Hall factor of doped n-type GaAs and n-type InP

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The Hall factor r_H is computed for n-type GaAs and n-type InP from 3 to 300 K for doping levels below the Mott limit. The calculation, under low-magnetic-field conditions, includes the usual elastic scattering mechanisms without assuming Matthiessen's rule, and accounts for the inelastic nature of collisions with polar optical phonons by the Rode iterative technique [D.L. Rode, in *Transport Phenomena*, edited by R. Willardson and A. Beer (Academic, New York, 1975) Vol. 10, pp. 7—46]. The results show that assuming $r_H=1$ at 77 K may lead to an underestimate of the impurity concentrations, giving a theoretical 300-K mobility higher than often observed.

The purity of routinely grown III-V semiconducting compounds, among which GaAs and InP are the most promising for technological applications, has increased considerably during the last few years, making the samples suitable for a precise analysis. Hall-mobility measurements are usually performed under low-magnetic-field conditions, and the corresponding data are used to extract the donor (N_D) and acceptor (N_A) impurity concentrations. For such calculation, the simplest technique is to choose a temperature where ionized impurity scattering is dominant and to use one of the available formulas for the corresponding drift mobility.[1] N_D and N_A can also be obtained from a fit to the drift mobility in a broad temperature range by including the appropriate scattering mechanisms and from considerations of the variation of the free-electron concentration as a function of the temperature T.[2] Nevertheless, the variations of the Hall factor r_H are in most cases not taken into account, and the drift mobility is generally chosen to equal the Hall mobility. This is only valid if the Hall mobility is measured under sufficiently high-magnetic-field conditions or if the semiconducting material is degenerate. In the latter case, impurity conduction plays an important role.[3] A model that does not account for impurity conduction can thus only be applied safely in a broad temperature range when the impurity concentrations considered fall well below the Mott limit.[4,5] On the other hand, for a given T, high-magnetic-field conditions are usually assumed, which implies that $\mu^2B^2 \gg 1$,[6] B being the magnetic field and μ the drift mobility. For very pure GaAs or InP samples, this condition can be satisfied in the liquid-nitrogen-temperature range when μ peaks, provided B is reasonably large. However, at room temperature, the condition cannot be met without an unusually large B field, which not only requires considerable instrumentation, but also alters the energy spectrum of the carriers.[7] The situation is similar at very low T, where the mobility decreases again. On the other hand, since we find experimentally in the liquid-nitrogen-temperature range a variation of mobility of only a few percent over the range $0.05<B<0.5$ T, low-field conditions are well satisfied and r_H is not unity for the usual laboratory conditions.

Our aim in this paper is to show that the variations of r_H cannot be neglected in the analysis of the Hall mobility and of the Hall electronic concentration n_H defined by

$$n_H=n/r_H ,$$

where n is the electronic concentration in the conduction band. We computed r_H by an iterative solution to the Boltzmann equation proposed by Rode[8] without having to assume Matthiessen's rule. Ionized impurity scattering has been accounted for by the Brooks-Herring relaxation time,[9] the other elastic scattering mechanisms included being deformation-potential acoustic and screened piezoelectric.[10] The small neutral impurity scattering has been neglected. The Rode iterative technique accounts then for polar optical scattering and has been applied in the form that does not account for nonparabolicity corrections in the conduction band. The computation requires the value of n and of the Fermi level, which are related to the impurity concentrations N_D and N_A and to the binding energy E_D through the neutrality equation. In our case, nondegenerate statistics were used and the degeneracy factor of the donor level has been taken as $\frac{1}{2}$. The values of N_D, N_A, and E_D allow the computation of $g(E)$, the perturbation to the equilibrium distribution function. $g(E)$ defines a pseudorelaxation time $\tau(E)$ which then allows the calculation of r_H by using the usual averaging integrals. Table I shows the values of the physical parameters of both InP and GaAs used in the computation. m^* is the relative effective mass, ϵ_s and ϵ_∞ the static and high-frequency dielectric constants, respectively, $T_{\rm po}$ the Debye temperature, where po stands for polar

TABLE I. Physical parameters of GaAs and InP used in the computation.

	InP	GaAs
m^* (a.u.)	0.082	0.068
ϵ_s	12.38	12.9
ϵ_∞	9.55	10.92
$T_{\rm po}$ (K)	497	420
ρ_m (g/cm^3)	4.487	5.36
E_1 (eV)	6.8	8.6
C_L (cm/s)	5.028×10^5	5.22×10^5
P	0.013	0.052

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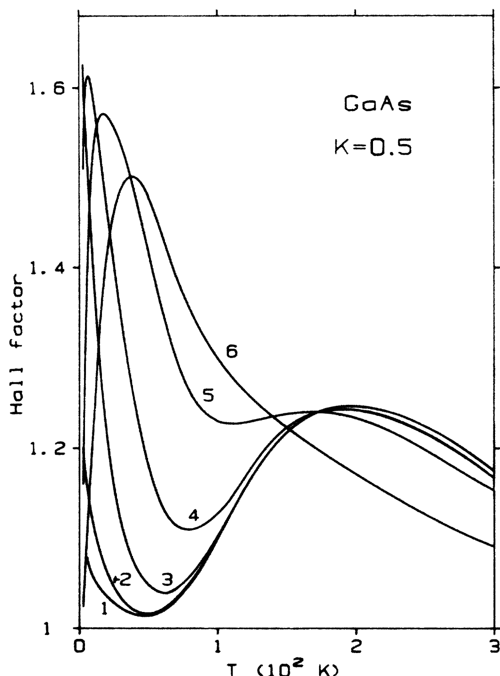

FIG. 1. r_H vs T for GaAs and different donor concentrations at 50% compensation. Curve 1, no impurities; curve 2, 10^{12} cm^{-3}; curve 3, 10^{13} cm^{-3}; curve 4, 10^{14} cm^{-3}; curve 5, 10^{15} cm^{-3}; curve 6, 10^{16} cm^{-3}.

