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Magnetoresistance in a GaAs-Al$_x$Ga$_{1-x}$As heterostructure with double subband occupancy

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A temperature-independent positive weak-field magnetoresistance is observed in a high-mobility GaAs-Al$_x$Ga$_{1-x}$As heterostructure with two occupied two-dimensional subbands. Persistent photoconductivity is used to study this effect for various electron-gas densities. The magnetoresistance is interpreted in terms of a simple classical model for two independent electron gases characterized by their respective number densities and mobilities. This analysis allows a direct determination of the mobility of the second subband.

Advances in molecular-beam epitaxy (MBE)[1] have permitted the growth of GaAs-Al$_x$Ga$_{1-x}$As heterostructures with extremely high mobility two-dimensional electron gases (2DEG). Magnetotransport studies[2] of such systems have shown a rich variety of quantum phenomena, such as weak localization and universal conductance fluctuations[3] (at low fields) and the quantum Hall effect (at large fields). Classically, a 2DEG does not have a transverse magnetoresistance if the electron gas can be characterized by a single relaxation time (or mobility μ). In this case the Hall field $E_H = -Bv_{\text{drift}}$ exactly compensates for the magnetic-field-induced lateral drift of the electrons, so that the current paths are essentially unperturbed. This is no longer the case, necessarily, in a situation where more than a single two-dimensional subband is occupied, as in GaAs-Al$_x$Ga$_{1-x}$As heterostructures with a high sheet carrier concentration[4] (typically above 5×10^{15} m^{-2}). In an independent electron-gas picture one would expect the two subbands to be characterized by two different mobilities. As is well known in the field of transport in metals and semiconductors with two types of mobile carriers, a positive magnetoresistance will develop if their mobilities differ. The reason for this is that the Hall field no longer exactly compensates for the magnetic-field-induced drift for each type of carrier individually. The GaAs-Al$_x$Ga$_{1-x}$As heterostructure offers excellent opportunities to study this effect in a quasi-two-dimensional system, since it has a very simple band structure (Fermi circle) and a high mobility. For this system it is straightforward to obtain independently the carrier densities in the two subbands from the high-field oscillatory magnetoresistance [Shubnikov-de Haas effect (SdH)].

We have studied the magnetotransport in a GaAs-Al$_x$Ga$_{1-x}$As heterostructure with various degrees of second subband occupancy. We observe a positive magnetoresistance at low magnetic fields, and a double periodicity in the SdH oscillations at higher fields, characteristic of the two subbands. As we will show, both transport phenomena can be interpreted in terms of an independent electron-gas picture.

The heterostructure samples were grown by MBE, and consisted of a 3-μm undoped GaAs layer on a semi-insulating substrate, followed by a 10-nm-thick undoped Al$_{0.3}$Ga$_{0.7}$As spacer layer, a 40 nm n-doped Al$_{0.3}$Ga$_{0.7}$As layer (1.33×10^{24} m^{-3} Si) and an undoped 20-nm-thick GaAs capping layer. In the dark the sample had an overall carrier density of 5×10^{15} m^{-2}, and the second subband was already slightly populated. The overall mobility was dominated by the first subband, and was typically 40 m^2/Vs. Persistent photoconduction (PPC) is used to increase the total carrier density up to 8×10^{15} m^{-2}, giving an overall mobility increase of $\sim50\%$. The layered structure was designed in such a way that no parallel conduction in the Al$_x$Ga$_{1-x}$As layer developed after illumination.[5] This indeed proved to be the case, as evidenced by the vanishing of the resistivity component ρ_{xx} under quantum Hall conditions. The samples were shaped into wide Hall-bar geometries using standard lithographic techniques.

