Anomalies in the magnetoresistance of 2D electrons during the filling of the second quantum-size subband in an AlGaAs–GaAs heterojunction: intersubband scattering

V. E. Zhitomirskiĭ

Institute of Solid State Physics, Russian Academy of Sciences, 142432, Chernogolovka, Moscow Oblast

(Submitted 7 May 1992)
Pis'ma Zh. Eksp. Teor. Fiz. **55**, No. 11, 657–661 (10 June 1992)

Oscillations in the magnetoresistance of electrons of the upper and lower quantum-size subbands are identified. The peak values of the conductivity of the upper subband are well above the predictions of the Ando theory, although the peak values of the conductivity of the lower subband are in all cases smaller than the predictions of this theory by a factor of several units. The Landau levels of the lower subband broaden as the parallel component of the magnetic field is strengthened. Nodes occur in the Shubnikov–de Haas oscillations when delocalized states of the different subbands coincide. The results found here are linked with intersubband scattering.

1. A substantial number of recent studies[2–7] have taken up the properties of an electron system with two filled quantum-size subbands. The reason for this interest is that fairly high mobilities can be achieved in this case, despite the low carrier density in the second subband. These high mobilities can be achieved because the electrons of the upper subband are farther from the interface than the electrons of the lower subband. As a result, scattering by remote impurities and surface roughness features is greatly suppressed. One contributing factor here is the screening of the random potential by the electrons of the lower subband. The inset in Fig. 1 (based on the theoretical predictions of Ref. 8) is a schematic diagram of the electron density distributions for the first and second subbands. Under these conditions, intersubband scattering may determine the behavior of the electron system of the second subband and place an upper limit on its mobility.

2. We have studied the magnetoresistance of a system of 2D electrons during the filling of the second quantum-size subband. The test sample had the Hall configuration. The measurements were carried out with an alternating current with a frequency of 17.6 Hz and an amplitude up to 100 nA at a temperature of 0.4 K. The initial electron density $n_{s0} = 3.2\times10^{11}$ cm^{-2} was increased, in order to fill the second subband, by briefly illuminating the sample until a density $n_{s0} = 6.6\times10^{11}$ cm^{-2} was reached, with $\mu_0 = 6\times10^5$ cm^2/(V·s). We should stress that since the illumination was carried out above the GaAs gap, electron–hole pairs were produced in the interior of the GaAs. As a result, the depletion layer was neutralized. The depletion layer could not be completely restored after the illumination, because the sample was kept at the low temperature at all times. This relative broadening of the well reduces the intersubband splitting, so the second subband can be filled at a lower overall density of the electron system.

Figure 1 shows typical curves of R_{xx} and R_{xy} versus the magnetic field. There are obviously two periods, which correspond to an electron density $n_{s1} = 5.6\times10^{11}$ cm^{-2}

