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Hole transport in pure and doped GaAs

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We have used a two-band model (heavy and light holes) to calculate the transport properties of p -type GaAs. The scattering mechanisms included are acoustic-mode deformation potential, acoustic-mode piezoelectric potential, polar- and nonpolar-mode deformation potential, ionized impurity, and space charge. Interband scattering is included explicitly for the optical phonons and phenomenologically for the acoustic phonons. The intraband polar optical-mode scattering, for which a relaxation time cannot be defined, was calculated by using the numerical method of Fletcher and Butcher. The acoustic deformation-potential parameter and the coupling coefficient for interband scattering were calculated by fitting the theory to Hall-mobility data for both pure and doped samples. We have determined ionized-impurity and space-charge contributions for two of our samples, one doped with Cr and exhibiting an 0.33-eV activation energy ($\text{Cr}^{4+}/\text{Cr}^{3+}$), and the other heat-treated and exhibiting an 0.14-eV activation energy. The transport fit was carried out self-consistently with a statistical fit of the p vs T data, to determine the relevant donor and acceptor concentrations. Individual plots of the mobility contributions from the various scattering mechanisms are also presented. Finally, useful plots of the Hall mobility and Hall r factor, as functions of carrier density and compensation ratio, are provided to aid others in the analysis of their samples. An important conclusion of this study is that the light-hole band strongly influences the transport properties, even though its density of states is small compared to that of the heavy-hole band.

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I. INTRODUCTION

Chromium-doped GaAs is important as a semi-insulating (SI) substrate material for several GaAs devices.¹ The relevant *acceptor* transition for the SI material is $\text{Cr}^{3+}/\text{Cr}^{2+}$, which has a room-temperature level near $E_v + 0.74$ eV.² If, however, the shallow acceptors outnumber the shallow donors, i.e., $N_{\text{AS}} > N_{\text{DS}}$, but also $N_{\text{DS}} + N_{\text{Cr}} > N_{\text{AS}}$, then the Fermi level will lie near the Cr *donor* transition, namely, $\text{Cr}^{4+}/\text{Cr}^{3+}$, where $E(4 + 1/3 +) \simeq E_v + 0.28$ eV, at room temperature.³ (See Ref. 3 for an explanation of the notation Cr^{n+} .) The latter transition lies well within the range for good temperature-dependent Hall-effect (TDH) measurements in GaAs, which is about 0–0.4 eV. (For energies much above 0.4 eV, intrinsic conduction often obscures the high temperature portion of the TDH curves.) Recently, the $\text{Cr}^{4+}/\text{Cr}^{3+}$ hole excitation was studied in some detail,³ but under the assumption of a unity Hall factor r . However, because of the importance of this problem, it seemed worthwhile to carry out a calculation of r for this set of data, and determine how much the deduced concentration and energy changed. To our knowledge, such a calculation has not been carried out for any actual data in p -type GaAs.

Another hole transition energy of some importance occurs in heat-treated GaAs, for which a TDH activation energy near 0.1 eV is often found after the heat treatment.⁴ In this paper we also have deduced r from an analysis of the TDH data for a sample annealed at 550 °C in vacuum for 24 h.

It should be noted that the values of r depend upon the donor and acceptor concentrations, which in turn are determined by a p vs T fit, where p depends on r . Thus, the whole

process must be carried out self-consistently. Fortunately, only one or two iterations are necessary for convergence.

In order to get information about the above-mentioned impurity characteristics, we carried out the transport calculation to fit the experimental Hall coefficient R_H and conductivity σ data measured as a function of temperature. In reality, the complexity of the valence band structure requires a very detailed numerical calculation, which sometimes obscures the physical picture involved. Furthermore, a sufficiently precise band structure does not seem to be well established experimentally. In this case we have assumed parabolic and nonparabolic forms for heavy and light hole bands, respectively, and spherical constant-energy surfaces for both bands. However, corrections to the r variation due to band anisotropy,⁵ and the p -like symmetry effects⁶ were included in this calculation.

