Intensification of spin splitting in the second subband of quantum-size electrons in a single GaAs-AlGaAs heterojunction

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(Submitted 17 February 1989)
Pis'ma Zh. Eksp. Teor. Fiz. **49**, No. 7, 402–406 (10 April 1989)

A recurrent extinction of the amplitude of the Shubnikov-de Haas oscillations (nodes), which is accompanied by an inversion of the oscillation phase, has been observed in single GaAs–$Al_{0.3}Ga_{0.7}As$ heterojunctions. This effect can be explained in terms of the emptying of the single magnetic-quantization levels of the second subband, suggesting that the spin splitting in the electron energy spectrum of this subband increases.

1. It is well known[1,2] that in two-dimensional electronic systems with a single filled quantum-size subband the minima of the Shubnikov-de Haas (SdH) oscillations, ρ_{xx}, are seen in magnetic fields $H_\nu = hcn_s/\nu e$, which correspond to the filling of an integer number ν of magnetic-quantization levels. Here n_S is the density of the carriers in a $2D$ system. Because of the small value of the g-factor [$g \approx -0.4$ (Ref. 3)] of the $2D$ electrons in a GaAs–AlGaAs heterojunction, the minima of the SdH oscillations, which stem from the spin splitting, can be observed only by using high-quality samples with slightly broadened magnetic levels in sufficiently strong magnetic fields ($\mu g H \gtrsim kT$, where μ is the Bohr magneton). As a result, the period of the SdH oscillations changes in this system as the magnetic field H is increased. This change in the period occurs because only a cyclotron splitting (even ν) occurs in weak fields and because both a cyclotron splitting and spin splitting (all integer ν) occur in strong fields.

Depending on the relationship between the energy splitting and the level broadening, two cases are possible when two quantum-size subbands are filled. In the case of narrow levels the position of the minima of ρ_{xx} is determined, as usual, by the equation given above. In the case of broad levels. Shubnikov-de Haas oscillations of various periods occur.[4] These oscillations are described by the equations $H_{\nu 1} = hcn_{S1}/\nu e$ and $H_{\nu 2} = hcn_{S2}/\nu e$. Here n_{S1} and n_{S2} are the electron densities in the first and second subbands, respectively.

In the range of densities n_S close to the point at which the second subband begins to be filled, we observed an unusual effect involving the onset of SdH oscillation nodes, where the groups of oscillations on the opposite sides of the nodes had the same period in the reciprocal field but opposite parity of the numbers ν. This effect is interpreted as a systematic emptying of the magnetic levels of the second subband as the field is increased. A change in the parity of the SdH oscillations indicates that the magnetic levels of the second subband, in contrast with the lower subband, are spin-allowed, and the spin splitting is seen in a field $H \approx 0.5$ T on condition that $\mu g H \ll kT$. The last result shows that spin splitting in the second subband is intensified. The intensification effect due to the exchange interaction of the spin splitting was previously observed up to the values $\tilde{g} = 10$–15 only in the lower subband[5] and in much stronger fields.

2. We have investigated single GaAs–Al$_{0.3}$Ga$_{0.7}$As heterojunctions with a 200-Å-thick spacer. In all the structures the concentration of $2D$ electrons, n_S, was varied by exposing them to light in the range from 3×10^{11} cm^{-2} to 5.5×10^{11} cm^{-2}. The shunting channel of the long-lived photoconductivity did not manifest itself, which was confirmed by the zero values of ρ_{xx} at the minima corresponding to the conditions under which the quantum Hall effect occurs. To reduce the electron density after a maximum exposure of the sample to light, we warmed the sample in darkness to $T\approx 20$ K and held it at this temperature for several hours. As a result of such a procedure, we were able to reduce n_S by 1–3×10^{10} cm^{-2}. All the structures had the geometry of Hall bridges. The measurements were carried out using an alternating current with a frequency in the range 17–200 Hz. The position of the minimum of the SdH oscillations in the magnetic field was determined within $\approx 0.1\%$.

