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Transport coefficients of InAs epilayers

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Heteroepitaxially grown single-crystal InAs layers exhibit anomalies in the magnetic field dependence of their Hall coefficients, their magnetoresistance, and the temperature dependence of their electron mobilities. These are attributed to a degenerate surface accumulation of electrons and are interpreted in terms of a two-layer model, one with bulklike and the other with surfacelike charge carrier transport coefficients.

Surface charge carrier transport must be taken into account in the evaluation[1] of the measured electrical and galvanomagnetic parameters of thin elemental semiconducting films. Surface currents may also represent an appreciable fraction of the total current impressed on relatively thick high-mobility III-V semiconducting compound layers with accumulated surfaces. Specific anomalies are likely to appear in the magnetic field and temperature dependence of experimentally derived electrical and galvanomagnetic coefficients of epitaxial layers in comparison with those of the same bulk crystalline materials. Such measurements were made on heteroepitaxially deposited single-crystal InAs layers with impurity concentrations of the order of $10^{15}/\mathrm{cm}^3$ and electron mobilities, at 77 °K, in excess of 10^5 $\mathrm{cm}^2/\mathrm{V\,sec}$, grown on (100)-oriented semi-insulating GaAs substrates using a chemical vapor phase growth process similar to that of Tietjen *et al.*[2,3] Detailed measurements of the temperature dependence of the conductivity σ_0 and of the Hall coefficient R_{h0} made on a representative 17-μm-thick InAs epilayer are in qualitative agreement with measurements made on bulk[4] InAs and on heteroepitaxially grown InAs epilayers.[5,6] However, the magnetic field dependences of the Hall coefficient and of the magnetoresistance shown in Fig. 1(a) are in marked contrast with those of bulk InAs. In particular, the Hall coefficient of bulk InAs is independent[7] of the magnetic induction B up to ~7 kG.

The contributions from both electron and hole conduction bands cannot account for more than ~1% of the values of $R_h(B)$ and $(\Delta\rho/\rho_0)$ shown in Fig. 1(a); furthermore, the magnetic field dependence of these parameters is even stronger in the extrinsic temperature region, as shown in Fig. 1(b). Inhomogeneities and spatial fluctuations in impurity concentration can be excluded from consideration as causes of these anomalies because scanning x-ray microprobe investigations show that the epilayer is homogeneous and uniform. C-V measurements made at 80 °K on MOS configurations suggest that the InAs epilayer surfaces are in strong accumulation with a typical space-charge density, $Q_{sc} = -4\times10^{12}/\mathrm{cm}^2$, an isotropic impurity distribution, and abrupt epilayer substrate interfaces. The specimen

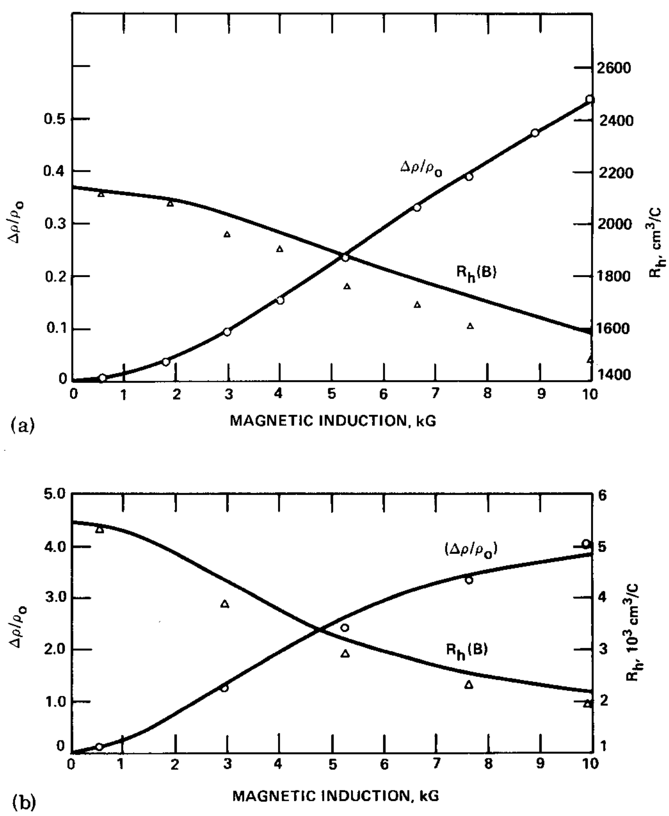

FIG. 1. Magnetic field dependence of the Hall coefficient and of the magnetoresistance; experimental data and theoretically derived curves from Eqs. (2)—(4) for a 17-μm InAs epilayer; (a) for T = 294.5 °K, (b) for T = 83.8 °K.

