Magnetoresistance anisotropy due to the 2D-electron subsystem at a GaAs/AlGaAs interface

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Effects of the coexistence of 2*D* and 3*D* electrons in the structure GaAs/*n*-AlGaAs have been studied for the first time over the temperature range $T = 4.2$–300 K. The angular dependence of the magnetoresistance might be used as a new test of the two-dimensionality of an electron subsystem. This test would work over broad ranges of T and H, in contrast with the Shubnikov–de Haas effect.

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The oribital motion of two-dimensional (2D) electrons in a magnetic field **H** is governed exclusively by the normal component of this field. In most cases, therefore, a 2D-electron system is detected by examining the angular dependence of the period of the quantum oscillations of the magnetoresistance $\Delta\rho_{xx}(H)$ (the classical value of this period is $\Delta\rho_{xx} = 0$ in the degenerate isotropic case). If there are two electron subsystems, one of which is two-dimensional, we would expect a characteristic anisotropy $\Delta\rho_{xx}(\mathbf{H})$ even in fields H at the classical level.

In this letter we report the first observation of a dependence of $\Delta\rho_{xx}$ on the orientation of a nonquantizing field **H** in the heterostructure GaAs/n-$Al_xGa_{1-x}As$.

A 2D-electron channel forms at a heterostructure interface because of the pronounced band curvature caused by the selective doping[1] (only the $Al_xGa_{1-x}As$. is doped with donors). Such heterostructures have the unique property that the scattering of the 2D electrons is very weak (in comparison with the inversion layers in silicon) at low temperatures: Impurity scattering is suppressed by the spatial separation of the electrons from the donors that produce them, while surface scattering is suppressed by the good lattice match in the heterostructure. This circumstance has been exploited, in Ref. 2, for example, for record-accuracy measurements of the fine-structure constant on the basis of the quantum Hall effect.

In the present experiments we measured the magnetoresistance, the Hall effect, and the Shubnikov–de Haas effect in heterostructures grown by liquid-phase epitaxy. The structures consisted of a (100) GaAs semi-insulating substrate, a tin-doped GaAs layer 20–30 μm thick, and an $Al_{0.3}Ga_{0.7}As$ layer ~ 1 μm thick at a tin concentration $\lesssim 5\times 10^{17}$ cm^{-3}. For comparison, "satellite" GaAs layers were grown on the same substrate. These samples had a four-probe Hall geometry and indium ohmic contacts. The plane of the heterostructure was the XY plane; the current flowed along the X axis; the measured Hall field was directed along the Y axis; and the magnetic field was in the YZ plane: $\mathbf{H} = (0, H\sin\theta, H\cos\theta)$, with $\theta = 0°$–$90°$, $H \leqslant 53$ kOe.

As we will see below, there are two electron subsystems in these heterostructures: a two-dimensional subsystem at the interface and a three-dimensional (3D) subsystem

TABLE I.

No.	μ_{eff} $cm^2/(V\cdot s)$	n_{eff} 10^{13} cm^{-2}	n_{2D} 10^{11} cm^{-2}	μ_{2D} $cm^2/(V\cdot s)$	n_{3D} 10^{13} cm^{-2}	μ_{3D} $cm^2/V\cdot s$	n_{sat} 10^{13} cm^{-2}	μ_{sat} $cm^2/V\cdot s$
1	5860	0.86	6.2	20200	3.37	1100	3.3	900 – 1200
2	4000	1.0	6.6	14050	3.25	960	3.3	900 – 1200

in the volume of the GaAs. According to *C-V* measurements, the 3D electrons resulting from the residual impurities are distributed nonuniformly over the thickness of the GaAs layer; specifically, their concentration in $n_{3D} \lesssim 10^{15}$ cm^{-3} in the vicinity of the channel and increases toward the substrate. The average value over the thickness is $n_{3D} = (1\text{–}3)\times 10^{16}$ cm^{-3}.

Table I shows the properties (the concentration n_i and the mobility μ_i) of some representative samples at $T = 4.2$ K. The effective parameters of the heterostructures, μ_{eff} and n_{eff}, and those of the satellites, μ_{sat} and n_{sat}, were determined from Hall-effect measurements in weak fields; n_{2D} was determined from the Shubnikov–de Haas effect; and n_{3D}, μ_{3D}, and μ_{2D} were determined from the field dependence of the Hall constant, $R(H)$, and from the resistance of the heterostructure at $H = 0$.

