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Random magnetic field and weak localization effects in a dimpled 2D electron gas

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We have studied negative magnetoresistance due to the weak localization effects in a 2D electron gas (2DEG) grown on dimpled substrates. Since the 2DEG is sensitive only to the normal component of B, depending on the orientation of the external magnetic field, electrons will move in a spatially inhomogeneous (B perpendicular to the substrate-$B_\perp$) or sign alternating, random magnetic field (B parallel to the substrate $B_{\parallel}$). A difference in the magnetoresistance at $B_{\parallel}$ and $B_\perp$ is seen for the sample with a coherence length larger than the spatial periodicity of magnetic field. We believe that the difference in the magnetic flux through the closed electron trajectories at $B_{\parallel}$ and $B_\perp$, taken into account random character of $B_{\parallel}$, is responsible for this behaviour. Features connected with Aharonov Bohm flux through the different areas on the dimpled surface were observed.

Much theoretical work has focused on transport studies in a random magnetic field [1,2]. Within the framework for the composite fermion-theory of the fractional Quantum Hall effect, the quasi-particles move in a static non-uniform or random magnetic field B. Here we present experimental evidence that electrons in an external magnetic field, and confined to a non-planar GaAs/AlGaAs heterojunction, experience a weak, random magnetic field B, and hence, this can be used as a model system. We find quantum corrections to the conductivity due to weak localization effects when the carriers move coherently through regions with alternating signs of B.

Samples were fabricated employing overgrowth of GaAs and AlGaAs materials by molecular

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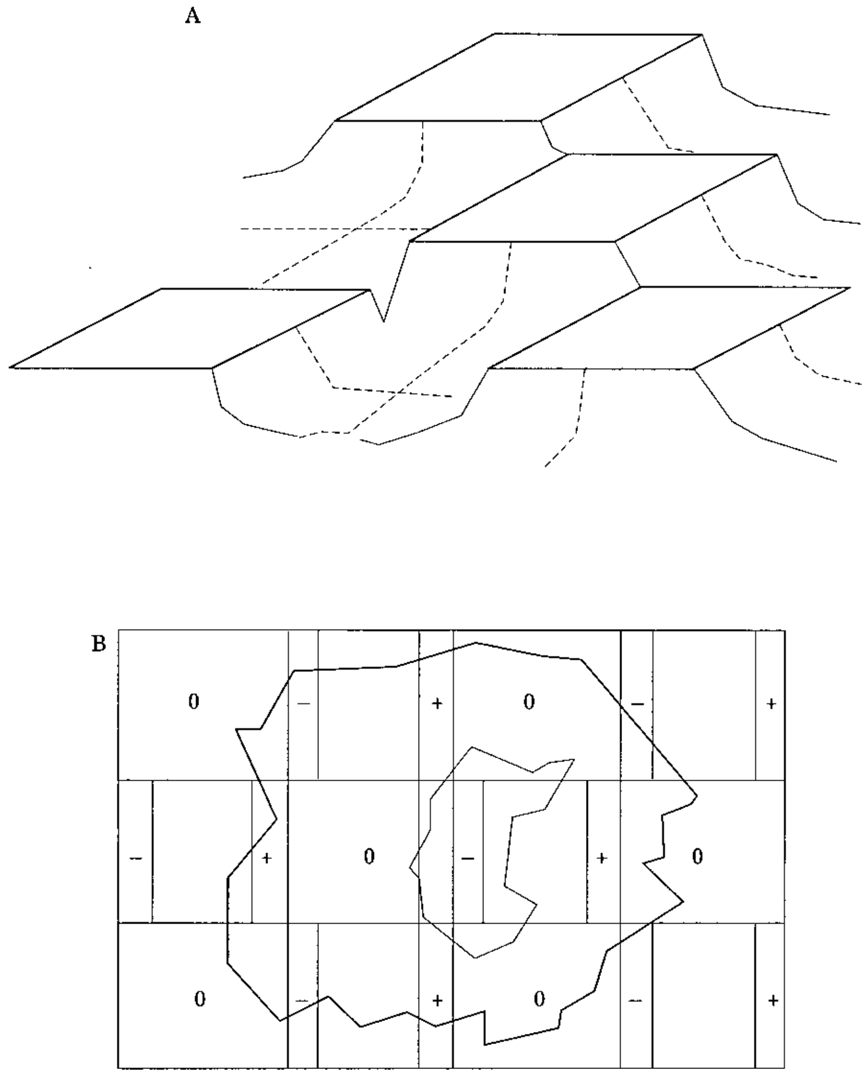

