Magnetotransport in a Spatially Modulated Magnetic Field

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Received February 6, 1999

We have measured the Shubnikov de Haas (SdH) oscillations of a nonplanar two-dimensional electron gas (2DEG) fabricated by overgrowth of a GaAs/AlGaAs heterojunction on a pre-patterned substrate. When placed in a uniform external magnetic field B, the field normal to the nonplanar 2DEG is spatially modulated, and electrons experience a nonuniform magnetic field. In a tilted magnetic field, the SdH oscillations are much more strongly damped than in a field perpendicular to the substrate. We consider several mechanisms and conclude that the electron scattering by the magnetic field spatial fluctuations plays a main role in the transport properties of a nonplanar 2DEG at low magnetic field.

Recently, new regrowth techniques have been reported to produce a two-dimensional electron gas (2DEG) on nonplanar pre-patterned GaAs substrates [1,2]. The interest in fabricating such systems is generated by the possibility to investigate the physics of electron motion in a nonuniform magnetic field. Since a 2DEG is sensitive to only the normal component of the magnetic field B, electrons confined to a nonplanar heterojunction experience nonuniform magnetic field varying with position, depending of the surface shape, if an uniform B is applied to such nonplanar surface.

This letter reports on the fabrication of 2DEG on a nonplanar stripe-shaped surface with small heights of the stripes. The 2DEG has the mobility of (250-400)$\times 10^3$ cm^2/Vs at a carrier density of $5.4\times 10^{11} cm^{-2}$. We studied the electron transport properties of nonplanar 2D electrons in a magnetic field.

Fig. 1a shows the profile of the surface in the direction along the stripes (x direction) and across the stripes (y direction) measured by atomic force microscopy. Along the x direction we can see both irregular and periodical components in the surface corrugation. The average periodicity is coincident with the antidot lattice periodicity before overgrowth. The corrugation height h varies between 20 and 65 $\AA$. Fig. 1a shows also a irregular surface profile along the y direction with smaller corrugation height and larger average periodicity than along the x direction. The origin of these irregularities in not understood. The patterned area was $140\times 140 \mu m^2$. After regrowth, the HEMT structure was processed into Hall bars, and the nonplanar surface was situated on the one side of Hall bar (see insert of fig 2). As was mentioned before, since 2DEG is sensitive only to the normal component of B, measuring the resistance for different angles between the field and the normal to the substrate surface allows us to vary the magnitude of the magnetic field fluctuations. If magnetic field is tilted away from the normal to the substrate, the normal component of B can be expressed as

$$B_N(x,y,z) = (\overline{B}\overline{\bigtriangledown} f)/\mid \overline{\bigtriangledown} f\mid, \quad (1)$$

where gradient $\overline{\bigtriangledown}$f(df/dx, df/dy, df/dz) is defined for the surface $f(x,y,z)=0$. In realistic samples we have $df/dy \sim h/d << 1$. Therefore, if the external magnetic field is tilted in the y direction, the expression (1) can be rewritten as $B_N \approx$Bsinθ + (df/dy) Bcos$\theta\approx \langle B_N\rangle +$ δB(x), where θ is the angle between the external magnetic field and the substrate plane, $\langle B_N\rangle$ = Bsinθ is the average normal component of B. At angles $\theta>>$ h/d $\approx 1^o$, the average magnetic field $\langle B_N\rangle$ is larger than the magnitude of the magnetic field fluctuations

δB(x). Fig. 1b shows the magnetic field profile when the external field is tilted in the x or in y direction. Fig.2 shows the longitudinal magnetoresistance of the one typical sample for different angles θ and ϕ between the field and the normal to the substrate plane as a function of the magnetic field component B_N perpendicular to the substrate. The magnetic field was tilted in the x (a) and y direction (b). At a magnetic field $\sim$ 0.4 T, the SdH oscillations are clearly seen. The oscillations are shifted towards higher total field, following, as expected, a $(sin\theta)^{-1}$ law. However, as B is tilted from the normal, SdH oscillations are more strongly damped than for the perpendicular field. This damping is much stronger when B is tilted away from the normal in the y direction (a) than in the x direction (b).

