Superlattices and Microstructures, Vol. 24, No. 3, 1998
Article No. sm960343

Magneto-oscillations in a trapezoidal two-dimensional electron gas grown over GaAs wires

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(Received 15 July 1996)

In this work we investigate a nonplanar two-dimensional electron gas (2DEG) that allows study of the electronic behaviour in random and sign-alternating magnetic fields. Shubnikov–de Haas oscillations were studied by measuring the magnetoresistance at different angles ϕ between the field and the substrate. We find that at low magnetic field the position of the oscillation peaks follows $B_p \sim B\sin(\phi - \theta)$, where θ is the angle between the field and the facets that effectively contribute to magnetoresistance. This is due to the fact that electrons follow different paths depending on the realization of a specific magnetic field.

1. Introduction

The motion of two-dimensional electrons in a random and inhomogeneous magnetic field has recently attracted considerable interest. Motivation for this work stems from theoretical predictions that, in the regime of the fractional quantum Hall effect, at filling factor $1/2$, a composite fermion moves in a static random effective magnetic field [1]. Both short-range and smooth magnetic field fluctuation models have been employed to describe such motion [2, 3]. In a situation where the correlation length of the random magnetic field B is large, compared to the typical magnetic length, electrons move along contours of constant B. The direction of such motion is determined by the sign of the field gradient on the contour. In the case of a random magnetic field with zero average value, the electronic motion describes classical snake-like trajectories around the $B = 0$ lines [4]. In two dimensions these trajectories form a network. The percolation properties of such a network have been considered in the case of zero [5] and nonzero [3] average magnetic fields. In the specific case where the magnetic field has a nonzero average, the network does not percolate, and a large positive magnetoresistance is expected. Nonuniform and spatially sign-alternating magnetic fields have been realized in a structure, which was obtained by molecular beam epitaxy (MBE) overgrowth of a two-dimensional electron gas (2DEG) on a nonplanar substrate [6, 7].

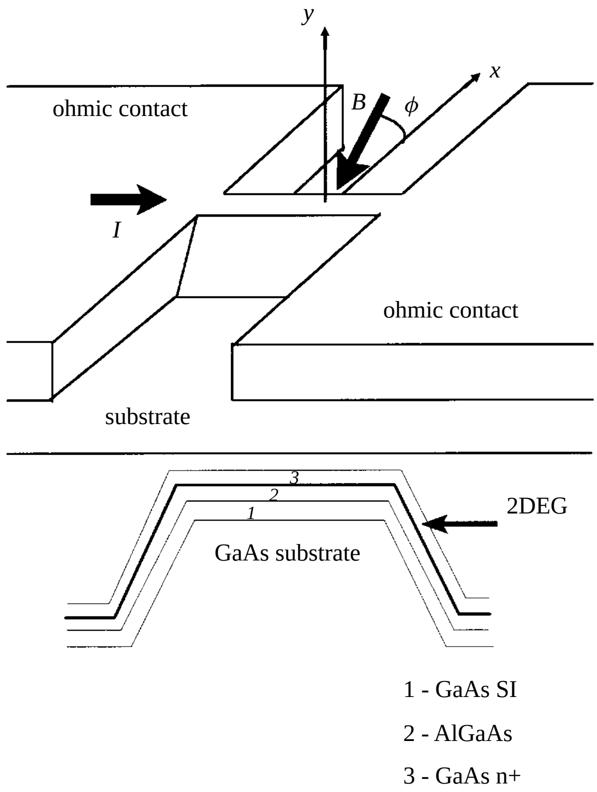

Fig. 1. Schematic view of the sample and diagram of the experiment. The trapezoidal cross section wire consists of a top plane and two facets containing 2DEG.

Since the 2D electrons are sensitive only to the normal component of $\boldsymbol{B}$, an electron will move either in a positive or negative magnetic field, depending on its position on the nonplanar surface and the angle between magnetic field and the facets [7]. In this work we realized a new nonplanar 2D system and have studied the magnetoresistance oscillations in nouniform magnetic fields.