Fig. 1. (A) Schematic illustration of the 'dimpled' surface containing the 2DEG. (B) Schematic illustration of the 'tiled' effective magnetic field, when the external field is applied parallel to the substrate.

beam epitaxy (MBE) on pre-patterned (100)-GaAs substrates. The pre-patterning consisted of lattices (periodicity $d=0.3$ and 1 μm) of holes (depth 1 μm, diameter 0.1–0.3 μm), made by electron beam lithography and wet etching. A thick (1 μm) GaAs buffer layer was grown to smooth out any steps in the crystal planes, and a rapid planarization of the initial surface is indeed seen in scanning electron microscope picture of the structure surface. Instead, a 'dimpled' surface is obtained with a modulation of the surface of 0.1 μm. This agrees with studies of MBE overgrowth on corrugated (100) GaAs substrates [3], which have demonstrated that growth on $\{001\}$ oriented grooves leads to the existence of $\{811\}$A crystal planes at the bottom of the grooves and $\{111\}$A on the slopes. Growth on $\{01\bar{1}\}$ grooves, on the other hand, is characterized by the formation of $\{100\}$ facets with smooth slopes forming on the edges of grooves. Thus the region of etched holes is non-planar and has a smooth slope on all edges. This shape of a 'dimpled' surface is shown schematically in Fig. 1. It consists of unetched planes, surrounding non-planar valleys with planes tilted towards the centre of the valley by 10° with respect to the normal of the substrate, and slopes with tilt-angles 45–60° between the valleys and the unetched surfaces. An AlGaAs/GaAs heterojunction was grown, with a doping set-back of 100 Å and a spacing of 100 Å, to obtain a 'dimpled' two-dimensional electron gas (dimpled 2DEG). The patterned area was $400 \times 400\ \mu m^2$. Here we present results of measurements in two samples with mobility of the 2DEG of $25 \times 10^3\ cm^2\ Vs^{-1}$ ($d = 1\ \mu m$) and $70 \times 10^3\ cm^2\ Vs^{-1}$ ($d = 0.3\ \mu m$), and the density $5.5 \times 10^{11}\ cm^{-2}$. For the measurements, the sample was mounted directly in the mixing chamber of a top loading dilution refrigerator. The sample could be illuminated in situ by a GaAs light emitting diode. Magnetic fields up to 15T were applied perpendicular to the 2DEG and the resistance measured using conventional phase sensitive detection with an ac current of less than 10 nA at 6.7 Hz.

When placed in a magnetic field, the field normal to the dimpled 2DEG is spatially modulated. Neglecting the spin degree of the freedom, the 2D electrons are sensitive only to this normal component, and they will experience either an effective inhomogeneous magnetic field (with the external magnetic field B perpendicular to the substrate ($B_\perp$)), or random magnetic field (with changing signs, when B is parallel to the substrate ($B_\parallel$)). Evidence for a contribution to the conduction of the electrons on the tilted surfaces has been presented elsewhere [4]. As B rotated from $B_\perp$ to $B_\parallel$, a change in the phase of the Shubnikov oscillations is seen, suggesting that tilting external magnetic field introduces an effective magnetic barrier in the y-direction, due to a mismatch between the Landau levels at the planes parallel to the substrate and on the slopes of the dimples. In this work, we concentrate on the results in a weak magnetic field, where a negative, highly temperature dependent magnetoresistance is observed.

