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Classical effects in the weak-field magnetoresistance of InGaAs/InAlAs quantum wells

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Much interest has been attracted recently by the properties of the two-dimensional (2D) electron gas in InGaAs/InAlAs quantum wells, like the strong spin-orbit Rashba interaction, large Lande g-factor, and small effective mass. The strong anisotropy of the mobility in (100) quantum wells with In content ≥ 0.75 was observed in a number of publications [1, 2]. In the work of Ref. [3], it was shown that the anisotropy originates largely from the modulation of In content that leads to the modulation of conduction band bottom. A relief on the sample surface was observed, reflecting the modulation of In content. The authors of Ref. [3] also suggested a way to simultaneously increase the electron mobility and reduce the mobility anisotropy by introducing an InAs layer into the center of the quantum well. As long as the fluctuations of In content are impossible in the binary composition, the degree of disorder in the quantum well should decrease. Indeed, the mobility anisotropy was found to decrease as a result of improving the growth structure. However, it remained unclear whether the residual anisotropy in the transport properties of InGaAs/InAlAs quantum wells is the only manifestation of the built-in growth anisotropy.

In this paper, we study the low-temperature magnetotransport properties of the 2D electron gas in InGaAs/InAlAs quantum wells with an InAs layer in weak perpendicular magnetic fields. The observed magnetoresistance is unusual in that it is qualitatively similar to that expected for the weak localization and antilocalization but its quantity exceeds significantly the scale of the quantum corrections. The calculations show that the obtained data can be explained by the classical effects in electron motion along the open orbits in a quasiperiodic potential relief manifested by the presence of ridges on the quantum well surface. The results indicate that the likely origin for the potential relief is the residual modulation of In content in the quantum well.

Measurements were performed in a dilution refrigerator in a range of temperatures between 0.03 and 1.2 K on Hall bar samples with [011] and [01-1] orientations fabricated based on InGaAs/InAlAs structures. After etching a mesa and evaporating Ni/Au contacts to the 2D electron gas, a SiO layer was evaporated on the wafer surface and then an Al gate was evaporated on the top of SiO. At zero gate voltage, the low-temperature mobility was about 48 m^2/Vs at electron density $n_s \simeq 5\times10^{11}\,\mathrm{cm}^{-2}$ for currents (and Hall bars) in both [011] and [01-1] directions. The resistance was studied using four-terminal measurements on four samples (two samples for each orientation).

The surface of the wafer was studied using an atomic-force microscope. Ridges are discernible along [011] and [01-1] directions with characteristic height 10 nm. The ridges along the [011] direction are quasiperiodic in the [01-1] direction with characteristic period 1.5 μm. The other set of ridges along the [01-1] direction is distinguished by a smaller characteristic period 0.5 μm in the [011] direction.

In Fig. 1, we show the inverse longitudinal resistance $1/\rho_{xx}$ as a function of magnetic field for the Hall bar along the [011] direction at different electron densities and temperatures. In the range of weak magnetic fields, over the unshaded area, the behavior is similar to that expected for the transition between the weak localization and anti-localization with a distinction that the amplitude of the effects is two orders of magnitude larger than the scale of the quantum corrections and the "anti-localization" peak amplitude is temperature independent in the range of temperatures studied. Moreover, as the electron density is decreased, there appears a behavior that can be interpreted as the suppression of the weak localization (Fig. 1c).

We find that the inverse magnetoresistance peak at $B = 0$ for the [01-1] orientation is much less pronounced and the adjacent minima correspond to smaller values of the magnetic field as compared to the [011] orientation. The ratio of the minimum magnetic fields is approxi-

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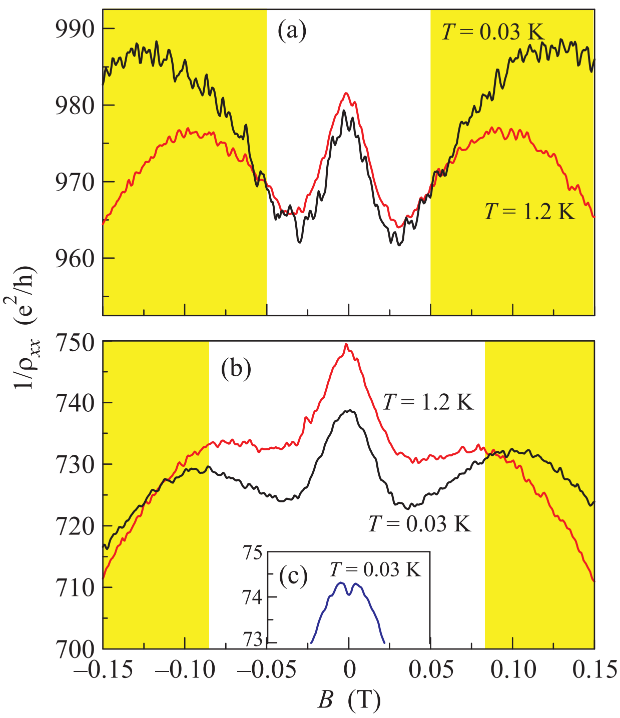

