Single-particle relaxation time in a spatially fluctuating magnetic field

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We study Shubnikov de Haas (SdH) oscillations in a nonplanar stripe-shaped two-dimensional electron gas (2DEG). The effective-field normal to the nonplanar 2DEG is spatially modulated, when uniform external magnetic field is applied. We find that the amplitude of the SdH oscillations dramatically drops in the tilted magnetic field. From the Dingle plot of SdH oscillations we extract single-particle relaxation time. Reduction of this time in the tilted field, which leads to the enhanced damping of SdH oscillations, is shown to be due to the scattering of the electron by magnetic-field fluctuations. We calculate quantum lifetime of the electron in a tilted magnetic field. The agreement between these calculations and experimental result is found. In order to explain the damping of the SdH oscillations for magnetic field $B>1$ T we also take into account the spatial variation of the Landau filling factor. [S0163-1829(99)01008-5]

Transport properties of a two-dimensional electron gas (2DEG) in a random magnetic field have been a subject of much experimental[1–4] and theoretical[5–8] studies. It has been suggested that a system of electrons at half-filled Landau level can be transformed to the weakly interacting quasiparticles (composite Fermions) at zero-average magnetic field.[9] Random electrostatic potential due to impurities experienced by electrons at zero field produces a local fluctuation of the effective magnetic field. Thus, the transport of composite Fermions (CF) is related to the problem of electron transport in a random magnetic field. Second nonuniform and weakly modulated magnetic field have been achieved by depositing patterned ferromagnetic or superconducting films[1] or attaching of small permanent magnet[2] on the top of $Al_xGa_{1-x}As/GaAs$ heterojunction. Finally, 2DEG grown on the nonplanar prepattering GaAs substrates has been used to produce nonuniform magnetic field.[3,4] Since orbital motion of 2DEG is sensitive to only the normal component of magnetic-field, electrons in such system experience nonuniform magnetic field varied with position, depending on the surface shape, when the uniform external field is applied to the nonplanar surface. All experimental realizations have yielded interesting transport results. Perhaps it is more important to compare transport measurements at filling factor of $\frac{1}{2}$ with the CF picture. However, in spite of the theory giving an explanation of many observation of Fermi surface features at half filling, there is some difference. In particular, magnetoresistance oscillations of CF,[10] which looks very much like conventional Shubnikov de Haas (SdH) oscillations, appear to be much strongly damped in comparison with theoretical prediction.[6] The origin of such discrepancy could lay in overestimation of the single-particle relaxation time, which is responsible for the damping of the SdH oscillations, or in the nature of the magneto-oscillations near half-filling. In particular, it was assumed that localization plays a more important role for CF than for electrons, and magneto-oscillations are originated from the localized-delocalized states transition in a percolation network like for the integer quantum-Hall effect.[11] Thus, the problem can be addressed to the study of SdH oscillations in a random magnetic field. There are two different characteristic times in a transport theory-transport scattering time τ_t and single-particle relaxation time τ_s, sometimes called the quantum lifetime.[12] From a many-body theory the quantum lifetime is related to the one-electron Green's function of the coupled electron-impurity system and determines the magnitude of the SdH oscillations. The scattering time is related to the two-electron correlation function that defines the conductivity in the system at zero magnetic field. For impurity scattering in $Al_xGa_{1-x}As/GaAs$ heterojunction the ratio of the transport time and the single-particle relaxation time was found to be 10–100.[12] In random magnetic-field time, τ_s was calculated in Refs. 5–7. Depending on the origin of a random magnetic field, single-particle relaxation rate $1/\tau_s$ is diverged.[7] This problem was solved using a quasiclassical approximation for the path-integral presentation of the density of states.[5,6] Employing this method time τ_s was introduced into the damping factor of the density of states and conductivity oscillations in the presence of a random and uniform average magnetic field. Transport scattering time in random magnetic field is not peculiar and can be found within the perturbation theory.[7,9] Since the discrepancy is found for the single-particle relaxation time of CF, we perform measurements of electron transport in a spatially fluctuating magnetic field in the SdH regime around zero magnetic field. We study 2DEG with nonplanar shape. Such system allows us to change the magnitude of magnetic-field fluctuations varying angles between the field and normal to the substrate surface. We observe a new scattering mechanism for two dimensional electrons scattering by magnetic-field fluctuations. This mechanism leads to the enhanced damping of the SdH amplitude in a tilted magnetic field.