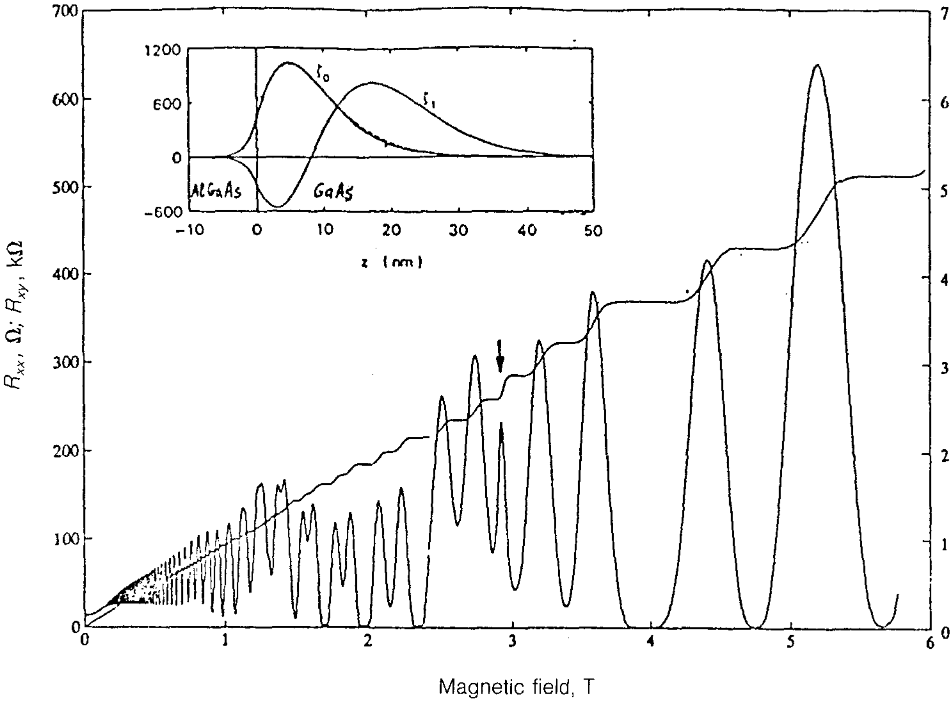

FIG. 1. Magnetoresistance of a 2D electron gas during the filling of the upper quantum-size subband. The arrow marks a peak corresponding to conductivity in the upper subband as the filling factor of this band is changed from 2 to 1.

in the ground subband and $n_{s2} = 1.0 \times 10^{11}$ cm^{-2} in the upper subband. The reason is that the measured quantities include $\sigma_{xx} = \sigma_{xx}(n_{s1}) + \sigma_{xx}(n_{s2})$ and $\sigma_{xy} = \sigma_{xy}(n_{s1}) + \sigma_{xy}(n_{s2})$.

3. The position of this peak marked by the arrow in Fig. 1 corresponds to a filling factor $\nu_1 = 8$ in the lower subband and $\nu_2 = 1.5$ in the second subband (i.e., the Fermi level is at the middle of the upper spin sublevel of the second subband with $N = 0$). In the same magnetic field, there is a transition on the plot of R_{xy} from a plateau corresponding to $\nu = 10$ to one corresponding to $\nu = 9$. This peak is therefore related to a conductivity in the second subband as the filling factor of this band is varied from 2 to 1. Figure 2 shows the results of a calculation of $\sigma_{xx} = \rho_{xx}/(\rho_{xy}^2 + \rho_{xy}^2)$ as a function of the magnetic field. The horizontal lines are the results of Ando's calculations[1] ($\sigma_{xx}^{\max} = (e^2/\pi^2\hbar)(N + 1/2)$) for Landau levels $N = 0$ and $N = 1$. We see that the peak value of σ_{xx} in the second subband with $N = 0$ is anomalously high, while the peak values of σ_{xx} of the ground subband are far smaller than would be expected from the formula. We should stress that there has been only a single reported observation, by Haug,[10] of values of the conductivity peaks in heterojunctions approaching the predictions of Ando's calculations, while in metal–insulator–semiconductor structures an