The analysis was carried out using the usual two-band transport calculation at low fields, i.e., R_H and σ were calculated for each band concerned and the results were combined using multiband equations.⁷ This method is valid when transport in each band can be described by a relaxation time and by a constant current density.⁷ In addition to the impurity characteristics, some of the important parameters, such as the acoustic deformation potential and coupling coefficient for interband scattering by optical phonons, are determined and discussed here.

II. EXPERIMENTAL RESULTS

One of the samples (781/9) was doped with Cr and the other (H550) was annealed at 550 °C for 24 h in a vacuum. These particular samples show rather low Hall mobilities,

FIG. 1. Variation of Hall coefficient R_H and conductivity σ with temperature; $\times$ and $+$, σ for samples H550 and 781/9, respectively; $\circ$ and $\square$, R_H for samples H550 and 781/9, respectively. Solid curves are from theoretical fit.

i.e., only about half the lattice-limited mobility at 296 °K. The Hall coefficient and conductivity were measured, using a Hall-bar configuration, from 140 to 660 °K for sample 781/9 and from 85 to 400 °K for H550, and the results are shown in Fig. 1. Temperatures were accurate to within 1%, and electric fields were held below 50 V/m. Other experimental conditions were typical for dc Hall-effect studies.

III. METHOD OF ANALYSIS

Some of the theories necessary for understanding the present analysis are briefly summarized here.

A simple nonparabolic Kane form⁸ was assumed for the light-hole band, i.e.,

$$E(k) = \frac{\hbar^2 k^2}{2m} + \frac{1}{2} \left[E_0^* - \left[E_0^{*2} + 2E_0^* \frac{\hbar^2 k^2}{m} \left(1 - \frac{m}{m_{l0}^*} \right) \right]^{1/2} \right]. \quad (1)$$

Here m_{l0}^* is the effective mass at the top of the band and may be expressed by

$$\frac{m}{m_{l0}^*} = 1 - \frac{4}{3} \frac{P^2}{E_0^*(T)}. \quad (2)$$

The temperature variation of the effective-mass band gap E_0^* has been previously discussed.⁹ The effective mass variation with energy is expressed by $m_l^* = \hbar^2 k / (dE/dk)$. For the heavy hole band we assumed spherical constant-energy surfaces and a parabolic band, and a temperature-independent effective mass. In the calculations below we will take $m_l^* = |m_l^*|$.

The carrier concentrations were calculated using

$$p_i = \frac{1}{3\pi^2 k_B T} \int k_i^3 \frac{\exp[(E - E_f)/k_B T]}{\{\exp[(E - E_f)/k_B T] + 1\}^2} dE, \quad (3)$$

where k_B is Boltzmann's constant, E_f is the Fermi energy, and i runs over the two hole bands. In Eq. (3), and Eqs. (6)–(14), the energies refer to holes.

The charge neutrality equation for sample 781/9 was assumed to have the form³

$$p = N_{AS} - N_{DS} - \frac{N_{Cr}}{1 + (g_1/g_0)e^{(-E_1 + E_f)/k_B T}}, \quad (4)$$

where $N_{DS}(N_{AS})$ is the concentration of all donors (acceptors) more than a few $k_B T$ above (below) the Fermi level, N_{Cr} is the Cr concentration, and E_1 is the energy relative to the valence band edge for the transition Cr^{4+} to Cr^{3+} . In Eqs. (4) and (5) below, the energies refer to electrons, following standard practice.

In the case of the heat-treated (and type-converted) sample H550, the neutrality condition is given by

$$p = N_{AS} - N_{DS} + \frac{N_A}{1 + (g_0/g_1)e^{(E_A - E_f)/k_B T}}, \quad (5)$$

where N_A is the conversion acceptor concentration and E_A is the activation energy. Here the degeneracies of the unoccupied (g_0) and occupied (g_1) states are unknown. The energy values in the above two equations were assumed to vary linearly with temperature, i.e., $E_T = E_{T0} - \alpha T$, where the subscript "T" denotes a general trap.