Fig. 1. (Color online) Dependence of $1/\rho_{xx}$ on magnetic field in sample 1 with Hall bar along [011] at different temperatures for the following electron densities: (a) 5×10^{11} cm^{-2}, (b) 4.2×10^{11} cm^{-2}, and (c) 1.9×10^{11} cm^{-2}

mately equal to 3, which corresponds to the ratio of the periods of the ridges in two perpendicular directions, indicating the classical origin of the inverse magnetoresistance maximum in zero magnetic field. Note that the mean free path of electrons is $l \approx 5.5\,\mu$m at density 5×10^{11} cm^{-2} in this electron system and the cyclotron radius is $R_c \approx 3.9\,\mu$m at field 0.03 T.

We also find that with decreasing electron density the inverse magnetoresistance peak broadens and its amplitude decays drastically.

The experimental behavior of the magnetoresistance can be explained in the spirit of Refs. [4, 5] where a periodic potential relief was introduced into the sample and a qualitatively similar magnetoresistance was observed in weak magnetic fields. Let us consider a model potential relief $eV_0 \cos(2\pi x/a)$, where the relative modulation $\varepsilon = eV_0/2E_\mathrm{F} \ll 1$, E_F is the Fermi energy, and a is the modulation period along the x-axis. As was shown in Ref. [4], in such a potential there arise open electron orbits in weak perpendicular magnetic fields. We have performed both the analytic and numerical calculations of the magnetoresistance modified by the open orbits.

The calculated magnetic field dependence of $1/\rho_{xx}$ is qualitatively similar to that shown in the unshaded area in Fig. 1a, b. The calculated half-width of the inverse magnetoresistance peak as a function of electron density is in satisfactory agreement with the experiment assuming that the amplitude V_0 is independent of electron density and the period a is equal to $a = 0.5\,\mu$m. The weak dependence of V_0 on electron density indicates that the main reason for the potential relief is the residual modulation of In content in the quantum well rather than the ridges on the quantum well surface. The amplitude of the inverse magnetoresistance peak versus electron density, calculated for the same values V_0 and the experimental relaxation time, is in qualitative agreement with the experiment. The quantitative discrepancy is a consequence of the too idealized model. Indeed, the real potential relief is unlikely to be close to a harmonic one.

The behavior of the magnetoresistance at fields above B_c is more complicated. As seen from Fig. 1a, b, with increasing B the value $1/\rho_{xx}$ passes a minimum and increases in some region of magnetic fields. The initial interval of the increase may be caused by the disappearance of the open orbits. However, the pronounced temperature dependence of $1/\rho_{xx}$ is observed in this region of magnetic fields, which cannot be explained by classical effects. Moreover, in the shaded area in Fig. 1a, b, the derivative $d\rho_{xx}/dB$ changes its sign again, the temperature dependence of the magnetoresistance being still present. Note that the quantum oscillations arise in a magnetic field ≈ 0.7 T in our samples so that the shaded area corresponds to the intermediate regime in which the quantum effects can already be significant despite the strong overlap of quantum levels.

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1. J. C. P. Chang, J. Chen, J. M. Fernandez, H. H. Wieder, and K. L. Kavanagh, Appl. Phys. Lett. **60**, 1129 (1992).
2. S. Lohr, S. Mendach, T. Vonau, C. Heyn, and W. Hansen, Phys. Rev. B **67**, 045309 (2003).
3. D. Ercolani, G. Biasiol, E. Cancellieri, M. Rosini, C. Jacoboni, F. Carillo, S. Heun, L. Sorba, and F. Nolting, Phys. Rev. B **77**, 235307 (2008).
4. P.H. Beton, E.S. Alves, P.C. Main, L. Eaves, M.W. Dellow, M. Henini, O.H. Hughes, S.P. Beaumont, and C.D.W. Wilkinson, Phys. Rev. B **42**, 9229 (1990).
5. D. Weiss, K. von Klitzing, K. Ploog, and G. Weimann, Europhys. Lett. **8**, 179 (1989).