt{\pi N}/ed\,. \tag{6}$$

This formula known from the literature [15] provides the value of the field at which a sharp decrease in the density of states accompanied with the corresponding decrease in conductance is expected and actually observed. Taking into account our derivation of formula (6), we can add that the states disappearing during the application of the magnetic field B_s' should be just the states represented by the out-of-plane weakly localized triangular orbits.

It is very instructive to compare formula (4) with that obtained by an exact analytical solution in the case where the transport along the couple of δ layers is controlled by variable range hopping [12]. In this dirty limit the solution is given by a universal function the oscillatory part of which has an argument of the form $(Bedr/2\hbar)$ where r is the maximum hopping length. Very satisfactory agreement between the B_s determined from this analytical formula and formula (4) can be achieved by formal substitution of $r/2$ for $2/\sqrt{N}$. It represents, in fact, the change from the variable range hopping to the nearest neighbor hopping and shows simultaneously the possible way for the generalization of our model and the explanation of the magnetoresistance oscillations observed (cf. Fig. 2).

In conclusion, we have investigated experimentally the influence of a parallel (in-plane) magnetic field on the transport in highly disordered 2DEG subsystems contained in GaAs and InP based multi-δ-layers. The observed negative magnetoresistance was explained using a model of potential fluctuations and the idea of destruction of out-of-plane weakly localized orbits by the magnetic field. A simple formula for the magnetic field B_s characterizing this effect was provided. Moreover, the relations between the behavior of our systems and others also containing parallel 2DEG subsystems (e.g., well ordered 2DEG bilayer, multi-δ-layers with a variable range hopping regime) were established.

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