A relaxation time appropriate to polar optical-phonon scattering is given by

$$\tau_{op} = -2 \frac{P_3(E)}{e} \frac{\hbar k}{(dE/dk)}, \quad (6)$$

where $P_3(E)$ is calculated using the numerical method of Fletcher and Butcher.¹⁰ The factor 2 is required because p -type wave functions are used in place of the s -type functions, as discussed elsewhere.⁶

Acoustic mode scattering may be expressed by

$$\frac{1}{\tau_{ac}} = \frac{k_B T E_{ac}^2}{\pi \hbar^2 p u^2} \frac{k^2}{(dE/dk)}, \quad (7)$$

where E_{ac} is the deformation potential constant, and u is the averaged sound velocity. Note that for heavy holes, $k/(dE/dk) = m_h^*/\hbar^2$, a constant.

Conwell¹¹ has shown that nonpolar (deformation-potential) optical-mode scattering is given by

$$\frac{1}{\tau_{npo}} = \frac{\eta E_{ac}^2 \omega_0}{2\pi p u^2} \frac{1}{e^{\hbar \omega_0/k_B T} - 1} \times \left(\frac{k_+^2}{(dE/dk_+)} + e^{\hbar \omega_0/k_B T} \frac{k_-^2}{(dE/dk_-)} \right), \quad (8)$$

where E_{npo} is the deformation potential for nonpolar optical-mode scattering, $\hbar \omega_0$ is the phonon energy, and $\eta = (E_{npo}/E_{ac})^2$. Here $k_{\pm}$ are defined by $E \pm \hbar \omega_0 = f(k_{\pm})$, where $f(k_{\pm})$ is the right-hand side of Eq. (1).

Piezoelectric scattering due to acoustic phonons has a relaxation time of the form¹²

$$\frac{1}{\tau_{pE}} = \frac{e^2 k_B T P_E^2}{2\pi\hbar\kappa_0\epsilon_0(dE/dk)}, \quad (9)$$

where P_E is the piezoelectric coefficient, and κ_0 is the low frequency dielectric constant. In the present calculation τ_{pE} was multiplied by a factor 2 to include p -type symmetry effects.¹³

Since the two valence bands are degenerate at $k = 0$, interband scattering is considered to be important, especially for the light holes. The combined inter- and intraband scattering due to the acoustic mode phonons may be expressed by Eqs. (7) and (8), if we simply replace $k^2/(dE/dk)$ by $k_l^2/(dE/dk_l) + k_h^2/(dE/dk_h)$, for both bands.¹³ The relaxation time due to interband scattering by optical phonons has the form¹⁴

$$\frac{1}{\tau_{ij0}} = \frac{D_{ij}^2}{2\pi\rho\omega_0} \frac{1}{e^{\hbar\omega_0/k_B T} - 1} \times \left(\frac{k_+^2}{(dE/dk_+)} + e^{\hbar\omega_0/k_B T} \frac{k_-^2}{(dE/dk_-)} \right), \quad (10)$$

where D_{ij} is the coupling constant for the scattering from band i to band j . Interband scattering due to the piezoelectric potential is not considered here because the basic mechanism itself is so weak.