shape chosen for electrical and galvanomagnetic measurements has a length-to-width ratio of ~6 in order to reduce electrostatic short circuiting of the Hall field to negligible proportions. Therefore, "geometrical" contributions[8] to $R_h(B)$ and $(\Delta\rho/\rho_0)$ can also be ruled out as causes for the experimentally observed anomalies.

Figure 2 shows the temperature dependence of the Hall mobility for the 17-μm-thick InAs epilayer; above ~250 °K it deviates from its proportionality to $T^{-1.47}$, an anomaly with respect to bulk InAs whose electron mobility[4,12] is proportional to T^{-x} with the exponent x having a value of 1.5 to 1.2 in the temperature range for which lattice scattering is the dominant mobility-limiting mechanism.

A simple analytical interpretation of these experimentally measured anomalies can be made in terms of the two-layer model of Nedoluha and Koch.[9] It consists of a surfacelike layer whose parameters are defined by the subscript s and a bulklike layer whose parameters are described by the subscript b. The intermediate surface contact between them is represented by a zero-resistance connecting loop. The constitutive Ohm-Hall equations for each of the two layers oriented along Cartesian axes, with $k=b, s$, are

$$\begin{aligned} E_x &= (1/\sigma_k)J_{x,k} - (R_kB)J_{y,k}, \\ E_y &= (R_kB)J_{x,k} + (1/\sigma_k)J_{y,k}, \\ J_x &= (1/d)(d_bJ_{x,b} + d_sJ_{x,s}), \\ 0 &= d_bJ_{y,b} + d_sJ_{y,s}, \end{aligned} \quad (1)$$

where E_x is the electric field along the impressed current density vector J_x, the transverse Hall field is E_y, and σ_k is the specific conductivity of a layer, while the combined thickness of the two layers is $d=d_b+d_s$.

The measured conductivity $\sigma_0=J_x/E_x$, in terms of Eq. (1) and of the combined electrical and galvanomagnetic parameters of the bulk and surface layers, is

$$\sigma_0 = (1/d)(\sigma_A + \sigma_B), \quad (2)$$

with the sheet conductivities defined as $\sigma_A=\sigma_b d_b$ and $\sigma_B=\sigma_s d_s$ while the combined magnetic induction-dependent Hall coefficient, $R_h(B)$ derived from Eq. (1), $R_h(B) = E_y/J_xB$, is

$$R_h(B) = \left(\frac{\mu_b\sigma_A + \mu_s\sigma_B + \mu_b\mu_s(\mu_s\sigma_A + \mu_b\sigma_B)B^2}{(\sigma_A+\sigma_B)^2 + (\mu_b\sigma_B + \mu_s\sigma_A)^2B^2}\right), \quad (3)$$

with μ_b the bulk electron mobility and μ_s the surface mobility. For $B=0$ the Hall coefficient $R_h(0)$ reduces to R_{h0}, the same expression developed by Petritz[10] from circuital considerations. The combined magnetoresistance of the two-layer system, is

$$\left(\frac{\Delta\rho}{\rho_0}\right) = \frac{(\mu_b - \mu_s)^2\sigma_A\sigma_B B^2}{(\sigma_A+\sigma_B)^2 + (\mu_b\sigma_B + \mu_s\sigma_A)^2B^2}. \quad (4)$$

Equations (3) and (4) are considered to express the magnetic field dependence introduced by a surface layer present on a semiconductor having a single conduction band or two bands but with an electron-to-hole mobility ratio so large and a hole density so small that to a fair approximation $(\Delta\rho/\rho_0)$ and $R_h \neq f(B)$.