Samples were fabricated employing overgrowth of GaAs and $Al_xGa_{1-x}As$ materials by molecular beam epitaxy on the prepatterned (100) GaAs substrate. In spite of the fact that prepattering consist of lattice of holes, a stripe-like shape of

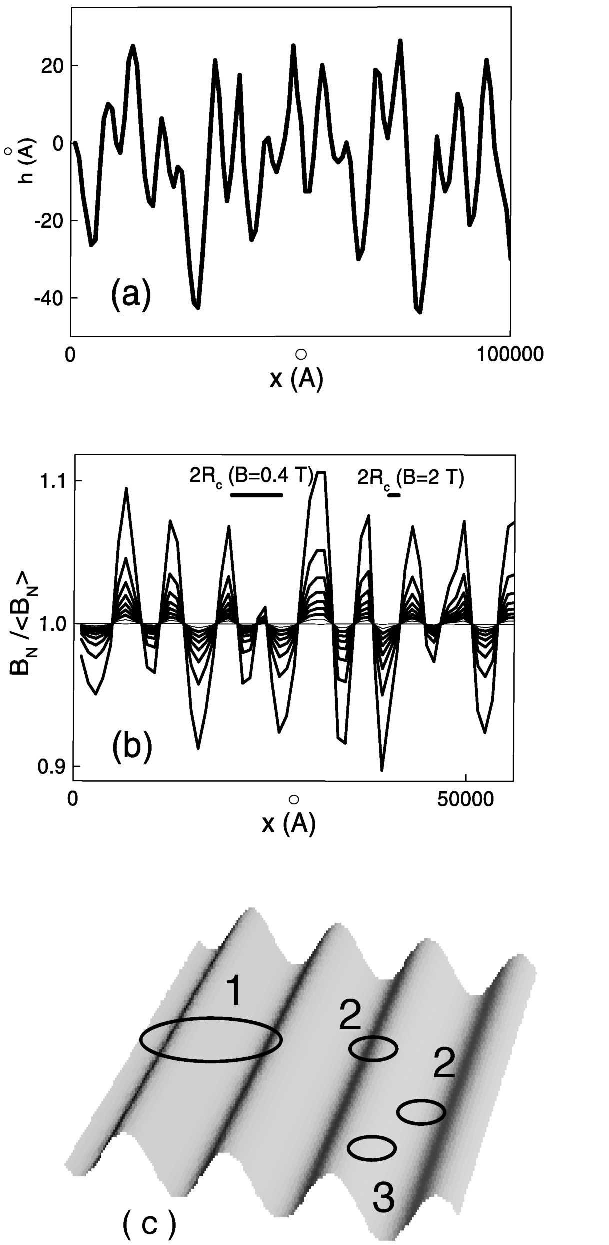

FIG. 1. (a) Profile of the sample surface across the stripes measured by atomic-force microscope. (b) Magnetic-field profile calculated for the surface profile shown in Fig. 1(a) when the magnetic field is tilted in the direction perpendicular to the stripes. The angle varies from 90° to 10° with 10° step. Bars are the cyclotron diameters at different magnetic fields. (c) Schematic view of the magnetic-field profile and cyclotron orbits at different magnetic fields: 1 is $B=0.4$ T; 2 is $B=2$ T, orbits are located in minima and maxima of magnetic field fluctuations, 3 is $B=2$ T, orbit is located between maxima and minima of magnetic field fluctuations.

the regrown surface has been obtained. Details of the sample preparation and preliminary results are reported in Ref. 13. Figure 1(a) shows the profile of the surface in the direction across the stripes (x direction). We can see both irregular and periodical components in the surface corrugation. The average periodicity $d=0.6\,\mu$m is coincident with the antidot lattice periodicity before overgrowth. The corrugation height h varies between 20 and 65 A. The patterned area was 140 $\times 140\,\mu\text{m}^2$. After regrowth, the (HEMT) structure was pro-