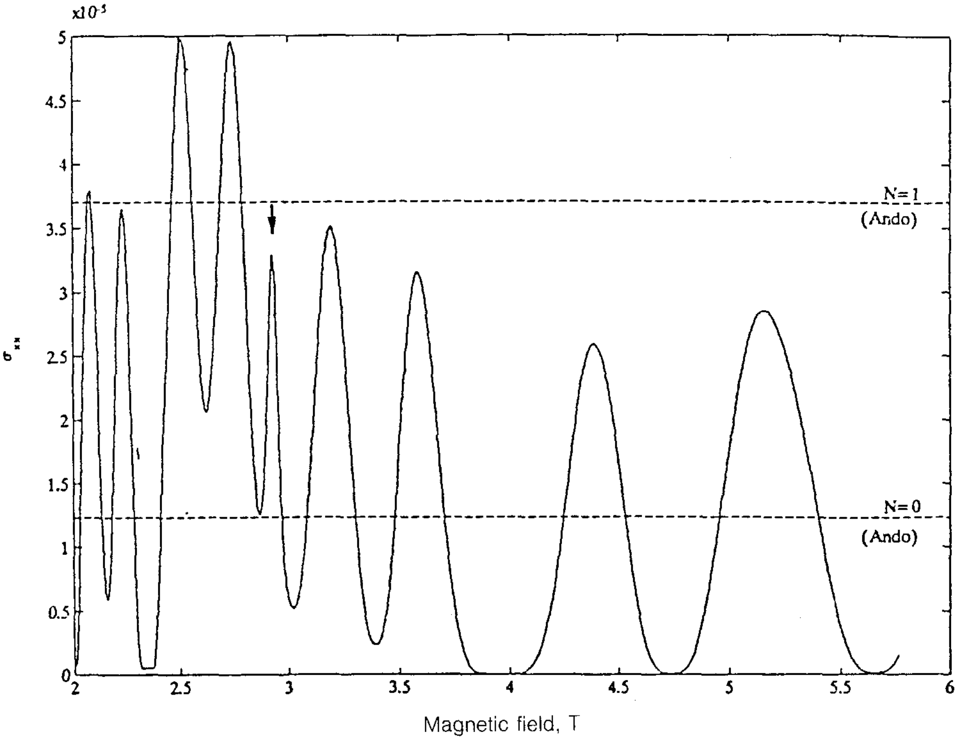

FIG. 2. Calculated values of $\sigma_{xx} = \rho_{xx}/(\rho_{xy}^2 + \rho_{xy}^2)$ versus the magnetic field. The dashed lines show Ando's theoretical predictions $\sigma_{xx}^{\max} = (e^2/\pi^2\hbar)(N + 1/2)$ for Landau levels $N = 0$ and $N = 1$. The arrow marks the same peak as in Fig. 1, which corresponds to $N = 0$ in the upper subband. The neighboring peaks correspond to $N = 4$ and 3 in the lower subband.

agreement with the theory has been observed in all cases (e.g., Ref. 9), because of a predominance of short-range scatterers. In order to change the nature of the scattering in a heterojunction, Haug introduced impurities (Si or Be) directly in the layer of 2D electrons. He monitored the growth of the peak values of σ_{xx} with increasing impurity concentration. In our case, the localized electrons of the lower subband ($\nu_l = 8$) may act as additional scattering centers, planted directly in the channel, for the electrons of the upper subband. The intersubband scattering should therefore play a decisive role in the anomalous increase in the conductivity.

4. Using the same sample and the same illumination, we measured the magnetoresistance in oblique magnetic fields. For comparison, Fig. 3 shows $R_{xx}(\nu)$ in a perpendicular magnetic field and for angles of 66° and 75° from the normal to the interface. The disappearance of the minima due to spin splitting (in a stronger resultant magnetic field) and the shrinkage of the Shubnikov–de Haas oscillations indicate a level broadening due to an intensification of intersubband scatttering. These anomalies disappear when the second subband is emptied by IR light. The depletion layer in the