The relevant relaxation time due to ionized-impurity scattering may be written in the conduction band as¹²

$$\frac{1}{\tau_I} = \frac{e^4 N_I}{8\pi\hbar^2 k^2 (\kappa_0\epsilon_0)^2 (dE/dk)} \ln\left(1 + \frac{4k^2}{\beta^2}\right), \quad (11)$$

with

$$\beta^2 = \frac{e^2}{\kappa_0\epsilon_0 k_B T} \left(\frac{k_B T}{\pi^2} \sum_i \int k_i^2 \frac{df_i(E)}{dE} dk_i + \frac{(N_A - N_D^- - p)(p + N_D^-)}{N_A} \right),$$

where N_I is the ionized-impurity density, N_A is the acceptor concentration, and N_D^- is the ionized donor concentration. τ_I was multiplied here by 1.5 for the same reason as that discussed for the polar optical-phonon scattering case.⁶ Interband transitions from ionized-impurity scatterings are considered to be rather improbable⁶ and are not included in our calculation.

Conwell and Vassel¹⁴ have shown that the relaxation time for space-charge scattering may be written as

$$\frac{1}{\tau_{sc}} = \frac{N_s Q_s}{\hbar} \frac{dE}{dk}, \quad (12)$$

where $N_s Q_s$ is the total effective scattering cross section. Overlap-integral corrections were not explicitly included for the acoustic mode, nonpolar optical mode, interband, and space-charge scattering mechanisms because the expressions for these mechanisms contain unknown parameters, such as E_{ac} , D_{ij} , N_I , and $N_s Q_s$, to be determined by the analysis. Thus, the deduced parameters are effective values, involving p -type symmetry effects, etc.

Using the various scattering mechanisms listed above, the conductivity for each band is given by

$$\sigma_i = \frac{e^2}{3\pi^2\hbar^2} \int k_i^2 \frac{df}{dE} \tau(E) \frac{dE}{dk_i} dE, \quad (13)$$

where

$$\tau(E) = \left\{ \sum_s 1/\tau_s(E) \right\}^{-1}.$$

Here s runs over all the scattering mechanisms concerned.

The Hall coefficient was calculated with the use of the expression,

$$R_{Hi} = \frac{1}{p_i e} r_{Ai} \frac{\int \tau_i^2(E) \frac{df}{dE} E^{3/2} dE}{\int \frac{df}{dE} E^{3/2} dE} \left/ \left[\frac{\left(\int \tau_i(E) \frac{df}{dE} E^{3/2} dE \right)^2}{\int \frac{df}{dE} E^{3/2} dE} \right] \right., \quad (14)$$

where r_A is the portion of the Hall factor which depends on both scattering anisotropy and anisotropy of the energy surface. The last term is the portion of the Hall factor due to

FIG. 2. Theoretical lattice-limited mobility values compared with experimental Hall mobility data for pure samples of Ref. 15; μ_H , Hall mobility; μ_{Dh} , drift mobility of heavy holes; μ_{Dl} , drift mobility of light holes.

scattering only. The calculated σ_i and R_{Hi} are combined by using the two-band equations and the results are fitted to the experimental data, using the adjustable parameters mentioned above. The resultant carrier concentration may be deduced from the Hall coefficient and the effective Hall factor by the relationship $r = peR_H$.

Experimental data for pure samples,¹⁵ as shown in Fig. 2, were analyzed in addition to the two samples discussed previously.

IV. RESULTS AND DISCUSSION

Tables I and II show the values of the parameters assumed or determined in the present analysis. By using these parameters, theoretical σ and R_H values are in good agreement with the corresponding experimental data for the whole temperature range, as shown in Fig. 1, except below ~ 120 °K for sample H550, where impurity-conduction effects are becoming important, and above 340 °K for the same sample, where a deeper acceptor is beginning to contribute.

The effective E_{ac} value 7.4 eV determined in this work is very high compared to the phenomenologically estimated value 3.5 eV.⁶ A similar large difference between the theoretical value and the value necessary to explain experimental data has also been found in the case of electron transport. For example, electron transport data analysis requires 16 eV,⁹ while the theoretical value is 8.6 eV.¹² Wiley and DiDomenico, Jr.¹⁹ have assumed unity for the Hall factor, and have used 5.3 eV for E_{ac} , in fitting their theory to experimental Hall-mobility data.