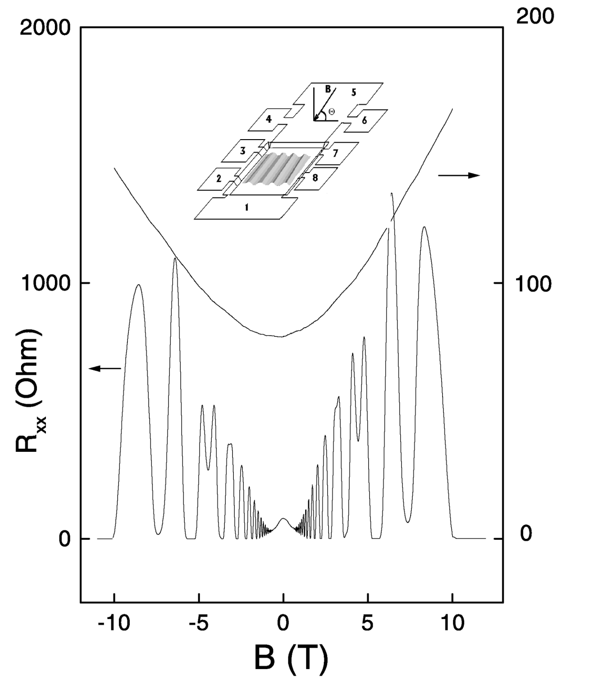

FIG. 2. Magnetoresistance as a function of B for field perpendicular (right axis) and parallel (left axis) to the surface. Inset schematic view of sample $T=1.5$ K.

cessed into Hall bars, and the nonplanar surface was situated on the one side of the Hall bar (see inset of Fig. 2). The distance between the voltage probes was 100 μm and the width of the bar was 50 μm. 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 the magnetic field is tilted away from the normal to the substrate, the normal component of B can be expressed as

$$B_N(x,y,z)=(\overline{B}\overline{\nabla}f)/|\overline{\nabla}f|, \tag{1}$$

where gradient $\overline{\nabla}f(df/dx,df/dy,df/dz)$ is defined for the surface $f(x,y,z)=0$. Let us consider the case when the external magnetic field is tilted in the x direction. For the surface profile shown in Fig. 1(a), $df/dy\sim h/d\ll 1$, and expression (1) can be rewritten as $B_N\approx B\sin\theta+(df/dy)(B\cos\theta-0.5B\sin\theta)\approx\langle B_N\rangle+\delta B(x)$, where θ is the angle between the external magnetic field and the substrate plane, $\langle B_N\rangle=B\sin\theta$ is the average normal component of B. At angles $\theta\gg h/d\approx 1°$, the average magnetic field $\langle B_N\rangle$ is larger than the magnitude of the magnetic field fluctuations $\delta B(x)$. Figure 1(b) shows the magnetic-field profile when the external field is tilted in the x direction for different tilt angles. We see that the magnetic-field modulation increases with the angle. When the applied magnetic field is quasiparallel to the substrate, at an angle $\theta\sim h/d\approx 1°$, the effective magnetic field becomes essentially nonuniform and sign alternating. In this paper we considered the case when $\langle B_N\rangle\gg\delta B$. The Hall voltage of the planar 2DEG was used to measure tilt angles with a precision of 1°–2°. The mobility of 2DEG is $(300-400)\times 10^3\,\text{cm}^2/\text{V s}$ and density $n_s=5.4\times 10^{11}\,\text{cm}^{-2}$. We studied seven samples with identical parameters.

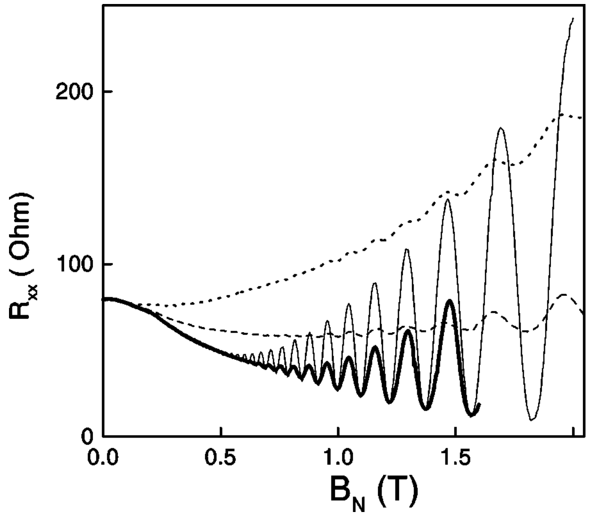

FIG. 3. Magnetoresistance as a function of the magnetic-field component perpendicular to the substrate, for different angles θ between the applied magnetic field and the normal to the substrate: $\theta=90°$ (thin line), 53° (thick line), 20° (dotted line), 10° (dashes), $T=1.5$ K.