In Fig. 2 the low-field magnetoresistance is shown for two samples with the magnetic field oriented either perpendicular or parallel to the substrate. We see, that for the sample with $d = 0.3\ \mu m$ magnetoresistance is strongly anisotropic, i.e. ρ_{xx} ($B_\perp$) saturates for smaller fields than ρ_{xx} ($B_\parallel$). The change in the conductivity with $B_\perp$ is well understood in terms of weak localization, where the magnetic field breaks the time-reversal symmetry of closed electron paths. Neglecting the effect of the small modulation in the effective magnetic field, the conductivity is given by [5]:

$$\Delta\sigma_{xx}(B) = (e^2/2\pi^2\hbar) f(x), \tag{1}$$

where $x = 4eBL_\varphi^2/\hbar c$, $f(x) = \ln x - \Psi(1/2 - 1/x)$ and $\Psi(y)$-digamma function. This correction to the conductivity fits well to the data in Fig. 2, assuming a phase-coherence length $L_\varphi = 1.2\ \mu m$ at $T = 40$ mK. However, in a parallel field the random character of effective field will lead to cancellation of most of the magnetic flux through the closed loops, as shown schematically in Fig. 1B. As the coherence length is slightly larger than the spatial periodicity of the random magnetic field, one expects to have a total flux equivalent to that of the homogeneous field passing through an area $S = a \times b$, where a- is the width of this step on the dimpled surface ($a \leq d/2$), and b is the height of the step. In this case $x_\parallel \approx 4eB_\parallel SL_\varphi^2/d^2\hbar < x_\perp$ if $L_\varphi^2 > S$. To this simple geometrical consideration, second order corrections to the magnetic flux change through the closed loop have to be added [6,7]. From the theory of the weak localizations, quantum corrections to the conductivity can be expressed as:

$$\Delta\sigma \sim e^2/h \int dt/t \exp(-t/\tau_\varphi) \langle \cos(2\pi\phi(t)/\phi_0) \rangle \tag{2}$$

where τ_φ is a phase coherence time, $\phi(t)$ is the magnetic flux and $\phi_0 = hc/e$. Since, in a random magnetic field, the flux is zero, it is possible to expand the average of the cosine-function: $\langle \cos(2\pi\phi(t)/\phi_0) \rangle \sim 1 - 1/2 \langle \phi(t)/\phi_0 \rangle^2$. Considering a 'chess board' magnetic field, where B changes sign in different cells, this is just a 'random walk' problem. The average of the square of the flux gives $\langle \phi \rangle^2 \approx N\Phi_N^2$, with $N = D\tau_B/d^2$ and $\Phi_N = d^2 B$, where τ_B is the magnetic relaxation time. In analogy with

