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On Hall scattering factors for holes in GaAs

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Hall scattering factors for electrons and holes in molecular beam epitaxial GaAs layers have been determined by comparing carrier concentrations measured by the Hall effect with those measured by the electrochemical capacitance–voltage technique. The conclusion is that both the electron and hole scattering factors are near unity for n ranging from 2×10^{16} to 7×10^{17} cm^{-3}, and p ranging from 5×10^{16} to 4×10^{19} cm^{-3}. This conclusion is consistent with the present theory for electrons, but not with that for holes. © *1996 American Institute of Physics.* [S0021-8979(96)06214-7]

Electron and hole concentrations in semiconductors are usually measured by the Hall effect.[1] The "Hall concentration" n_H is defined as $n_H = 1/eR$ for electrons, where R is the measured Hall coefficient; however, the true concentration n is given by $n = r_n n_H$, where r_n is known as the "Hall scattering factor," or simply the "Hall factor." For holes, $p = r_p p_H$. The theory of electron scattering in GaAs can be carried out accurately, because electrons move in a single, nearly spherical energy band.[1–3] Such theory predicts $r_n \approx 1.0$–1.2 over a wide range of concentrations and compensation ratios at 296 K. Thus, the common assumption $r_n = 1$, in experimental work, does not lead to a large error for n-type GaAs.

The theory of hole scattering, on the other hand, is much more difficult because two, degenerate, nonspherical energy bands (the light- and heavy-hole bands) are involved. Although the individual band Hall factors, r_{pl} and r_{ph}, respectively, are also in the range 1.0–1.2 (if the bands are noninteracting), the combined Hall factor can be much larger.[4] A few calculations have included much (although not all) of the necessary complexity of hole transport in GaAs;[4–8] Wiley has given an excellent discussion of the various problems involved.[9] Values of r_p determined in most of the calculations are significantly larger than unity, ranging from 1.25 to greater than 2.[4,6,8,10,11] Such large r_p's, if accurate, can lead to significant error in determining p from a Hall-effect measurement, since most workers simply assume $r=1$ for holes, as they do for electrons.

The problem is illustrated below. If the light- and heavy-hole bands are considered to be independent (decoupled), then the combined Hall coefficient is given by[1,4]

$$R = \frac{R_h \sigma_h^2 + R_l \sigma_l^2}{(\sigma_h + \sigma_l)^2} = \frac{1}{e} \frac{r_h \mu_h^2 p_h + r_l \mu_l^2 p_l}{(\mu_h p_h + \mu_l p_l)^2} \qquad (1)$$

where σ_h and σ_l are the heavy-hole and light-hole conductivities, respectively. The combined Hall factor is then defined as

$$r_p = epR = (p_h + p_l)\frac{r_h \mu_h^2 p_h + r_l \mu_l^2 p_l}{(\mu_h p_h + \mu_l p_l)^2}. \qquad (2)$$

Equation (2) clearly shows that even if $r_h = r_l = 1$, the combined r can be much different than 1. Although the light- and heavy-hole bands are not really decoupled (e.g., interband scattering is important), still the possibility of large r_p values, according to Eq. (2), must be allowed.

A separate measurement of r_n or r_p is usually not convenient, which is why most workers set $r_n = r_p = 1$. For high mobility electrons, the relationship $r_n = n_H(B=0)/n_H(B=\infty)$ has sometimes been employed.[12,13] Here B is the magnetic field strength, and the condition "$B=\infty$" requires that $\mu B \gg 10^8$, where μ is in units of cm^2/V s and B, in Gauss. However, this condition is difficult to achieve for holes in GaAs because of the low mobilities. In the present work, we have applied another technique, electrochemical capacitance voltage (ECV) measurements,[14] which, in principle, gives the true carrier concentration. In this case, $r_n = n_{CV}/n_H$ and $r_p = p_{CV}/p_H$. (Note that in some cases, frozen-out electrons on deeper centers can also contribute to the CV signal; however, concentrations of such centers are too small to affect results in the present samples, and, in any case, would only lead to a strengthening of the final conclusions.)

The samples used in this study were 2-μm-thick molecular beam epitaxial layers grown on semi-insulating GaAs substrates in a Varian Gen II system. Hall (van der Pauw) measurements were carried out on 6 mm$\times$6 mm pieces with In dots soldered on the corners, and ECV measurements were performed on 5 mm$\times$10 mm pieces adjacent to the Hall pieces. The diode area, an important factor in the determination of concentration and depth for ECV (or any type of CV) measurements, was determined by a profilometer scan of the etched crater. A total of three n-type and four p-type samples, of different concentrations, were analyzed, as listed in Table I. An example of the ECV data is given in Fig. 1. Since a Hall measurement essentially gives a sheet concentration

$$n_{H\square} = \int_0^\infty n_H \, dz, \qquad (3)$$

we should compare this quantity with the integral of the ECV curve:

TABLE I. Hall and ECV data at 296 K, and experimental and calculated Hall factors.