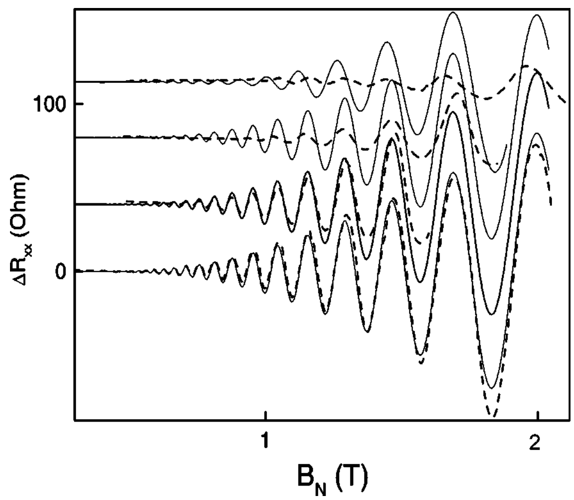

FIG. 4. Magnetoresistance oscillations as a function of the magnetic-field component perpendicular to the substrate for different angles θ between the applied magnetic field and the normal to the substrate at $T=1.5$ K. Solid lines-experimental curves, dashes-Eq. (2) with position-dependent oscillations periodicity for the magnetic-field profile shown in Fig. 1(b). From the bottom to the top $\theta=90°$, 53°, 40°, and 20°. Curves are shifted for clarity.

The results of the measurements for one of the typical specimen are presented in Fig. 2 for the external magnetic field oriented perpendicular and parallel to the substrate plane. In the perpendicular field there are SdH oscillations followed by well-defined zeroes and peaks in resistance at the integer Landau-level filling factor. In the parallel field pronounced positive magnetoresistance appears. Figure 3 shows resistance measured between voltage probes on the nonplanar region (voltage probe 2–3, current probe 1–5) for different tilt angles. We see that the oscillations in the R_{xx} vs B_N plot are not shifted with the angle, which means that they follow, as expected, $(\sin\theta)^{-1}$ law. However, the amplitude of the SdH oscillations for nonplanar 2DEG falls down several times, in comparison with $\theta=90°$. The amplitude of SdH oscillations in planar 2DEG in the presence of an in-plane magnetic field has been investigated in Ref. 14. The small (3–5%) increase of the effective mass has been found at $\theta=10°$ due to the distortion of the Fermi contour by the parallel magnetic field. In accordance with Eq. (2) it leads to a small (3%) increase of the SdH amplitude in the tilted magnetic field, which disagrees with our experimental observations. The measurements of the SdH oscillations of the planar 2DEG with the same mobility and electron density in the tilted magnetic field demonstrate that 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 the magnetic field arising from the surface corrugation, as seen in the atomic force microscope (AFM) image [Fig. 1(a)]. It can be understood in terms of the scattering of electrons by magnetic-field fluctuations and in terms of a macroscopic variation of the Landau-levels filling factor. If the cyclotron diameter $2R_c=2v_F/\omega_c$ (v_F is Fermi velocity, ω_c is cyclotron frequency) is larger than the magnetic periodicity the magnetic field is no longer homogeneous inside of the circular orbit (however, the random field is sufficiently weak that circular orbits persist), which leads to a broadening of Landau levels.[5] This broadening can be used to define a single-particle relaxation time. If the cyclotron diameter is smaller than magnetic periodicity, it is still possible to define scattering time due to magnetic-field fluctuations.[6] As for the long-range potential, however, we should take into account that the energy of the Landau level, and consequently, periodicity of the SdH oscillations becomes position dependent. It also leads to the broadening of Shubnikov oscillations. Figures 1(b) and 1(c) show the size of the cyclotron circle at $B=0.4$ T (when SdH oscillations start to appear) and at $B=2$ T. We can see that at $B<0.85$ T the cyclotron diameter is larger than the average scale of the magnetic-field variation. In this case the average magnetic field inside of the cyclotron circle does not depend on the position of electron orbits. At higher field $2R_c<d/2$, however, the diameter is still larger than the width of the transition between maxima and minima of the magnetic-field fluctuations. Figure 1(c) shows different orbits located at the maxima and minima of the magnetic field. For orbits (2) the average magnetic field inside of the circle is almost constant, and we can neglect magnetic-field scattering. However, the cyclotron energy of orbits (2) depends on their positions. For orbits (3), located between extremes of field, we can introduce single-particle relaxation time due to magnetic-fluctuations scattering. We can assume that the contribution of the orbits (2) and (3) to the conductivity is roughly proportional to the area covered by these orbits. In this case at least 50% of the effect at $B>1$ T should be due to the variation of the single-particle relaxation time. In order to separate inhomogeneous broadening and the magnetic-field scattering mechanism at $B>1$ T we have calculated SdH oscillations for position-dependent Landau energy level considering the realistic profile of the magnetic field [Fig. 1(b)]. Existing theories[15,16] predict that SdH oscillations in resistivity should behave as:

$$\Delta R/R=A(4X/\mathrm{Sinh}\,X)\exp(-\pi/\omega_c\tau_s)\cos(2\pi^2\hbar n_s/eB), \tag{2}$$