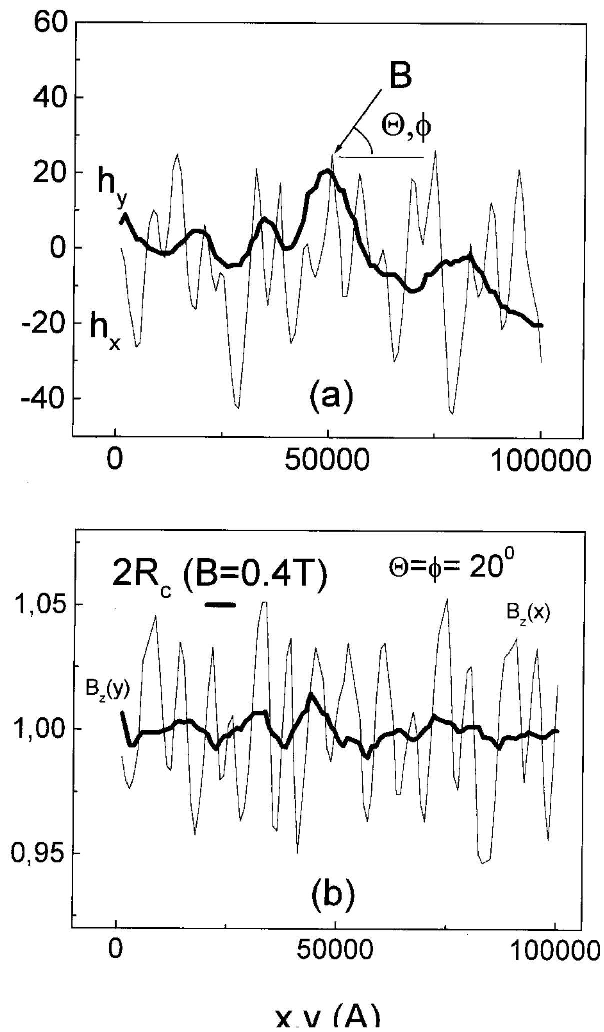

Figure 1. a) Profile of the surface along the x and y direction of the sample shown in fig.1b .
b) Magnetic -field profile calculated for the surface profile shown in fig.2a when the magnetic field is tilted in the x (thick line) or y (thin line) direction. Bars-cyclotron diameter at 0.4 T.

In the 2D case, the amplitude of the SdH oscillations is given by [3]:

$$\Delta R/R = (4A_T/sinhA_T)\exp(-\pi/\omega_c\tau_s)cos(2\pi^2\hbar n_s/eB) \quad (2)$$

where A_T= $2\pi^2$kT$/\hbar\omega_c$, τ_s is a single-particle relaxation time which is typically 10-100 times smaller than the momentum relaxation time extracted from the mobility measurements at B=0 [4]. Fig.3 a, b shows the amplitude of the magnetoresistance oscillations as a function of the tilt angles θ and ϕ, when B is tilted away from the normal, consequently, in the y and x directions, for two values of magnetic field 0.6 and 0.95 T. We should note, that in the planar 2DEG the magnitude of SdH oscillations does not change (within the accuracy of 10%). Therefore, the observed decrease of the SdH amplitude with the angle in our nonplanar samples can be attributed to the fluctuations of magnetic field arising from the surface corrugation, as seen in AFM image.

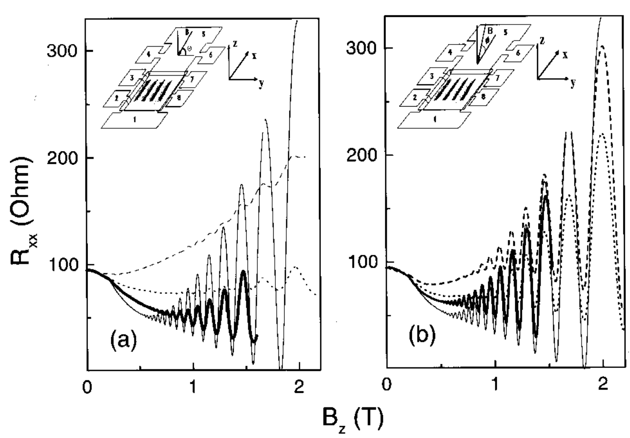

Figure 2. Magnetoresistance as a function of the magnetic field component perpendicular to the substrate for different angles between the applied magnetic field and the normal to the substrate at T=1.5 K. The insets show a schematic view of the experimental geometry. a) θ: 90^o (thin line), 53^o (thick line), 20^o (dotted line), 10^o (dashes).
b) ϕ: 90^o (thin line), 38^o (thick line), 20^o (dotted line), 12^o (dashes).

The several effects can be responsible for the damping of the SdH oscillations in the tilted magnetic field. At small magnetic field the cyclotron diameter $2R_c$=$2v_F/\omega_c$ (v_F-Fermi velocity, ω_c=eB$/m_c$- cyclotron frequency) is larger than magnetic periodicity. For example, fig. 1b shows the size of the cyclotron circle at B=0.4 T, when SdH oscillations start to appear. Magnetic field is no longer homogeneous inside of the circular orbit, $\langle B_N\rangle$ does not depends on the position of circle, however the magnetic field fluctuations $\langle\delta$B$\rangle$ are zero in average. This broadening can be used to define a single particle relaxation time due to the scattering by magnetic field fluctuations [5]. At high magnetic field the cyclotron diameter becomes smaller than magnetic periodicity. In this case average magnetic field, and, consequently, the cyclotron energy of the orbits depend on their position. It also leads to the additional broadening of Landau levels and SdH oscillations. Finally, it has been assumed that the damping factor of the SdH oscillations is governed by localization effects [6]. If the magnetic field is strong, the particles can drift along the percolation trajectories with zero $\langle B_N \rangle$. The number of such trajectories decreases with decreasing B, which also leads to the extremely sharp falloff of the amplitude of the oscillations.