Measurements of the transverse magnetoresistance at 30 mK are shown in Fig. 1 for two extreme PPC conditions: no illumination and fully saturated PPC. Due to the high-mobility pronounced SdH oscillations are apparent even in the rather low-field range shown (<1 T). In Fig. 2 the corresponding (non-spin-degenerate) Landau level index i of the minima in R_{xx} is plotted as a function of $1/B$ for both periodicities.[6] From the slope $s\equiv i/(1/B)$ of the straight lines the sheet carrier concentration of each subband is found according to $n=(e/h)s$. The resulting values are given below.

In Fig. 1 a positive magnetoresistance is indeed evident at low magnetic fields, and its relative magnitude increases after illumination. This effect is shown on an expanded scale in Fig. 3 for the saturated PPC case for 30 mK and 1 K. It is seen that the positive magnetoresistance is temperature independent. This is a signature of a classical effect, for which the relevant length scales (mean free path and cyclotron radius $l_{\text{cycl}}=v_F/\omega_c$, with v_F the Fermi velocity, and ω_c the cyclotron frequency) are constant in the temperature range studied. The SdH oscillations, on the other hand, are quantum mechanical in origin, and they are strongly suppressed at 1 K (see Fig. 3) as a consequence of the thermal broadening of the Fermi-Dirac distribution over Landau levels ($\hbar\omega_c \sim kT$).

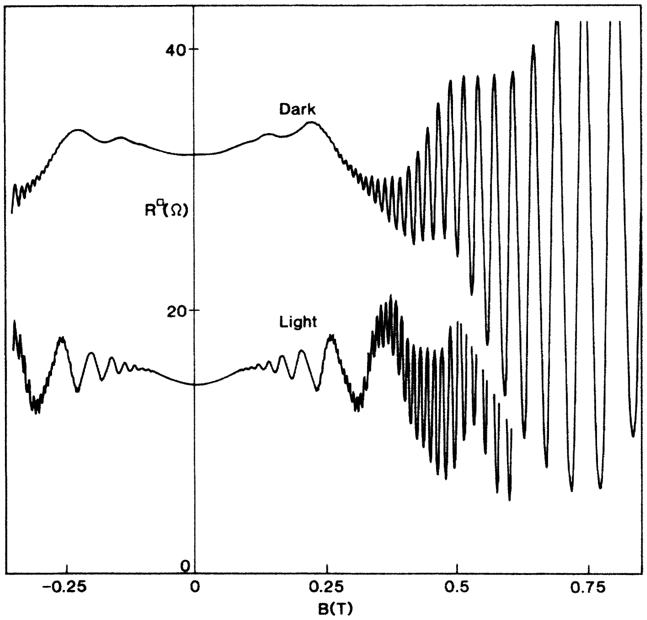

FIG. 1. The resistance per square for a GaAs-Al$_x$Ga$_{1-x}$As heterostructure with two two-dimensional subbands occupied as a function of magnetic field at 30 mK. Persistent photoconduction is used to change the carrier densities. The fast oscillations pertain to the lowest subband and the slow oscillations to the second subband.

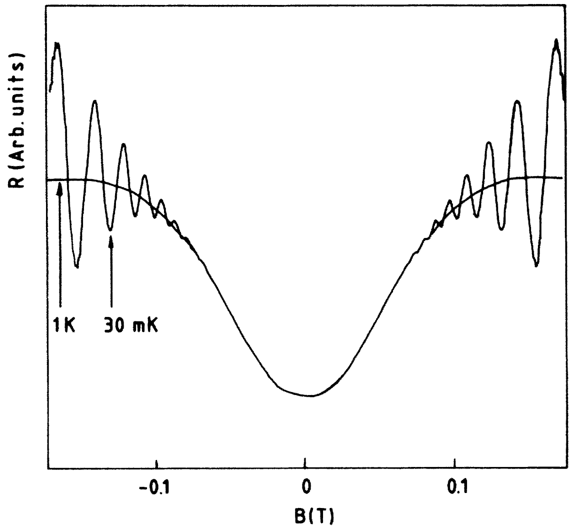

FIG. 3. Positive magnetoresistance for the sample with saturated persistent photoconduction at 30 mK and 1 K.