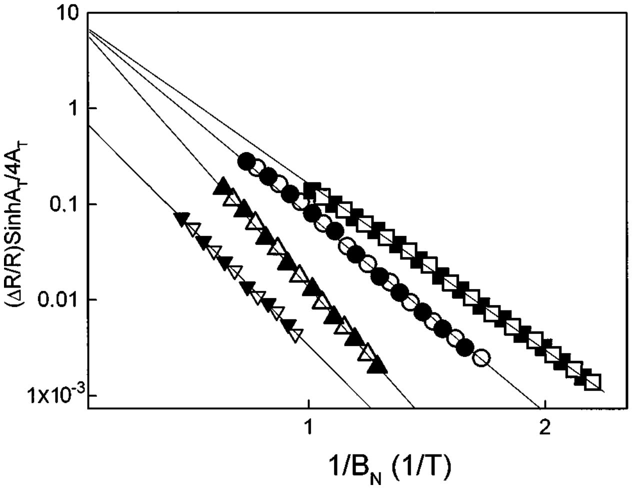

FIG. 5. Dingle plot of the SdH oscillations for different angles θ: $\theta=90°$ (squares), 53° (circles), 40° (up triangles), 13° (down triangles). Solid (open) symbols are resistance minima (maxima).

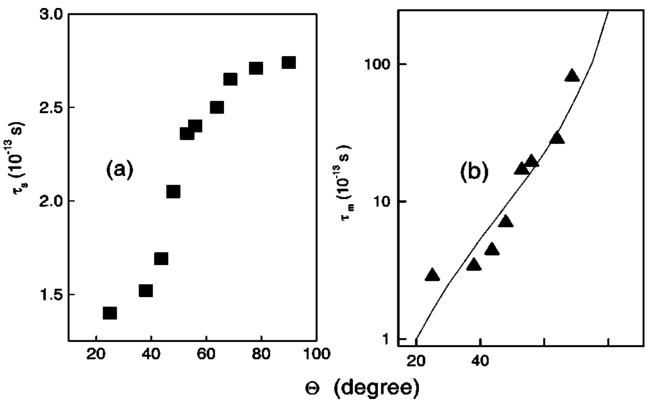

FIG. 6. (a) Single-particle relaxation time extracted from the Dingle plot of the Shubnikov de Haas oscillations as a function of θ. (b) Magnetic-scattering time as a function of θ, solid curve is fit to Eq. (6).

where $X=2\pi^2 kT/\hbar\omega_c$, $\omega_c=eB/mc$ is the cyclotron frequency, m is the effective electron mass, R is the resistance in zero magnetic field, and A is the numerical coefficient in the order of unity. Figure 4 shows the experimental and theoretical dependence of oscillatory part ΔR as a function of $\langle B_N\rangle$ for different tilt angles. We assume the constant single-particle relaxation time, which is used as an adjustable parameter at $\theta=90°$. We also obtain coefficient $A=9$ (we discuss parameter A below). We can see that for all angles (all magnetic-field modulation) and magnetic-field experimental value, the amplitude of the SdH oscillations is smaller than the theoretical one. We should emphasize here that if we fit the high-field side of the SdH oscillations with theoretical calculations for larger surface corrugation, the low-field side SdH amplitude is still much smaller than the calculated one. It supports our argument that the low-field side SdH oscillations should be described by the quantum-lifetime variation due to magnetic-field scattering. Moreover, the variation in the periodicity and beating effect at tilt angle $\theta<20°$ is found for theoretical curves, which is not observed in the experiment. At $B>1$ T the decrease of SdH oscillation amplitude can be attributed by the position dependent of the Landau levels for electron orbits (2) and by the quantum-lifetime decrease for orbits (3) [Fig. 1(c)]. Therefore, at least at $B<1$ T we can analyze amplitude of the SDH oscillations in terms of the single-particle relaxation time. This time can be determined experimentally from Eq. (2). If the logarithm of amplitude, corrected by the thermal-damping factor, i.e., $\ln(\Delta R/4R)(\mathrm{Sinh}\,X/X)$ is plotted against $1/B$ (Dingle plot), the slope gives $1/\tau_s$. Typical Dingle plots for magneto-oscillations measured at different tilted angles for both nonplanar are shown in Fig. 5. We see that the Dingle plots are well described by straight lines, assuming an effective mass of $0.067\,m_e$ [from the T dependence of SdH oscillations we obtained $m=(0.07\pm0.01)m_e$]. However, we observe some differences. Not only was it required that the Dingle plot be a straight line, but also with the correct intercept results at $1/B=0$, $A=1$. In our case we obtain for the nonplanar 2DEG $A=7-9$ for different samples. High values of $A=4-6$ has been obtained in planar 2DEG with very high (10^6 cm^2/V s),[2] and low mobility.[17] There is still disagreement in the literature about the value of numerical coefficient A.[15] In Ref. 18 it was argued that the high value of A could be due to the presence of inhomogeneities in the 2DEG electron density. However, it should lead to nonlinear dependence of the Dingle plots. The deviation from nonlinearity indeed was observed at a strong magnetic field and was explained by the formation of quantum-Hall states at $\omega_c\tau\gg1$, when $\Delta R/R\sim1$.[2] We did not find beating of the SdH oscillations at low magnetic field, which occurs due to the inhomogeneity in the sample. However, probably there is a small undetectable variation in the electron concentration (1–3%) on the different facets of the regrown surface. From analysis of the available data,[2,17] we conclude that the slope of the Dingle plot with a high value of intercept at the infinite field still gives a good value for the quantum lifetime, which is in agreement with theoretical calculations.[12]