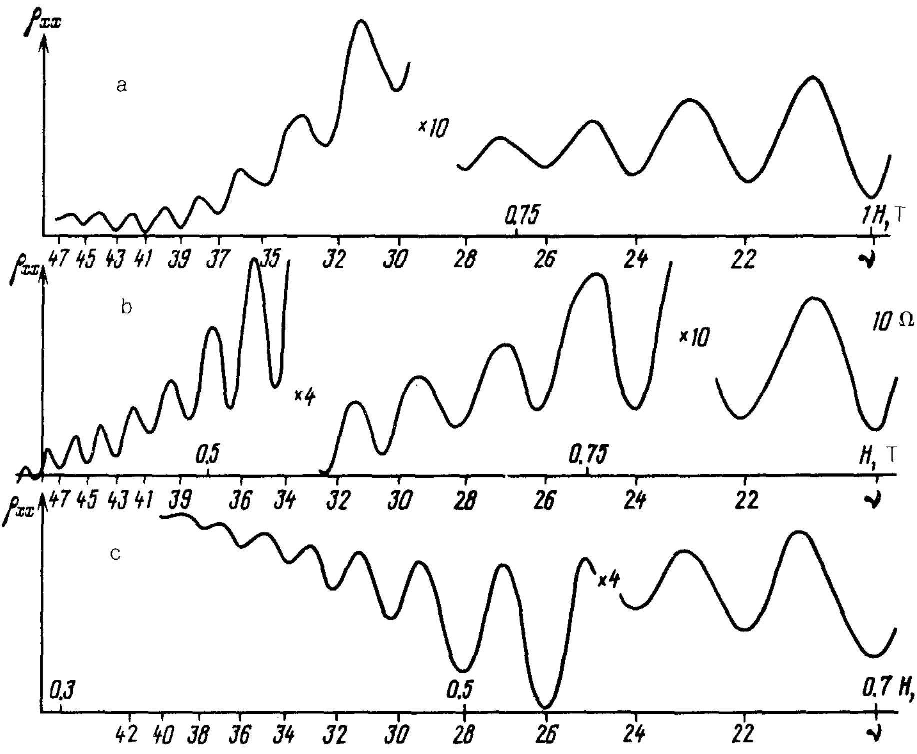

FIG. 1. Experimental traces of the SdH oscillations of the diagonal component of the magnetoresistance tensor ρ_{xx} at various electron densities: a—$n_S = 4.85\times10^{11}$ cm^{-2}; b—$n_S = 4.53\times10^{11}$ cm^{-2}; c—$n_S = 3.4\times10^{11}$ cm^{-2}; $T = 0.4$ K. Individual groups of oscillations were plotted along the ρ_{xx} axis using different scales. The change of scales for each group is shown in the figure. The 10 Ω scale corresponds to the group of oscillations shown at the extreme right in all figures. Sample 1.

3. The Shubnikov-de Haas oscillations measured in sample 1 at various electron concentrations n_S are shown in Fig. 1. The most clearly defined structural feature of this sample is seen at $n_S = 4.85 \times 10^{11}$ cm^{-2} (Fig. 1a). In the interval of numbers ν from 33 to 36, the SdH oscillation amplitudes are augmented (a node is formed) and a transition from even numbers $\nu \lesssim 32$ to odd numbers $\nu \gtrsim 37$ occurs. This transition is equivalent to a change in the SdH oscillation phase by π (a phase reversal occurs). It should be noted that by choosing only one parameter (the electron density n_S) from the equation $H_\nu = hcn_S/\nu e$ we can make all the minima of ρ_{xx} correspond to integer values of ν ($\nu \leqslant 32$, $\nu \geqslant 37$) within better than 1% error limits. A reduction of n_S to 4.5×10^{11} cm^{-2} has no effect on the phase reversal other than to cause it to smear (spread) over roughly 20 numbers (Fig. 1b). A greater than 1% deviation of the position of the minima of ρ_{xx} from the integer values of ν occurs in the transition