In order to compare the features of the two-layer model to the experimentally measured data on the InAs epilayers, n_b and μ_b are considered to be adjustable parameters and $d_s \ll d_b$. Measurements made at room temperature on bulk crystalline InAs indicate[4,7] that $\mu_b \le 3\times10^4$ cm^2/V sec, depending on donor density and on the degree of impurity compensation; the electron density of the bulklike portion of the epilayers can be estimated from the sum of the measured extrinsic electron density, $n_x = 1.1\times10^{15}$/cm^3 and n_i, the intrinsic carrier density calculated with due account[7,11] of the nonparabolicity of the conduction band and the spin-orbit splitting energy of InAs.

With μ_b and n_b selected in terms of these considerations, the calculated value $n_i(294.5\,°K) = 8.75\times10^{14}$/cm^3 and the measured $\sigma_0(294.5\,°K) = 10.647$ $(\Omega\,cm)^{-1}$, σ_B can be calculated from Eq. (2). Then, using the experimentally measured value $R_{h0}(294.5\,°K) = 2130$ cm^3/C, the mobility of the accumulation layer is $\mu_s = 4498$ cm^2/V sec calculated from the relation

$$\mu_s = (1/\sigma_b)[(R_{h0}/d)(\sigma_A+\sigma_B)^2 - \mu_b\sigma_A]. \quad (5)$$

Figure 1(a) shows that the theoretically calculated curves of $R_h(B)$ and $(\Delta\rho/\rho_0)$ versus B can be fitted to the experimentally measured data with $\mu_b = 2.9\times10^4$/V sec and $n_b = 1.7\times10^{15}$/cm^3; consequently $\sigma_A = 1.342\times10^{-1}$ and $\sigma_B = 4.674\times10^{-3}$ Ω^{-1}. Also by assuming that $d_s = L_D$, the Debye length L_D is

$$L_D = (\epsilon\kappa k_0T/e^2n_b)^{1/2}, \quad (6)$$

where e is the charge on the electron, k_0 is Boltzmann's constant, $\kappa = 12.5$ is the dielectric constant of InAs, and ϵ_0 the permittivity of free space. From Eq. (6), $L_D = 1016$ Å and, in consequence, $\sigma_s = 460$ $(\Omega\,cm)^{-1}$ and $n_s = 6.38\times10^{17}$/cm^3.

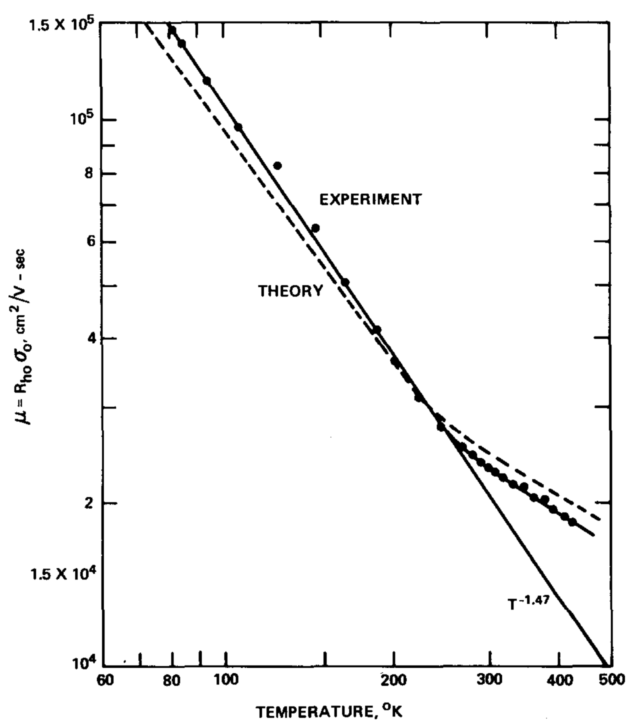

FIG. 2. Temperature dependence of the Hall mobility of the same 17-μm-thick InAs epilary showing experimental data and theoretically derived curve using Eqs. (7) and (8).