We have analyzed the data using a standard classical model[7] for the positive magnetoresistance in the case that two types of noninteracting carriers are present, characterized by their respective sheet carrier densities n_1, n_2 and mobilities μ_1, μ_2. According to the model the total conductivity $\sigma = \sigma_1 + \sigma_2$ with $\sigma_1 = n_1 e \mu_1$ and $\sigma_2 = n_2 e \mu_2$. The weak-field[8] Hall ratio is $R_H = (n_1 e \mu_1^2 + n_2 e \mu_2^2)/\sigma^2$, and the resistance change in a magnetic field $\Delta R \equiv R(B) - R(0)$ (Ref. 9) is given by

$$\Delta R/R = \sigma_1 \sigma_2 (\mu_1 - \mu_2)^2 B^2 / \{\sigma^2 + [\mu_1 \mu_2 e (n_1 - n_2) B]^2\} \ . \tag{1}$$

The saturation value of the effect at high magnetic fields in the limit that $n_2 \ll n_1$ is given by $(n_2/n_1)[(\mu_1 - \mu_2)^2/\mu_1\mu_2]$. Obviously, a large effect will occur if the mobility difference is large and the fraction of electrons in the second subband is not too low. Since n_1 and n_2 are known from the SdH periodicities, the two mobilities could in principle directly be obtained from the measured conductivity and Hall ratio, without using the information from $\Delta R(B)$. This approach is, however, not very useful, since a very high accuracy in R_H is necessary (typically 0.1%)

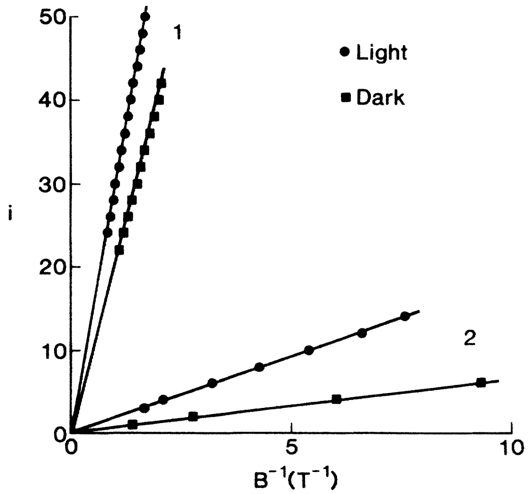

FIG. 2. Landau-level index i vs reciprocal magnetic field for the two traces of Fig. 1. Results are given for the lowest subband (1) and the second subband (2), for which spin splitting is already resolved at $B \sim 0.5$ T.

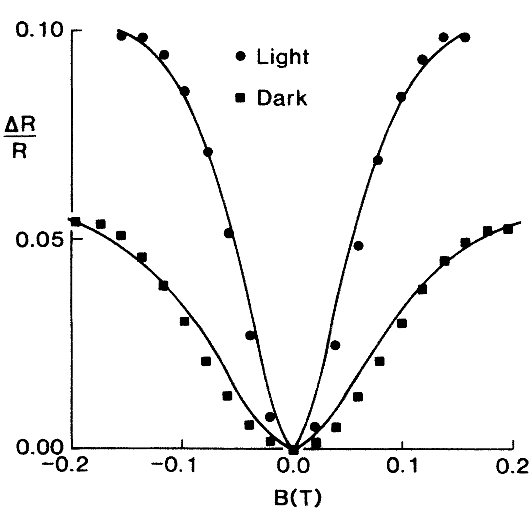

FIG. 4. Fit of Eq. (1) to the positive magnetoresistance data for two illuminations at 1 K with a single free parameter.

to obtain reliable values for μ_2 in the case that $n_1 \ll n_2$. A better approach is to use $\Delta R(B)$ instead of R_H, and find μ_2 from a one-parameter fit to Eq. (1). As an independent check on the results for n_1, n_2, μ_1, and μ_2 we compared the resulting value for R_H with the measured value. In all cases the two values agreed within the experimental uncertainties ($\sim 1\%$).