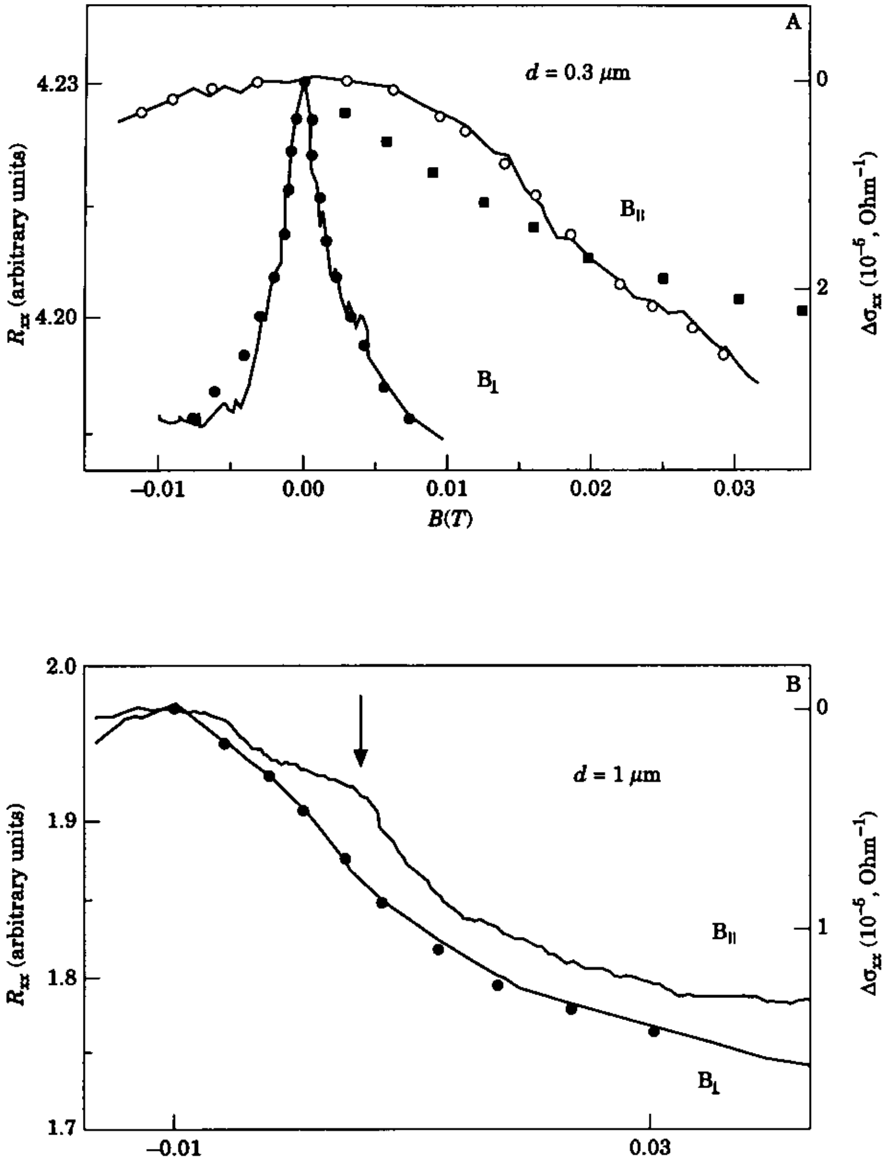

Fig. 2. Magnetoresistance as a function of the magnetic field perpendicular and parallel to the substrate, $T=50$ mK, (A) $d=0.3\,\mu$m, circles are fits based on eqn (1) with the parameter $L_{\varphi}=1.2\,\mu$m, squares eqn (1) with $x_{\parallel}\approx 4eB_{\parallel}SL_{\varphi}^2/d^2\hbar$ and parameters $S=0.01\,\mu\text{m}^2$, empty circles eqn (1) when second order correction due to the random walk through the tiled magnetic field was taken into account with $x_{\parallel}=(Se/2d\hbar c)^2\,(B_{\parallel}L_{\varphi})^2$ and $S=0.04\,\mu\text{m}^2$, (B) $d=1\,\mu$m, circles are fits based on eqn (1) with $L_{\varphi}=0.25\,\mu$m.

an uniform magnetic field, the effect of a magnetic field is essentially to introduce a long time cut off in eqn (2), which is the magnetic relaxation time. For the second order corrections to the flux, the criteria is $1/2\langle\phi(t)/\phi_0\rangle^2\sim 1$ thus implying $\tau_B\sim 2(\hbar c/de\text{B})^2/D$. The argument of the digamma function of eqn 1 $x\approx\tau_{\varphi}/\tau_B$, thus in random 'tiled' magnetic field $x_{\parallel}\approx\,(Se/2d\hbar c)^2\,(\text{B}_{\parallel}L_{\varphi})^2$. This gives a good fit to the experimental curves for $S=0.04\,\mu\text{m}^2$, obtained from a simple geometrical consideration of the structure ($S=4a\times b$). For a comparison, the experimental curve is not described by eqn (1) (see