We find that the slope of the Dingle plot increases in the tilted magnetic field with the same intercept at the infinite field at $\theta>25°$. Therefore, the enhanced damping of the SdH oscillations at $B<1$ T and at $\theta>25°$ is connected with the reduction of the single particle relaxation time and not with the decrease of the coefficient A. However, at a smaller angle, A starts to decrease and approaches the value $A=1$ at $\theta=12°$ (Fig. 5). This behavior indicates the change in the transport mechanism at small angles, when magnetic field fluctuations are comparable with the normal component of B. Further, we are restricted on the results obtained at $\theta>25°$ and $B<1$ T. Figure 6(a) shows single-particle relaxation time as a function of angle θ for the nonplanar structure. We see that in stripe-shaped 2DEG, quantum lifetime drops in two times. The drop of τ_s with the increase of the parallel component of the magnetic field could be due to the additional scattering mechanism of the electron. In the parallel field the amplitude of fluctuations δB increases and leads to the additional electron scattering. Assuming the individual scattering mechanism to be independent of one another, which means that the inverse of the total scattering time is the sum of the inverse of the individual ones (Matthiesen's rule), we extract the quantum lifetime due to the scattering by the magnetic-field fluctuations $\tau_m=\tau_s\tau_0/(\tau_s-\tau_0)$, where τ_0 is the quantum lifetime due to impurity scattering ($\tau_0=\tau_s$ at $\theta=90°$). Figure 6(b) shows the dependence of τ_m on the angle. We see that at $\theta\approx20°$ time τ_m is comparable with single-particle relaxation time due to impurity scattering. It means that magnetic scattering becomes a dominant mechanism in the nonplanar structure at smaller tilt angles.

As we mentioned above, quantum lifetime in a random magnetic field has been calculated in Refs. 5 and 6. It was considered in large part due to its relevance for the fractional quantum-Hall effect. It is generally accepted that the composite Fermion particles in fractional quantum-Hall effect regime move in a smooth random magnetic-field potential. The theory[5] predicts dependence $\Delta R \sim \exp[-\pi^4/(\omega\tau)^4]$, where τ is a quantum lifetime of quasiparticles. The theoretical model of electron transport in random short-range magnetic potential (in the presence of an additional uniform magnetic field) has been reported in Ref. 5. It was obtained that $\Delta R \sim \exp[-\pi^2/(\omega\tau)^2]$. We see that the predicted $1/B^4$ and $1/B^2$ dependencies of the Dingle plots are different from the behavior of the conventional SdH oscillations in a random-impurity potential [Eq. (2)]. In the case of nonplanar stripe-shaped 2DEG we use the results of the quasiclassical approach for conductivity in the random magnetic field.[5,6] We assume that in spite of the magnetic field created by the lattice of lines being periodic due to the large irregularity in the position and heights of these lines [Fig. 1(a)], and due to impurity potential (carrier is scattered in a random direction), the electrons will experience a ''random'' magnetic field. This assumption is supported by the AFM image and the following observation. In the low magnetic field magnetoresistance reveals an additional peak, which reflects interplay of the cyclotron radius and the period d of the superlattice [Fig. 3]: $2R_c \approx 2d \approx 1.2\,\mu$m. Such kind of commensurability oscillations have been observed in Ref. 1, when nonuniform and weakly periodically modulated magnetic fields have been realized by depositing patterned ferromagnetic or superconductor stripes on the top of samples containing a 2DEG. In spite of high-electron mobility (mean free path is larger than 5 μm), the amplitude of peaks in our samples is much smaller than observed in Ref. 1. The irregularity in the position and heights of the surface modulation is responsible for the small amplitude of the commensurability oscillation. Irregular stripes in the external magnetic field produce ''random'' magnetic field with small amplitude fluctuations and constant average background. Small fluctuations will not change Landau quantization; therefore, conventional Landau levels are formed in accordance with the value of the average magnetic field. From the quasiclassical approach[6] the amplitude of the conductivity oscillations is given by:

$$\sigma \sim \mathrm{Re}\exp(iS/\hbar), \tag{3}$$

where $S = \int p\,dl = B_t A\hbar/\Phi_0$, $A = \pi R_c^2$, $\Phi_0 = hc/e$. If $B_t = \mathbf{B} + \delta B$, where $\mathbf{B} \gg \delta B$, the expression for action S can be rewritten as, $S = F/B_t \approx F/\mathbf{B} + F\,\delta B/\mathbf{B}^2 + O(\delta B^2)$, where $F = 2\pi^2 m^2 v_F^2 c^2 h/(e^2\Phi_0)$. Substituting this approximation in Eq. (2), we find

$$\sigma \sim \cos(S/\hbar)\exp(-F^2\,\delta B^2/2\mathbf{B}^4). \tag{4}$$

Equation (3) shows that the dependence of the oscillations amplitude on B has an oscillatory part and the damping exponent. Thus, we obtain the same $1/B^4$ dependence for the Dingle plot of the conductivity oscillations as was predicted for composite Fermions in the long-range magnetic potential.[5] However, in our case, magnetic-field fluctuations δB are proportional to the applied magnetic field. The average of the square of field fluctuations is given by $\delta B^2 \approx \alpha^2 B^2 \xi/R_c$, if $\xi < R_c$, and $\delta B \approx \alpha B$, if $\xi > R_c$, where $\alpha \sim h/d$. Thus, in the low magnetic field we have

$$\Delta R \sim \exp(-\pi/\omega_c\tau_m), \tag{5}$$

where

$$1/\tau_m = C\alpha^2\omega_0^2\xi/v_F, \tag{6}$$

$\omega_0^2 = (\pi^3 v_F^4/2)(\mathrm{mc/e}\Phi_0)^2$, C is the numerical coefficient of order of unity. In the strong magnetic field

$$\Delta R \sim \exp[-\pi/(\omega_c\tau_m)^2], \tag{7}$$

where

$$1/\tau_m = \alpha\pi^{3/2}v_F^2\,\mathrm{mc}/(2e\Phi_0). \tag{8}$$

Therefore, it is expected that at low field the Dingle plot should have $1/B$ dependence followed by $1/B^2$ dependence at a higher field. This situation is very similar to the impurity random potential. As was mentioned in Ref. 6, the damping coefficient for conductivity oscillations can be rewritten as $\exp(-\varphi^2)$, where φ is a random phase acquired by the particle moving along its classical trajectory. In the random magnetic field, this phase is equal to $F\,\delta B/2\mathbf{B}^2$ [Eq. (4)], which is proportional to the magnetic flux through the cyclotron circle. In the presence of the smooth impurity potential, this phase factor is given by $\langle\varphi^2\rangle \sim e^2E^2t^2$, where E is a random electric field, and $t \sim 2\pi/\omega_c$ is the time spent by the particle on the trajectory. For random impurity potential $V(r)$ with correlator $\langle V(r)V(r')\rangle = (U^2/\xi^2)\exp[-(r-r')^2/\xi^2]$, we have $\langle\varphi^2\rangle \sim \langle U^2\rangle t^2/\xi^2$. If $\xi < R_c$, $\langle U^2\rangle \approx U^2\xi/R_c$, and we obtain $\Delta R \sim \exp(-\pi/\omega_c\tau_s)$, where $1/\tau_s \approx U^2/v_F\xi$. On the other hand, if $\xi > R_c$ $\langle U^2\rangle \approx U^2$, $\langle\varphi^2\rangle \sim U^2/(\xi^2\omega_c^2)$, therefore $\Delta R \sim \exp[-\pi/(\omega_c\tau_s)^2]$, where $1/\tau_s \approx U/\xi$. Detailed calculations for the heterostructure with impurities located at distance d_s from 2DEG (remote impurity doping)[6] give the results