In Fig. 4 the results at 1 K are shown for the two extreme PPC cases[10] for which the low-temperature data were presented in Fig. 1. Considering the fact that we have only a single free parameter, the agreement between the model and the experimental data is very satisfactory. It indicates that the classical independent electron-gas picture is indeed adequate in describing the perpendicular field magnetoresistance, without need to consider intersubband scattering.

From the analysis we find $n_1 = 4.9 \times 10^{15}$ m^{-2}, $\mu_1 = 40$ m^2/Vs and $n_2 = 1.6 \times 10^{14}$ m^{-2}, $\mu_2 = 9.9$ m^2/Vs. After illumination we find $n_1 = 7.1 \times 10^{15}$ m^{-2}, $\mu_1 = 60$ m^2/Vs and $n_2 = 4.5 \times 10^{14}$ m^{-2}, $\mu_2 = 15.9$ m^2/Vs. The effect of the PPC is seen to be twofold. The overall carrier density, and thus n_1 and n_2 increase, but because of a change in the confining potential the separation between the subbands increases too, so that the change in n_1 is larger than the change in n_2. Secondly, the mobilities of both subbands are enhanced after illumination by $\sim 50\%$. We attribute this effect to the reduced scattering at higher densities, because of the higher Fermi velocity. The mobility of the electron gas in the second subband is lower by as much as a factor of 4 compared to the lower subband. This is not unexpected, since the Fermi velocity in the second subband is much less because $n_2 \ll n_1$. The dominant scattering mechanism at low temperatures, ionized impurity scattering, will be more effective for the slowly moving electrons in the second subband.

In conclusion, we have observed a positive weak-field magnetoresistance in a GaAs-Al$_x$Ga$_{1-x}$As heterostructure in which two two-dimensional subbands are populated. From the analysis of this effect the mobilities of the electrons in the two subbands can be reliably determined. Similar information is also contained in the line shape of the SdH oscillations. However, the effect discussed in this paper combined with the positions of the SdH minima yields this information in a more straightforward way.

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[1] C. T. Foxon and J. J. Harris, Philips J. Res. **41**, 313 (1986), and references therein.

[2] For a review of transport properties of two-dimensional electron gases (mainly in silicon MOSFET's, see T. Ando, A. B. Fowler, and F. Stern, Rev. Mod. Phys. **54**, 437 (1982).

[3] P. A. Lee, A. Douglas Stone, and H. Fukuyama, Phys. Rev. B **35**, 1039 (1987).

[4] J. J. Harris, D. E. Lacklison, C. T. Foxon, F. M. Selten, A. M. Suckling, R. J. Nicholas, and K. W. J. Barnham, Semicond. Sci. Technol. **2**, 783 (1987).

[5] A similar magnetoresistance effect as discussed in this paper occurs in the presence of parallel conduction in the Al$_x$Ga$_{1-x}$As layer, see M. J. Kane, N. Apsley, D. A. Anderson, L. L. Taylor, and T. Kerr, J. Phys. C **18**, 5629 (1985).

[6] In the analysis of the SdH minima for the second subband in the unilluminated sample the position of the $i = 3$ minimum is somewhat uncertain because it is superimposed on a negative trend. We have corrected for this effect.

[7] R. G. Chambers, Proc. Phys. Soc. A **65**, 903 (1952). A simple derivation of Eq. (1) is given in, e.g., J. M. Ziman, *Electrons and Phonons* (Oxford Univ. Press, Oxford, 1960).

[8] Deviations from this weak-field result are extremely small in our case, where $n_1 \gg n_2$ and $\mu_1 \gg \mu_2$ (cf. Ref. 7).

[9] We abbreviate R_{xx} by R.

[10] A small ($< 10\%$ of the saturation value) asymmetry in the magnetoresistance occurs in the unilluminated sample probably due to slight inhomogeneities (see Fig. 1). This asymmetry has been subtracted in Fig. 4.