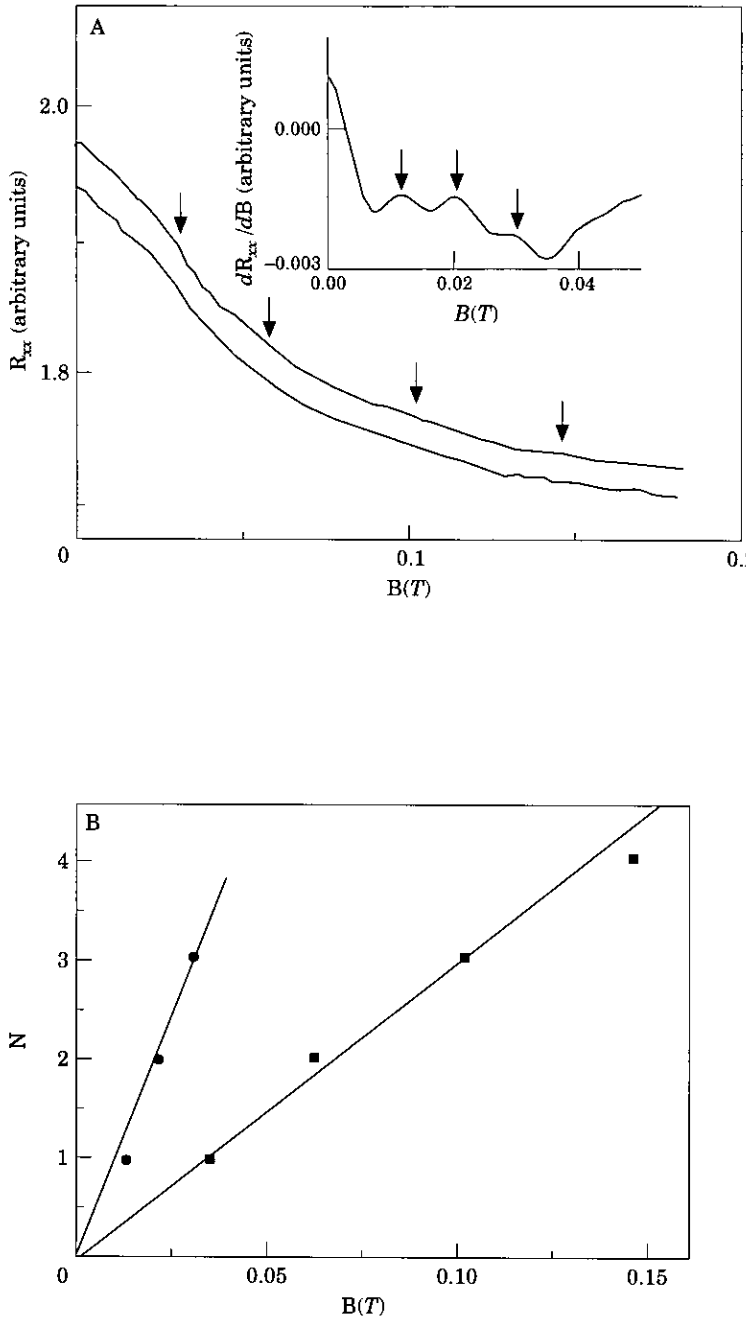

Fig. 3. (A) Magnetoresistance as a function of the magnetic field perpendicular to the substrate for the sample with periodicity 1 μm in wider range of the magnetic field. Insert derivative in the smaller range of magnetic field, $T=50$ mK. (B) Position of the maxima as a function of B.

Fig. 2A) without the second order correction due to the random walk through the chess-board magnetic field.

The difference between the magnetoresistance curves for $B_{\perp}$ and $B_{\parallel}$ is not as large for the sample with $d = 1$ μm as for the $d = 0.3$ μm sample. This can be explained by the lower mobility, and consequently lower phase coherence length found in the higher periodicity sample. Comparing the experimental curves with eqn (1) gives $L_\varphi = 0.2$–0.25 μm. Thus, in contrast to the first sample, L_φ is smaller than the magnetic field spatial periodicity, and the typical electron trajectories in a time τ_φ encloses an area of $L_\varphi^2 \sim S$. For such a small area, the ratio between magnetic field flux through enclosed area at perpendicular and parallel field is around $(B_\perp d^2 L_\varphi^2 / B_{II} L_\varphi^2 S)\cos\alpha$, where α is the angle between the tilted planes on the dimples surface and the substrate. From the experiments (see Fig. 2), α is estimated to be ≈ 45–$50°$.