$$\Delta R \sim \exp[-(1/\beta)(\pi/\omega_c\tau_s)^\beta],$$

$$\hbar/\tau_s = E_F/(2k_F ds), \tag{9}$$

where $\beta = 2$ for $R_c \ll d_s$ and $\beta = 1$ for $R_c \ll d_s$, $k_F = (2\pi n_s)^{1/2}$, E_F is the Fermi energy. For typical heterostructures $d_s = 0.02 - 0.06\,\mu$m and for $n_s = (1-5)\times 10^{11}\,\mathrm{cm}^{-2}$, $R_c = 0.1 - 0.2\,\mu$m at magnetic field $B \sim 1$ T. Therefore, below some critical magnetic field, the Dingle plot obeys $1/B$ dependence and at a higher field changes to $1/B^2$ dependence. However, as we mentioned above, in experiment deviations of the Dingle plot from the $1/B$ line at a higher field is connected with formation of the quantum-Hall state. In our samples with nonplanar 2DEG all Dingle plots of SdH oscillations at $\theta = 90°$ and in tilted field are linear (Fig. 5). It means that we have short-range magnetic-field scattering in our case, as we discussed above. At magnetic field $B > 1$ T we have $R_c < d/2$, and the situation is more complicated, because we should take into account inhomogeneous broadening of Landau levels (Fig. 4). However, we also observe $1/B$

dependence of the Dingle plot at $B>1$ T. Further theoretical study is necessary to explain this behavior.

Before we calculate the single-particle relaxation time in a random magnetic field, we compare results with quantum lifetime due to impurity scattering. We obtain $\tau_s=2.7\times10^{-13}$ s for nonplanar 2DEG and 3×10^{-13} s for the planar structure. At the same time, theoretical estimation according to Eq. (9) gives the value 2.5×10^{-13} s for $d_s=200$ A. Numerical results including homogeneous background doping gives $\tau_s=3.8\times10^{-11}$ s at acceptor doping level $N_A=5\times10^{14}$ cm^{-3}.[12] As we mentioned above, the transport scattering time τ_t, which is related to the conductivity at zero magnetic field, should be 10–100 times larger than single-particle relaxation time in the system with long-range potential.[12,17] The analytical result[6,9] is

$$\hbar/\tau_t=E_F/(2k_Fd_s)^3, \tag{10}$$

and using Eq. (9) we get the ratio $\tau_t/\tau_s=(2k_Fd_s)^2$. The numerical calculation for the doping level $N_A=5\times10^{14}$ cm^{-3} gives the value $\tau_t=1.1\times10^{-11}$ s, which is in excellent agreement with experimental value 1.14×10^{-11} s. Thus, we obtain the ratio $\tau_t/\tau_s=38.5$, which is close to the numerical ($\tau_t/\tau_s=30$) and analytical ($\tau_t/\tau_s=50$) theoretical values. This agreement supports our assumption that from the Dingle plot we extract a reliable quantum lifetime. For the estimation of the theoretical value of τ_m due to magnetic-field fluctuations, we should know the average amplitude of these fluctuations, which is possible to find from the realistic surface profile [Figs. 1(a) and 1(b)]. We calculate single-particle relaxation time using Eq. (6) with $\alpha=\langle\delta B\rangle/\langle B_N\rangle$ extracted from Fig. 1(b) and assuming that $\xi\approx d/2$. Figure 6(b) shows the fit of Eq. (6) to the experimental results with adjustable parameter $C=3$. Considering the approximate character of our calculations, the agreement is good.

In conclusion, we have studied Shubnikov de Haas oscillations in stripe-shaped 2DEG. When placed in an external magnetic field, the effective field normal to the nonplanar 2DEG is spatially modulated. Because of the small height of the stripe, and consequently, field fluctuations, Landau levels are formed in the quantized magnetic field, and magnetoresistance reveals conventional Shubnikov de Haas oscillations. However, particle moving along different trajectories gain random phase due to magnetic-field fluctuations. This phase leads to the damping of SdH oscillations, which can be interpreted as magnetic scattering. We separate two different scattering mechanisms—magnetic and impurity scattering by rotating sample in the external magnetic field. From the Dingle plot of the SdH oscillations we extract the single-particle relaxation time. When the magnetic field is tilted away from the normal to the substrate, magnetic scattering time decreases because the amplitude of the magnetic field fluctuations increases in parallel field. We find that the relatively small fluctuations of the magnetic field (several percents of the average B) lead to a strong scattering, which can be a dominant scattering mechanism in a two-dimensional system. At $B>1$ T, the spatial variation of Landau-level energy also leads to the additional damping of the SdH oscillations.

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