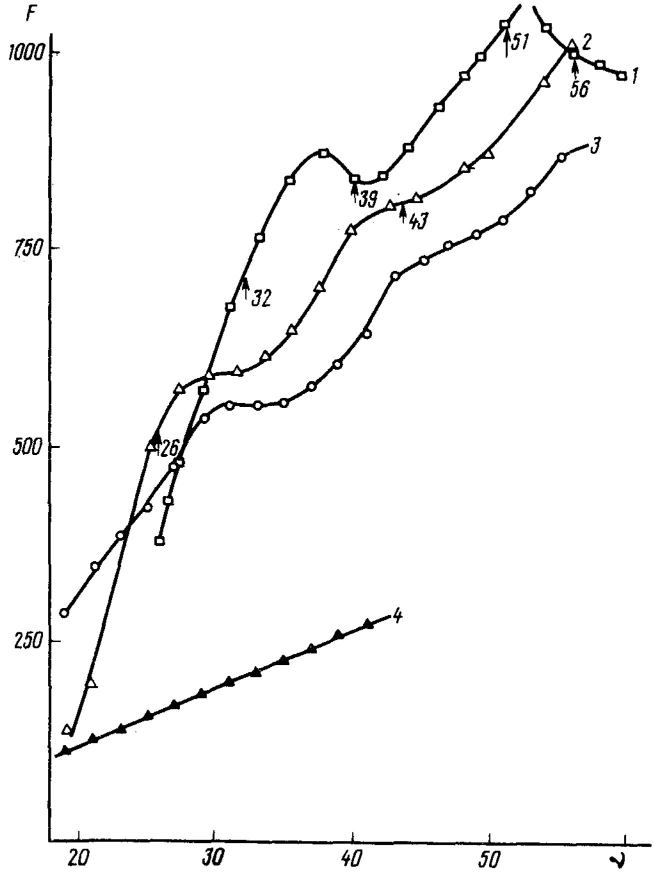

FIG. 2. The normalized amplitude ρ_{xx} of the SdH oscillations versus ν for various electron concentrations: (1) ■—$n_S = 4.85 \times 10^{11}$ cm^{-2}; (2) ▲—$n_S = 4.53 \times 10^{11}$ cm^{-2}; (3) ●—$n_S = 4.0 \times 10^{11}$ cm^{-2}; (4) ◆—$n_S = 3.4 \times 10^{11}$ cm^{-2}. $F = -(h/\pi e^2 \rho_0) \ln \{(\delta \rho_{xx}/\hat{\rho}_0)[\mathrm{Sh}(2\pi^2 kT/\hbar\omega_c)/4\pi^2 kT/\hbar\omega_c]\}$, where $\omega_c = eH/m^*c$ is the cyclotron frequency. Sample 1.

region. A further reduction of n_S below $\approx 4\times 10^{11}$ cm^{-2} causes all the characteristic features of the amplitude and phase of the SdH oscillations to vanish and leads to the appearance of even values of ν (Fig. 1c).

Figure 2 is a plot of the normalized SdH oscillation amplitude versus ν (the Dingle diagrams). The arrows near the curves indicate the boundaries of the transition regions. The positions of the characteristic slope change on the Dingle diagrams correlate with the boundaries mentioned above. Note that the characteristic features of the SdH oscillation amplitudes remain in force to lower electron densities n_S than those at which the phase inversion of the oscillations occurs (curve 3 in Fig. 2).

As can be seen in Fig. 3, these effects repeat themselves in lower fields (at large values of ν). While the first phase inversion at $n_S = 4.85\times 10^{11}$ cm^{-2} occurred at $\nu_1 = 33$–36 (Fig. 1a), the second one occurred at $\nu_2 = 51$–54 (Fig. 3). At this concentration we see a third node at $\nu_3 = 75$–78, which manifests itself, however, much less clearly because the SdH oscillation amplitude is small at such large values of ν. With a decrease in n_S, the second and third phase inversions spread much faster than the first one and vanished very rapidly. The slope of the magnetic field at angles up to 70° with respect to the normal to the heterojunction has virtually no effect on the values of ν corresponding to the characteristic features described above. In sample 2 the first phase inversion occurred at $n_S = 5.2\times 10^{11}$ cm^{-2} and $\nu_1 = 46$–49, suggesting that this effect is highly sensitive to the particular features of the potential well which forms the 2*D* electron layer.