An order-of-magnitude estimate of n_s can also be made by comparing it to the earlier-mentioned space-charge density $Q_{sc} = -4.34\times10^{12}/\text{cm}^2$, assuming that it is uniform within the accumulation layer and bounded by L_D. In consequence, $(Q_{sc}/L_D) = -4.27\times10^{17}/\text{cm}^3$, in fair agreement with the calculated value of n_s.

If the presence of the accumulation layer is ignored, then the calculated electron density from $R_{h0}(294.5\,°\text{K})$ is $n = 2.9\times10^{15}/\text{cm}^3$ and the corresponding mobility $\mu = R_{h0}\sigma_0$ is $2.27\times10^4\ \text{cm}^2/\text{V sec}$. This overestimates the electron concentration of the epilayer by 71% and underestimates the mobility by ~22%. Figure 1(b) shows that at 83.8 °K there is also fair agreement between the calculated $R_h(B)$ and $(\Delta\rho/\rho_0)$ versus B curves and the experimental data; the calculations were made with the initial assumption that σ_B is invariant with temperature. Since the measured $\sigma_0(83.8\,°\text{K}) = 25.465\ (\Omega\,\text{cm})^{-1}$ and $R_{h0}(83.8\,°\text{K}) = 5500\ \text{cm}^3/\text{C}$, it follows that $\sigma_A = 3.86\times10^{-2}\ \Omega^{-1}$, therefore $\mu_b = 1.56\times10^5\ \text{cm}^2/\text{V sec}$ and $n_b = 9.06\times10^{14}/\text{cm}^3$. This suggests that by ignoring the accumulation layer the 83.8 °K electron mobility is underestimated by ~ 11% and the electron density is overestimated by ~30%.

The anomaly in the temperature dependence of the mobility $\mu = R_{h0}\sigma_0$ shown in Fig. 2 can be interpreted in terms of

$$\mu = \frac{\mu_b^2 n_b + \mu_s^2 n_s (d_s/d)}{\mu_b n_b + \mu_s n_s (d_s/d)} \qquad (7)$$

derived from Eqs. (2) and (3) by introducing the appropriate temperature dependence[7,11,12] of μ_b and n_b and again considering σ_B to be temperature independent:

$$\mu_b(T) = n_i(T) + 9\times10^{14}/\text{cm}^3,$$

$$n_b(T) = 2.8\times10^7 T^{-1.2}. \qquad (8)$$

It is evident from Fig. 2 that in the extrinsic temperature region where $dn_b/dT \simeq 0$ the experimentally measured mobility is proportional to $T^{-1.47}$ in agreement[4,7] with that of bulk InAs; at higher temperatures, the theoretically derived curve from Eqs. (7) and (8) provides a good fit to the anomalous $\mu(T)$ measured experimentally.

The two-layer model thus provides an adequate explanation of the magnetic field and temperature dependence anomalies of the transport coefficients of the InAs epilayer described here in detail. Qualitatively similar results were also obtained on eight additional specimens from 8 to 15 μm in thickness.

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Selectively etched diffraction gratings in GaAs

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Selective etching techniques are described which have been utilized to fabricate V-groove diffraction gratings with spatial frequencies greater than 4000 lines/mm in {100} surfaces of GaAs.

Selective etching is a chemical technique which can be utilized to make geometrically shaped grooves on surfaces of single-crystal silicon[1] and gallium arsenide (GaAs).[2,3] The usefulness of this technique for isolating devices on silicon wafers[4] and in fabricating ridged waveguides for surface acoustic waves[5] has been demonstrated previously. To our knowledge, it has not previously been demonstrated that selective etching can be utilized to fabricate high-quality diffraction gratings in either silicon or GaAs with selected groove shapes of submicron dimension. In this letter, we describe the techniques we have utilized to make V-groove gratings with spatial frequencies greater than 4000 lines/mm in polished {100} surfaces of GaAs.

As reported previously,[2] groove shapes of two basic types are obtained when {100} planes of GaAs are etched through slotted masks using bromine-methanol (Fig. 1). In both types, the groove walls correspond to A {111} crystallographic planes. These planes are selected