Figure 1 shows the second derivative of the resistance of the heterostructure, ρ_{xx}, in quantizing fields H. The period of the oscillation in the inverse field, $\Delta(H^{-1})$, is

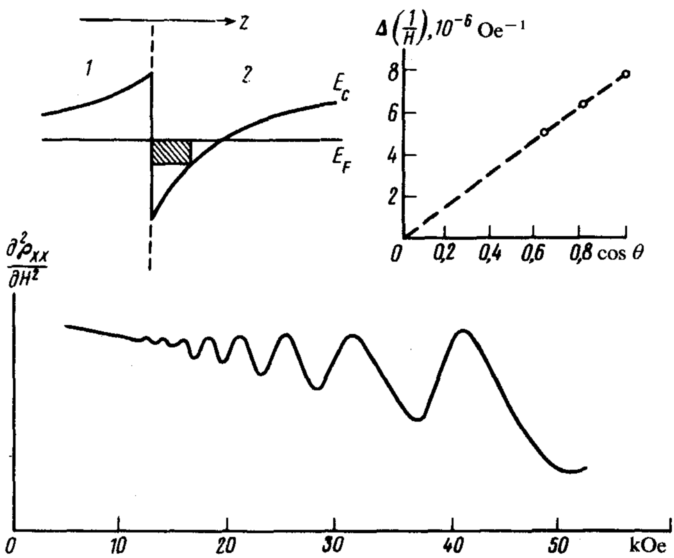

FIG. 1. Shubnikov–de Haas oscillations in heterostructure No. 1 ($T = 4.2$ K, $\theta = 0°$). The inset at the upper left shows the energy-band diagram near the interface; that at the upper right shows the angular dependence of the oscillation period. 1—$n = Al_xGa_{1-x}As$; 2—GaAs (E_c is the bottom of the conduction band, and E_F is the Fermi level).

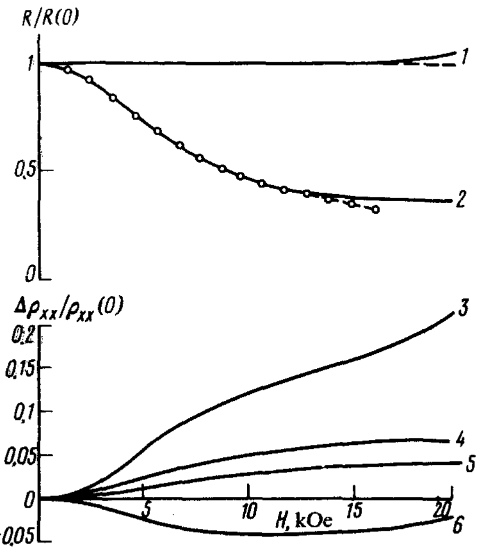

FIG. 2. The Hall constant (curves 1 and 2) and the magnetoresistance (3–6) vs the magnetic field H for structure No. 1 (2–6) and for the "satellite" (1). 1, 2, 3, 6—$T = 4.2$ K; 4, 5—$T = 77$ K. 1–4—$\theta = 0°$; 5, 6—$\theta = 90°$. Solid curves—experimental; points—theoretical.

linear in cos θ, unambiguously proving that a degenerate 2D electron gas with a concentration $n_{2D} = e\cos\theta/\pi\hbar\Delta\,(H^{-1})$ exists in the heterostructure. The observation of one period implies that only the ground 2D subband is filled. The Shubnikov–de Haas effect is not observed in the satellites.

The H dependence of $R = \rho_{xy}/H$ (Fig. 2) is important for the heterostructure (curve 2), in contrast with the satellite (curve 1), even at low fields H; this is a consequence of the 2D subsystem. The experimental results at $H < 15$ kOe can be described well by the classical dependence $R(H)$ for two types of carriers (2D and 3D electrons) with a single adjustable parameter n_{3D}. The values found for n_{3D} and μ_{3D} by this approach (Table I) are in reasonable agreement with the data for the satellite.