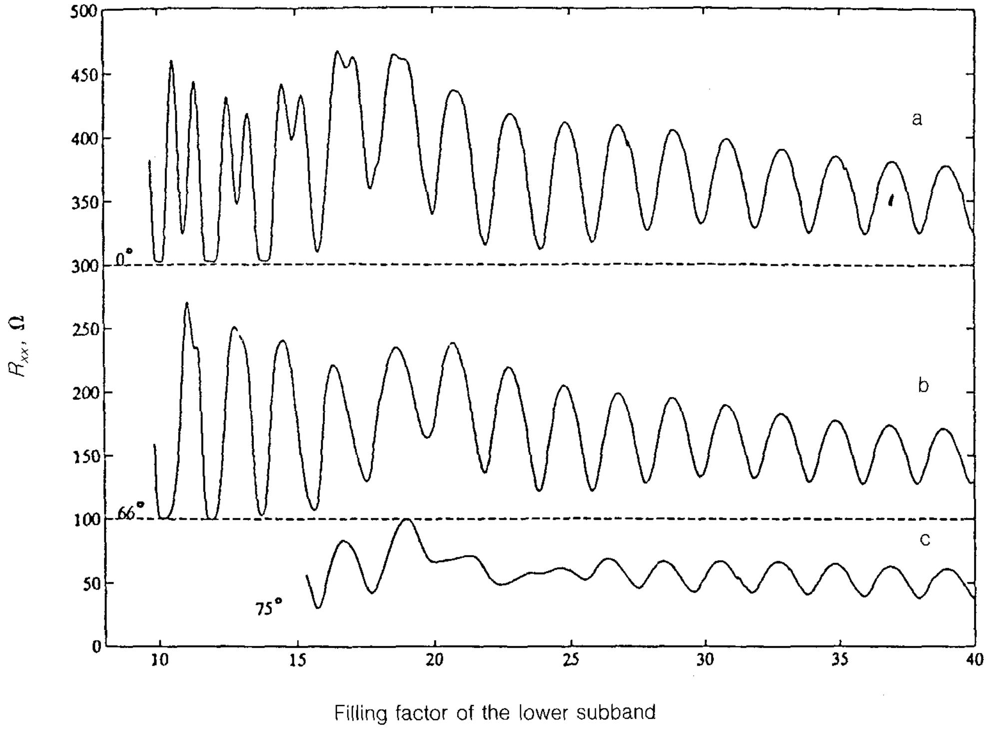

FIG. 3. R_{xx} versus the filling factor of the lower subband at three values (0, 66°, and 75°) of the angle between the magnetic field and the normal to the interface. The minima (which result from spin splitting) disappear at odd filling factors. A node forms in the oscillations near a filling factor of 20.

interior of the GaAs is completely restored in the process, so there is a narrowing of the well. In other words, there is an increase in the intersubband splitting. A second interesting feature is the decrease in the oscillation amplitude at that point along the magnetic-field scale at which the chemical potential of the system enters the region of delocalized states of the second subband. In the case at hand, this event occurs near $\nu_2 = 3$. With increasing angle, a node can form here (Fig. 3c). This effect can be attributed to the appearance of a resonant channel for electron scattering by delocalized states of the lower subband into delocalized states of the upper subband, at the same energies, upon an intensification of intersubband scattering in a parallel magnetic field. With a further increase in the angle, the node begins to move toward larger filling factors of the lower subband. The reason is a difference between the diamagnetic shifts of the bottoms of the first and second subbands in the parallel field. This effect corresponds to an increase in intersubband splitting and thus a decrease in the electron density in the upper subband.

In a parallel magnetic field, intersubband scattering thus becomes the decisive factor for the behavior of the electrons of the lower subband.

5. In summary, the magnetotransport oscillations of 2D electrons have been studied during the filling of the second quantum-size subband. It has been shown that the peak values of the conductivity in the upper subband can reach anomalously large values. As the sample is rotated with respect to the magnetic field, we see effects which can be attributed to an intensification of intersubband scattering in a parallel magnetic field.

These results indicate that it would be impossible in principle to study the fractional quantum Hall effect and Wigner crystallization (both of which require low densities) through the use of the electrons of the upper subband, because of the strong influence of intersubband scattering.

I would like to express my gratitude to S. I. Dorozhkin and I. V. Kukushkin for their interest in this study.

[1] T. Ando, A. B. Fowler, and F. Stern, Rev. Mod. Phys. **54**, 437 (1982).
[2] H. van Houten, J. G. Williamson, M. E. I. Broekaart *et al.*, Phys. Rev. B **37**, 2756 (1988).
[3] T. W. Hickmott, Phys. Rev. B **39**, 5198 (1989).
[4] V. C. Karavolas and P. N. Butcher, J. Phys. Cond. Matt. **2**, 3947 (1990).
[5] D. R. Leadley, R. J. Nicholas, J. J. Harris, and C. T. Foxon, Semicond. Sci. Technol. **5**, 1081 (1990).
[6] P. T. Coleridge, Semicond. Sci. Technol. **5**, 961 (1990).
[7] M. G. Gavrilov, S. I. Dorozhkin, V. E. Khitomirskiĭ, and I. V. Kukushkin, Pis'ma Zh. Eksp. Teor. Fiz. **49**, 402 (1989) [JETP Lett. **49**, 462 (1989)].
[8] F. Stern and S. Das Sarma, Phys. Rev. B **30**, 840 (1984).
[9] A. B. Babkin, M. G. Gavrilov, I. V. Kukushkin, and M. A. Chernikov, Fiz. Tverd. Tela (Leningrad) **29**, 3288 (1987) [Sov. Phys. Solid State **29**, 1886 (1987)].
[10] R. J. Haug, PhD Thesis, MPI FKF, Stuttgart, 1988.

Translated by D. Parsons