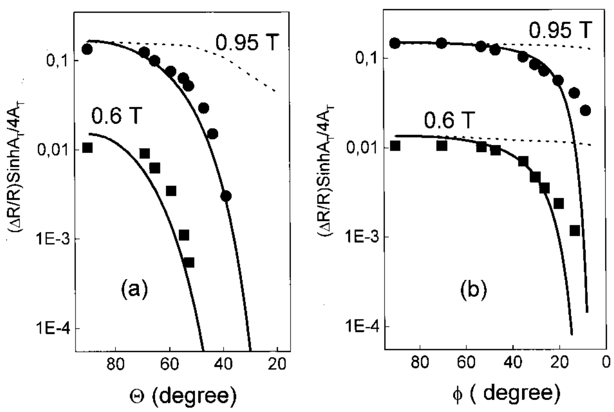

Figure 3. Amplitude of the SdH oscillation at fixed normal component of magnetic field as a function of tilt angle, when the magnetic field is tilted in x (a) and y directions (b). Thick lines- equations (3-5) calculated for realisitic surface profile (fig.2a). Dashed lines- equation (2) with position dependent filling factor calculated for realistic surface profile.

A theoretical model of electron transport in a random short-range and long -range magnetic potential (in the presence of additional uniform magnetic field) has been reported in [5]. In contrast to the typical case of impurity random potential (equation 2) it was obtained that ΔR$\sim$exp[-π^4 /$(\omega_c\tau_m)^4$] when the average periodicity of the magnetic- field fluctuations d is much larger than the cyclotron diameter $2R_c$, and that
ΔR $\sim$ exp[-$\pi^2/(\omega_c\tau_m)^2$] for short correlation lentgh d<<$2R_c$, where τ_m is a single-particle relaxation time due to the random magnetic field. Because in our case the magnitude of the magnetic field fluctuations is proportional to the external magnetic field (see eq.(1)), it leads to dependencies ΔR $\sim$ exp[-$\pi^2/(\omega_c\tau_m)^2$] for d>> $2R_c$ and ΔR $\sim$ exp[-$\pi/(\omega_c\tau_m)$] for d<< $2R_c$. More detailed calculations are presented elsewhere [7]. Taking into account that the impurity electric field and nonuniform magnetic field induce the random phase along the classical paths independently, it leads to the following damping of the SdH oscillations in the presence of impurities and random magnetic potentials [7]:

ΔR$\sim$ exp[-π /$(\omega_c\tau_s)$-$\pi/(\omega_c\tau_m)$] (3)
$1/\tau_m = (2\pi^3 m^3 v_F^3 c^3/e^3\Phi_0{}^2)\langle\delta B^2\rangle/\langle B_N\rangle^3$ (4) ,
where Φ_0=hc/e.
Substituting equation (1) into formula (4) and taking into account that
$\langle\delta B^2\rangle/\langle B_N\rangle^3 \approx\langle df/dy^2\rangle(\mathrm{ctg}\theta)^2(\mathrm{d}/2R_c)(1/\langle B_N\rangle)$, we find
$1/\tau_m\approx(1/\tau_0)^2(\mathrm{d}/v_F)\approx\langle df/dy^2\rangle(\mathrm{ctg}\theta)^2$ (5) ,
where τ_0=h/E_F is characteristic time of 2DEG . We calculate $1/\tau_m$ for realistic profile of the surface measured by AFM (fig.1b,c) and substitute it into the equation (3) in order to compare our theoretical estimation with experimental results. Single particle relaxation time due to impurity scattering $1/\tau_s$ we find from the Dingle plot (lnΔR/R vs 1/B) in perpendicular B, when magnetic fluctuations are very small, and we can neglect magnetic scattering. Fig. 3 a , b shows results of calculations. We see that the theoretical curves fit experimental results very well without any adjustable parameters for both cases, when magnetic field are tilted in x and y directions.

When magnetic field is tilted in the y direction cyclotron diameter is smaller than magnetic periodicity even at B=0.6 T , and for comparison our theoretical model with experimental results we calculate time (m using equation (4) . If $2R_c$<d the additional mechanism- broadening due to the spatial fluctuation of Landau level factor should be also taken into account. In order to compare this mechanism with experimental results we calculate the amplitude of the SdH oscillations considering realistic profile of magnetic field (fig.1 b). Results of these calculations are shown in fig. 3 a ,b by dotted line. We see, that this effect is smaller than the damping of SdH oscillations due to the magnetic scattering, and we can neglect it. However, we should note that at stronger magnetic field and for smaller tilt angle this inhomogeneous broadening of Landau levels can play an important role.

In summary, we report the fabrication of the nonplanar stripe-shaped 2DEG with small amplitude of the surface corrugation. By rotating the sample in an external magnetic field, we demonstrate that the nonplanar 2DEG has transport properties, which are different from planar 2DEG. In particular, a strong damping of the SdH oscillations is found in tilted magnetic field. This damping arises from the additional electron scattering by a nonuniform magnetic field.

The work was supported by the RFFI grant N 97-02-18402-a,FAPESP and CNPq (Brazilian agencies).

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