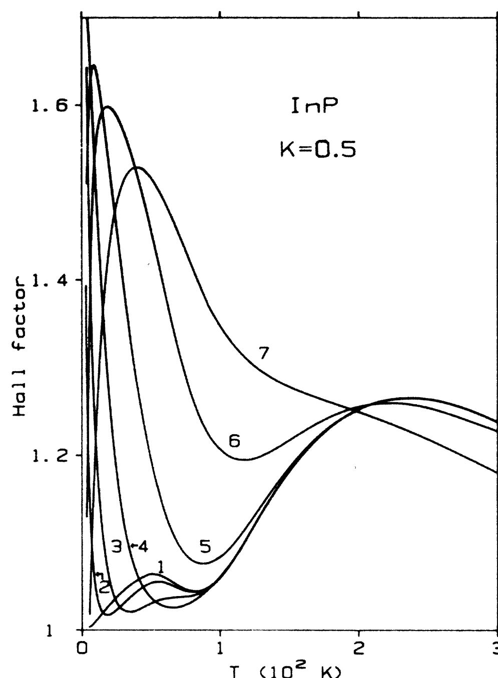

FIG. 2. r_H vs T for InP and different donor concentrations at 50% compensation. Curve 1, no impurities; curve 2, 10^{11} cm^{-3}; curve 3, 10^{12} cm^{-3}; curve 4, 10^{13} cm^{-3}; curve 5, 10^{14} cm^{-3}; curve 6, 10^{15} cm^{-3}; curve 7, 10^{16} cm^{-3}.

optical, ρ_m the mass density, E_1 the acoustical deformation potential, C_L the longitudinal speed of sound, and P a dimensionless piezoelectric coefficient defined by Hutson.[10] The average binding energies for GaAs and InP were, respectively, taken as 5.5 and 6.5 meV.

Figure 1 shows the results obtained for GaAs for a set of values of N_D and 50% compensation. Curve 1 corresponds to the pure material, when ionized impurity scattering is negligible, and is identical to the result previously obtained by Rode[11] except for T above 270 K, where nonparabolicity corrections play a role. A 5% maximum overestimate is observed in our results for such a temperature range. This can be partially reduced by increasing the precision of the calculation, but leads to considerable computation time. The same remarks apply for curve 1 of Fig. 2, corresponding to pure InP. The behavior of r_H has been analyzed in both cases by Rode[11] on the basis of the dominant scattering mechanisms corresponding to each particular T case. When ionized impurity scattering is included in our computation and the amount of centers is progressively increased, a drastic increase in r_H is first obtained for both GaAs (Fig. 1) and InP (Fig. 2) at the lowest temperatures, with almost no change at high T. Maximum values above 1.6 and 1.7 are respectively obtained for GaAs (curve 3 of Fig. 1) and InP (curve 4 of Fig. 2), the maximum theoretical value expected for pure ionized impurity scattering being of the order of 1.9.[7] This indicates an admixture with piezoelectric acoustic scattering, impurity scattering being dominant. As the impurity concentrations are further increased, a low-T peak appears. The corresponding maximum of r_H diminishes and occurs at higher T as the impurity concentrations are increased. Simultaneously a decrease of r_H is obtained at higher T. Such a trend closely resembles the mobility behavior, and can be interpreted on the basis of the partial mobilities corresponding to ionized impurities and polar optical scattering. The latter is a decreasing function of T, and is only slightly affected by a variation of N_D and N_A. The former is an increasing function of T, and the whole function decreases when the impurity concentrations are increased. The combination of both effects yields the observed result for the mobility, which is reflected in the behavior of r_H.

In conclusion, the effect of r_H cannot be neglected under low-magnetic-field conditions for both GaAs and InP, in particular in the liquid-nitrogen-temperature range, where N_D and N_A are usually extracted, and where r_H peaks for samples of reasonable purity. If the condition $r_H = 1$ is assumed, the value of the drift mobility can be considerably overestimated, the consequence being both an underestimate of the impurity concentrations and an overcompensation when one attempts to have consistency with $n = N_D - N_A$ at room temperature. Although the corresponding theoretical mobility may properly fit the experimental points at low and intermediate T, a discrepancy is often observed at high T, where theory falls above experiment. To explain this discrepancy in GaAs, a new scattering mechanism related to carbon centers has been introduced[12] and should probably be reexamined on the basis of the fact that accounting for r_H instead of the previous centers can give a good agreement for both the Hall mobility and n_H in the whole temperature range for GaAs and InP samples.[3]

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