Samples were fabricated by MBE overgrowth of GaAs and AlGaAs materials on a pre-patterned GaAs substrate. Pre-patterning consists of wires produced by electron beam lithography at the center of a conventional Hall bar. After selective deep wet etching, several wires with a trapezoidal cross-section (diameter 0.5–1 μm and length 10 μm) were created (Fig. 1). Magnetoresistance at $T = 1.5$ K was measured in magnetic fields up to 10 T, for different angles ϕ between the field and the normal substrate plane. Figure 2 shows magnetoresistance as a function of B for different ϕ. One can see a large positive magnetoresistance and also Shubnikov–de Haas (SdH) oscillations starting at higher magnetic fields. As the external field is tilted away from the normal direction with respect to the substrate, the SdH oscillations associated with planar facets shift towards higher total fields according to a $1/(\sin\phi)$ law. However, there are some differences between SdH oscillations when comparing nonplanar and planar 2DEGs. Such differences are presented in Fig. 3, which shows the derivative of the magnetoresistance as a function of $1/(B\sin\Phi)$, where Φ is a characteristic angle. This angle is determined by fitting the position of six–seven SdH oscillations at low magnetic fields (for planar electrons $\Phi = \phi$).

We must emphasize two points in these observations. First, the periodicity of the oscillations is not constant on the $1/B$ scale, as expected for a planar 2DEG. At higher B, the peak and minima positions are

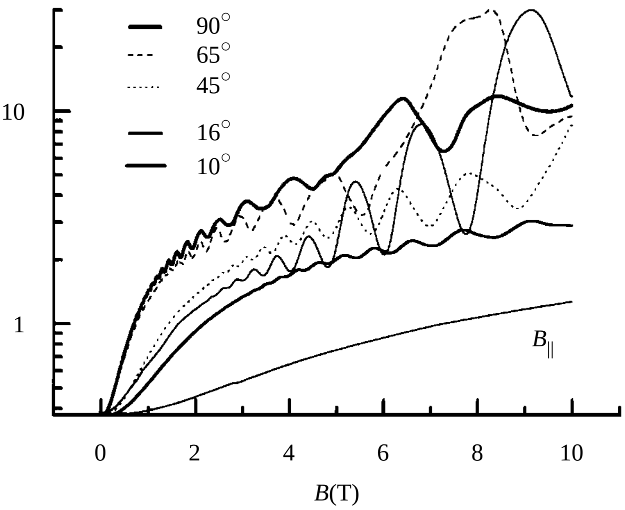

Fig. 2. Magnetoresistance of sample with trapezoidal 2DEG as a function of magnetic field at different angles ϕ.

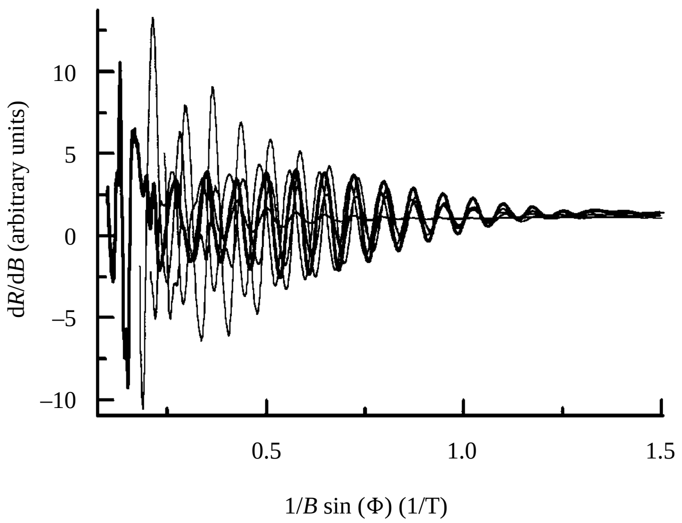

Fig. 3. Derivative of the magnetoresistance for different angles ϕ as a function of $1/B\sin\Phi$, where Φ is parameter determined by fitting the SdH oscillations at low magnetic field.

shifted with respect to each other, even if their positions are coincident at low magnetic field. In order to compare the magnetoresistance curves measured at different angles, we divide the $1/B$ periodicity of each curve by the periodicity of $\phi = 90°$ curve. Figure 4A shows this ratio as a function of inverse Landau index number N. We see that, for $\phi > 45°$, this ratio increases with increasing magnetic field. However for $\phi < 45°$, the ratio decreases with B. So there is a critical angle ϕ_c, where the SdH oscillations change their behaviour. The second point we want to emphasize is that the adjusted angle Φ is not equal to angle ϕ, as in the case of a planar 2DEG. Figure 4B shows $\theta = \phi - \Phi$ as a function of ϕ. It can be seen that this difference changes sign at angle $\phi \approx 40°$. We have to mention that such a change in the sign of θ