Sample	Type	n_H (cm^{-3})[a]	n_{CV} (cm^{-3})[b]	$r = n_{CV}/n_H$	$r = n_{CV\square}/n_{H\square}$[c]	r(theo)[d]
2025	n	1.76×10^{16}	1.71×10^{16}	0.97	0.96	1.095
2031	n	7.07×10^{16}	7.27×10^{16}	1.03	0.96	1.032
2030	n	7.61×10^{17}	7.35×10^{17}	0.96	0.93	1.046
2029	p	4.74×10^{16}	4.99×10^{16}	1.05	0.97	2.0
2028	p	5.32×10^{17}	4.91×10^{17}	0.92	0.80	2.0
2027	p	6.03×10^{18}	5.62×10^{18}	0.93	0.81	2.3
2026	p	4.51×10^{19}	4.46×10^{19}	0.99	0.88	

[a]Assuming layer thickness of 2.0 μm, and correcting for expected depletion effects at surface and interface (Ref. 1, p. 45).
[b]Average over the nearly flat region in the C–V profile (see Fig. 1).
[c]Using integrated C–V profile ($n_{CV\square}$), and sheet Hall concentration ($n_{H\square}$).
[d]For n-type, Refs. 1–3 (accurate theory); for p-type, Ref. 11 (approximate theory).

$$n_{CV\square} = \int_0^\infty n_{CV} dz_{CV} = \int_0^\infty n \, dz, \qquad (4)$$

where the last equality is well known. For the validity of Eq. (3) we must assume that μ is constant in the conducting region, but this assumption is valid since the concentration is quite uniform, as seen in Fig. 1. The Hall factor determined from these integrals is $r = n_{CV\square}/n_{H\square}$, and is given in Table I.

We have also listed in Table I a Hall factor calculated from the *volume* concentrations, n_{CV} and n_H, respectively; i.e., $r = n_{CV}/n_H$. In this case, n_{CV} is an average over the nearly flat region in the ECV profile (see Fig. 1), and n_H is given by $n_H = n_{H\square}/d_{elec}$, where d_{elec} is the electrical thickness (conducting region). Here $d_{elec} = d - w_s - w_i$, where d is the metallurgical thickness (2.0 μm) and w_s and w_i are the calculated depletion thicknesses for the surface and interface regions, respectively.[1] For the p-type samples, the values $r = p_{CV}/p_H$ are 8%–14% less than the corresponding values $r = p_{CV\square}/p_{H\square}$, because the experimental depletion regions near the interface (but not those near the surface) are larger than expected from the concentrations. The reason for this disagreement is probably the fact that the growth rates were slightly lower than expected; in any case, the values of r have additional uncertainty due to this problem.
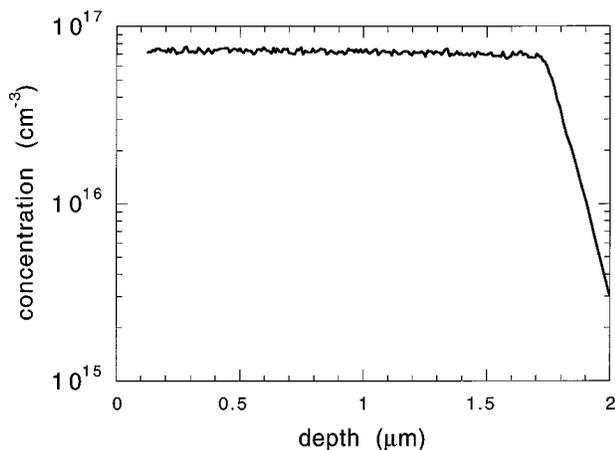
The theoretical r's, listed in the last column of Table I, are calculated according to the formalisms in Refs. 1–3 (n type) and Ref. 11 (p–type). The electron r's should be accurate, but the hole r's only approximate. More accurate hole scattering calculations than those presented in Ref. 11 also give Hall factors on the order of 1.6–2.0 for pure material.[4–6] Thus, at 296 K, theory predicts that $r_n \simeq 1$ and $r_p \simeq 2$ over the range of concentrations presented here.

The experimental results of Table I may be summarized as follows: $r_n \simeq 0.98 \pm 0.05$ and $r_p \simeq 0.93 \pm 0.12$; i.e., within error, $r_n \simeq 1$ and $r_p \simeq 1$. The value of r_n agrees reasonably well with theory, but the value of r_p is significantly lower than that predicted by theory. It must be acknowledged, of course, that the theoretical r_p's presented in Table I are derived from an approximate theory, but more complete theories also find values of r_p much larger than unity. Thus, we must conclude that either none of the hole scattering theories presented so far adequately describe Hall-effect data in GaAs, or that the ECV technique greatly underestimates concentrations in p-type material, but not in n-type material. From a practical point of view, until these questions are resolved, it would seem reasonable for workers to set $r_p = 1$ when interpreting Hall measurements in p-type GaAs.

FIG. 1. Hole concentration p vs depth z as determined by electrochemical capacitance voltage measurements.

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