At all fields H the magnetoresistance $\Delta\rho_{xx}$ for the heterostructure, in contrast with that for the satellites, depends on the inclination of **H** with respect to the heterostructure interface (Fig. 2). At $\theta = 90°$ the magnetic field does not affect the 2D electrons, so that the curves of $\Delta\rho_{xx}(H)$ for the heterostructure and the satellites are qualitatively the same ($\Delta\rho_{xx}$ is frequenctly observed to be negative at $T = 4.2$ K in disordered 3D systems, and we will not discuss this negative sign here). With decreasing θ, the 2D contribution to $\Delta\rho_{xx}$ increases and may even change the sign of $\Delta\rho_{xx}$ (curve 3). The anisotropy of $\Delta\rho_{xx}$ with respect to θ was observed only in those heterostructures which exhibited the 2D Shubnikov–de Haas effect, and it was more pronounced at the higher values of the ratio μ_{2D}/μ_{3D}. This effect is of classical origin and thus not a weak effect. It stems from the presence of two electron subsystems (for a single group of degenerate carriers, the classical value is $\Delta\rho_{xx} = 0$) and is observed not only at 4.2 K but also at 77 K (curves 4 and 5 in Fig. 2). Some of the heterostructures, with high values of μ, exhibit this effect even at 300 K. The angular anisotropy of $\Delta\rho_{xx}$

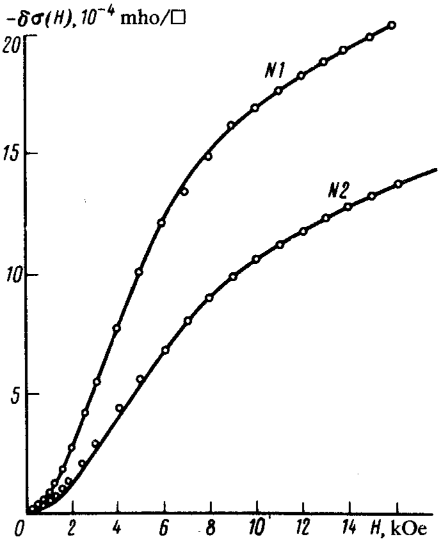

FIG. 3. The conductivity anisotropy function $\delta\sigma(H)$ for heterostructures Nos. 1 and 2 ($T = 4.2$ K). Points—experimental; solid curves—theoretical [Eq. (2)].

can thus be exploited to detect 2D subsystems over broad ranges of T and H.

For a quantitative description of the effect we work from the function $\delta\sigma(H) \equiv \sigma_{xx}(H,\theta = 0°) - \sigma_{xx} \times (H,\theta = 90°)$, which is a measure of the angular anisotropy of the conductivity. A model-independent calculation of $\delta\sigma(H)$ yields

$$\delta\sigma(H) = \left(\frac{\rho_{xx}}{\rho_{xx}^2 + \rho_{xy}^2}\right)_{\theta = 0°} - \left(\frac{1}{\rho_{xx}}\right)_{\theta = 90°} = \left[\Delta\sigma_{xx}^{2D} - \frac{(\sigma_{xy}^{3D})^2}{\sigma_{xx}^{3D}}\right]_{\theta = 0°}, \tag{1}$$

where we have introduced the magnetoconductivity of the $2D$ subsystem, $\Delta\sigma_{xx}^{2D} = \sigma_{xx}^{2D}(H) - \sigma_{xx}^{2D}(0)$. In the classical model of a degenerate electron gas we would have

$$\delta\sigma(H) = (\Delta\sigma_{xx}^{2D} + \Delta\sigma_{xx}^{3D}) = -\sum_i^{2D,3D} \frac{\sigma_{xx}^i(0)\mu_i^2 H^2}{1 + \mu_i^2 H^2}. \tag{2}$$

The points in Fig. 3 show the values of $-\delta\sigma(H)$ calculated from the measured values of ρ_{ij} by means of expression (1). For structure No. 1 the result is in excellent agreement with the classical model, (2). For structure No. 2, with a lower value of μ_{2D}, there is a discrepancy in weak fields which cannot be explained in terms of the experimental error. One possible explanation for the discrepancy is that it is a consequence of quantum-localization effects and an electron-electron interaction.[3,4] This question requires a more thorough study.

We also observed a frozen photoconductivity,[1] which might be exploited to control the parameters of the $2D$ channel. Illumination of heterostructure No. 1 at 4.2 K increased μ_{2D} by 24%, n_{2D} by 23%, and n_{3D} by nearly 100%.

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