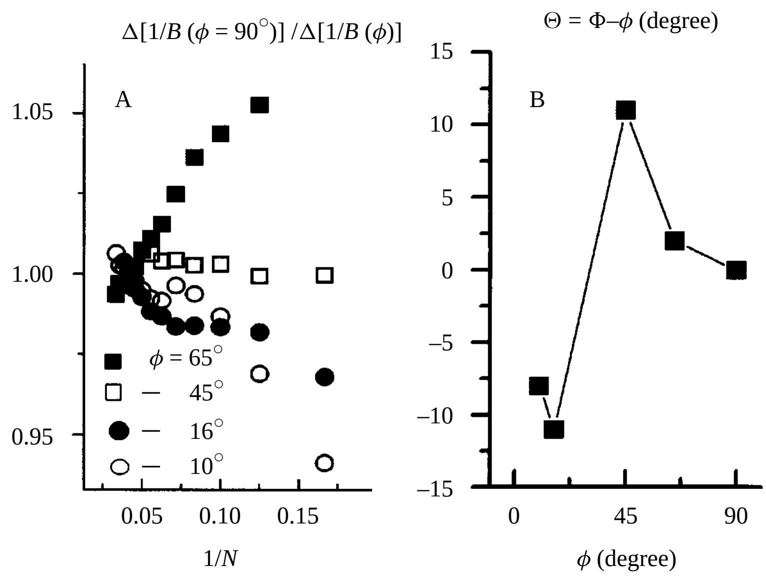

Fig. 4. (A) $\Delta[1/B(\phi = 90°)]/\Delta[1/B(\phi)]$ as a function of inverse Landau index number. $\Delta[1/B(\phi)]$ is a periodicity of SdH oscillations in a tilted magnetic fields. (B) The difference $\phi - \Phi$ determined from the fitting of SdH oscillations at low field (Fig. 3) as a function of ϕ.

occurs at approximately the same critical angle ϕ_C as that observed in Fig. 4A. Finally, the amplitude of the SdH oscillations decreases dramatically for ϕ close to ϕ_C, and increases again for higher ϕ.

We believe that the complexity of the electronic transport in our samples originates from two kinds of inhomogeneity in the magnetic field and also from the random character of the impurity potential. The latter type of disorder is smooth, so electrons drift along lines, where $V(r) = \hbar\omega_C(n + \frac{1}{2})$ or $B(r) = 0$; $V(r)$ is the random impurity potential and ω_C is the cyclotron frequency. In this case scattering between the lines at the saddle-point potential occurs, which increases the probability for passing through the sample. If the magnetic field is perpendicular to the top plane of the trapezoid and contact region 2DEGs (see Fig. 1), these electrons percolate through the sample via the top plane of the trapezoid, following the equipotential line and Landau number index. For a tilted field, when $\phi > 45°$, electrons traverse the sample through one of the facets, where the magnetic field is smaller. In such a situation Φ is less than ϕ, and this can be seen in Fig. 4B. Electrons move in the region with a smaller field, because the probability of scattering through the saddle point between different equipotential lines becomes higher for larger magnetic lengths. We can assume that for $\phi \sim \phi_C$ ($\phi_C = 45°$) the magnetic field on one of the facets is close to zero. This is due to the fact that the angle between facets and the substrate is approximately 45° (Fig. 1). So for ϕ around 45°, the amplitude of the SdH oscillations is reduced (Figs 2 and 3) because the majority of electrons cross the sample without experiencing the magnetic field. When $\phi < 45°$, the magnetic field on one of the facets is negative. Therefore, electrons in this facet drift in an opposite direction to that of the electrons in the contact region. Thus, the electrons cannot percolate through the region of negative magnetic field, and start moving through another facet, where the magnetic field is positive. This explains the behaviour of the SdH oscillations in the case of $\Phi > \phi$ (Fig. 4B). Therefore, by tilting the external magnetic field, we have modified the magnetic field configuration acting on the electrons in the same sample. As a result, the electrons follow different paths, depending on the value and sign of the effective magnetic field in each facet. We must mention that in the interpretation of our results we have assumed that the electron density on each facet is equal to the density in the top plane 2DEG. However, the angular dependence of the SdH oscillations (Fig. 4) cannot be explained by a difference in the density of 2DEG in the planar and facet regions. If a large difference exists, we have to assume that even at $\phi = 90°$ electrons from the facets make the main contribution to the SdH oscillations, because the planar area of the 2DEG is small.

Acknowledgements—This work was supported by CNRS (France), CNPq, FAPESP (Brazil) and COFE-CUB. G.M.G. is supported by CNPq.

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