In addition to the negative magnetoresistance, Fig. 2B shows a weak reproducible feature (marked by an arrow) on the shoulder of the curve in parallel field. The same feature, but less pronounced and shifted to the smaller field, is seen for perpendicular magnetic field. In Fig. 3A additional oscillations are indicated for a wider range of the perpendicular magnetic field up to 0.15 T. Furthermore, in the insert of Fig. 3A, additional periodical oscillations are found for a lower interval of $B_\perp$. The peak positions for the two groups of oscillations are shown in Fig. 3B.

A possible explanation for these oscillations may be the Aharonov–Bohm flux through the well-defined area. In a parallel field, the only areas where the perpendicular component is non-zero, are the sides of the dimples. All electron trajectories enclosed this area experience a phase shift $B_{II} S \sin\alpha / \Phi_0$. In a macroscopic sample the interference of the pair of time-reversed trajectories do not average out, and hence only $h/2e$ flux periodicity should be observed (Altshuler–Aronov–Spivak effect [8] -AAS). Two characteristic areas are obtained from the two series of oscillations displayed in Fig. 3 with $S_1 = 0.22$ μm^2 and $S_2 = 0.06$ μm^2. These coincide fairly well with the surface of the unetched planes of the dimpled surface ($a \times a = 0.45 \times 0.45$ μm^2) and with the steps ($a \times b = 0.45 \times 0.1$ μm^2), respectively. For the latter case, the sine-factor has been taken into account, which gives an effective area of $S_2 = 0.04$ μm^2.

As mentioned above, one weak feature was seen also in parallel field, though no series of oscillations can be detected in the range explored for B_{II}. Therefore it was not possible to state whether this single feature has the same origin as those seen in a parallel field. We therefore limit ourselves to a few (speculative) comments. A priori, one would not expect any AAS effect in this configuration, since the magnetic field now only has a small (periodic) modulation, and the sample cannot be divided into well defined areas S_1 and S_2. The weak localization correction to the conductivity is a result of the interference of the many trajectories with a wide distribution of loops areas, and the maximum area contributing to the weak localization is determined by the phase coherence time. In a magnetic field, when considering the distribution of flux enclosed by loops, one has to take into account that loops with an area $S > h/eB$ no longer contribute to the weak localization effects. In a homogeneous magnetic field the distribution of loops is determined by $1/Dt$ decay of the return probability (where D- is diffusion coefficient), which is provided by the short-time cut-off (elastic scattering time) and long-time cut off (phase coherence time). It is therefore conceivable, that in inhomogeneous (but periodic) magnetic field the distribution of flux through closed loops has features due to the change in magnetic field, when the loops become larger than area for which the magnetic field is uniform (in our case S_1 or S_2). Such fluctuations may be responsible for the features observed in the magnetoresistance, but it is clear that computer simulations, as well as further experiments are necessary to verify this speculation.

Finally, we note, that for the observation of an AAS effect, the coherence length should be ≈ 1 μm, which is higher than value of L_φ, extracted from the comparison of the measurement and equation (1) for the sample with $d = 1$ μm. This discrepancy may be due to a difference in electron mobility on the different dimpled areas. Electrons on the slopes of the dimpled surface have lower mobility and contribute to the negative magnetoresistance, whereas electrons on the other areas have higher mobility and are responsible for the AAS effect. AAS features are not seen in the sample with

$d = 0.3\ \mu m$, since these would appear at higher magnetic field, where positive magnetoresistance due to the influence of **B** on the orbital electron motion is found.

In conclusion, we have studied negative magnetoresistance due to weak localization effects in a 2D electron gas grown on the dimpled surface. Electrons move in an inhomogeneous or sign alternating, random magnetic field, when the external magnetic field is, respectively, perpendicular or parallel to the substrate. If the coherence length is larger, than the spatial periodicity of magnetic field, the low-field magnetoresistance differs in parallel and perpendicular fields. In a random magnetic field it is necessary to take into account the second order corrections to the magnetic flux change through the closed loops. AAS oscillations have been found due to the spatial periodicity of the magnetic field.

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