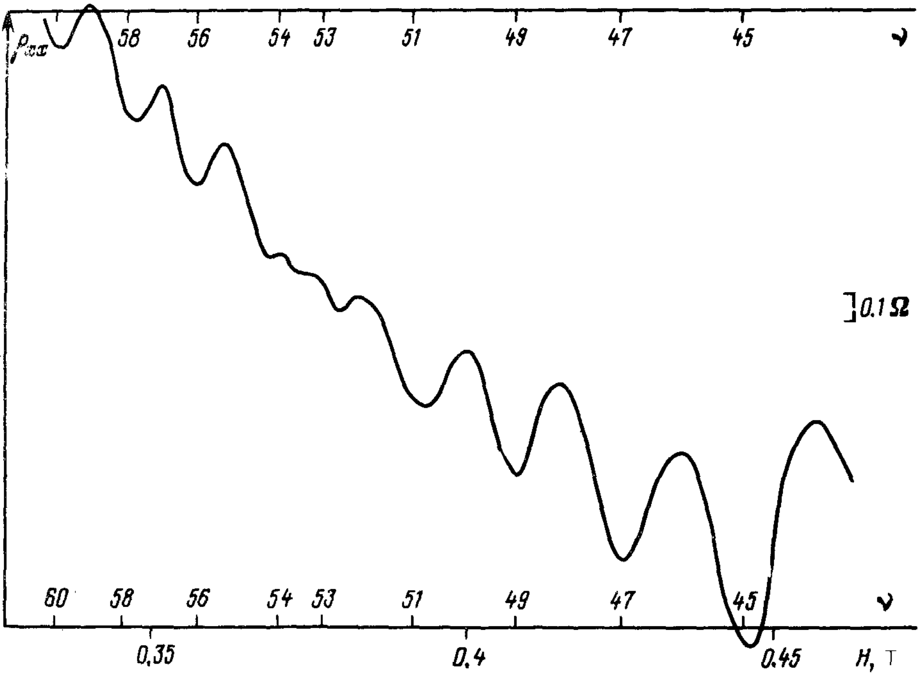

FIG. 3. Experimental trace of ρ_{xx} versus the magnetic field, $T = 0.4$ K, $n_S = 4.85\times 10^{11}$ cm^{-2}. Sample 1.

4. The pattern of the Shubnikov-de Haas oscillations obtained by us strongly resembles the results obtained in Ref. 6. However, the clear explanation of the effect in Ref. 6 on the basis of the energy spectrum of $2D$ systems with a strong spin-orbit coupling clearly is inapplicable in our case. This conclusion is suggested by the narrow region of the electron concentration n_S in which this effect occurs and by the proximity of this region to the point at which the second quantum-size subband begins to be filled. In this case it is natural to link this phenomenon with the emptying of the single magnetic-quantization levels in the second subband. Since the first phase inversion ($\nu_1 = 33$–36 at $n_S = 4.85 \times 10^{11}$ cm^{-2}, $H_1 \approx 0.5$ T) occurred in sample 1 at a temperature of 1.5 K, i.e., under the conditions such that $T \gg \mu g H_1/k \approx 0.13$ K, the offered explanation requires that the spin splitting of the electrons in the second subband be intensified. An exchange interaction might be such an intensification mechanism.[7] Note that a spin splitting of electrons in the lower subband was not observed under the same conditions (it begins to manifest itself in sample 1 only in fields $H \gtrsim 3.5$ T). Clearly, this circumstance suggests that the magnetic levels are broader in this subband. In general, a result of this sort is quite natural, since the electrons in the lower subband are closer to the ionized donors which are concentrated behind the spacer in AlGaAs. These electrons partially screen their scattering potential which acts on the carriers of the second subband.

An observation of several phase inversions could yield, with the help of an appropriate calculation, the parameter values of the electron energy spectrum of the heterojunction. These data obviously could be used to determine the difference in the energies of the donors in the two lower subbands and the spin splitting of the electrons in the second subband. This calculation would have to take into account, in a self-consistent way, the change in the shape of the potential well, which forms the $2D$ layer, due to the redistribution of the carriers in the subbands, the oscillatory nature of the spin splitting, and the broadening of the magnetic-quantization levels due to scattering.

We wish to thank B. K. Medvedev for assistance, and É. I. Rashba and Yu. A. Bychkov for useful discussions.

After this article was submitted to press, we learned of an observation of an alternating sequence of the Shubnikov-de Haas oscillation nodes [B. Das *et al.*, Phys. Rev. B **39**, 1411 (1989)] in $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}/\mathrm{In}_{0.52}\mathrm{Al}_{0.48}\mathrm{As}$ heterojunctions. The authors of this article did not analyze the dependence of this effect on n_S, nor did they specify the parity of the oscillation numbers. They explained their results in terms of the lifting of the spin degeneracy, in qualitative agreement with the explanation of the results of Ref. 6.

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Translated by S. J. Amoretty