The D_{hl} value, 2.1×10^{11} eV m⁻¹, may be compared to that in the conduction band,⁹ 8×10^{10} eV m⁻¹, but no data on D_{hl} have been previously reported for the valence band. However, considering that we have neglected the additional complexity of the scattering calculation due to the real band structure, these two parameters must be considered phenomenological, and their absolute values judged accordingly.

In Fig. 2 the calculated μ_H values are compared with the experimental data for the samples known to be very pure.¹⁵ Impurity scattering effects are very small for low

TABLE I. Parameter values assumed in the present work.

E_g^* at 0 °K	1.519 eV ^a
m_h	0.475 m ^b
m_l at 0 °K	0.087 m ^b
u	3.9×10^3 m/sec ^c
ρ	5307 kg/m ^{3d}
κ_s	12.91 ^e
κ_∞	10.91 ^e
P^2	14.23 eV ^f
(E_{npo}/E_{ac})	1.89 ^e
$\hbar\omega_0$	0.0362 eV ^g
P_E	0.052 ^e
E_{ac}	7.4 ± 0.3 eV ^h
D_{hl}	$(2.1 \pm 0.1) \times 10^{11}$ eV m ^{-1h}
r_{Ah}	0.659 ^c
r_{Al}	0.996 ^c

^a Reference 16.

^b Reference 15.

^c Reference 6.

^d Reference 17.

^e Reference 12.

^f Calculated from E_g^* and m_l at 0 °K.

^g Reference 18.

^h This work.

carrier-density samples, even up to quite high impurity-compensation ratios, as can be seen from Fig. 6. Therefore, only the lattice-limited mobility was included in the data of Fig. 2. Except at very low temperatures, where impurity scattering would be dominant, the theoretically calculated lattice-limited mobility values are in good agreement with the experimental data. At room temperature, the carrier concentration ratio, p_l/p_h , is 0.078. The drift mobility values μ_{Dh} and μ_{Dl} were calculated to be 0.0144 and 0.076 m²/V sec for the heavy- and light-hole bands, respectively, considering lattice scattering only at this temperature. The corresponding Hall mobilities, μ_{Hh} and μ_{Hl} , are 0.013 and 0.106 m²/V sec, respectively, and the combined value of μ_H is 0.0402 m²/V sec, with an r value of 2.15. Similarly high r values have previously been observed in the conduction bands, at the band cross-over points in GaAs under a hydrostatic pressure of 3.3 GPa,^{20,21} and in Ga_{1-x}Al_xAs at $x = 0.37$.²²

TABLE II. Parameters deduced for Cr-doped GaAs sample 781/9, and heat treated GaAs sample H550, from (a) transport calculations and (b) statistical calculations. Error ranges quoted involve only precision of fit, and do not include theoretical approximations, etc.

(a) Transport calculations					
Sample	$N_{DS}(10^{21} \text{ m}^{-3})$	$N_{AS}(10^{22} \text{ m}^{-3})$	$QN(10^7 \text{ m}^{-1})$		
781/9	...	8.0 ± 0.7	0.85 ± 0.08		
H550	6.0 ± 0.5	...	5.2 ± 0.5		
(b) Statistical calculations (subscript "T" denotes center of interest)					
Sample	$N_T(10^{23} \text{ m}^{-3})$	$N_{AS} - N_{DS}(10^{22} \text{ m}^{-3})$	$E_{TO} - E_V(\text{eV})$	$(g_1/g_0) \exp(\alpha/k)$	$\alpha(10^{-4} \text{ eV}/^\circ\text{K})$
781/9	1.8 ± 0.1	8.9 ± 0.4	0.329 ± 0.003	21 ± 3^a	2.4 ± 0.1^b
781/9($r = 1$)	0.9 ± 0.1	5.6 ± 0.5	0.324 ± 0.002	6 ± 2^a	1.4 ± 0.3^b
H550	0.16 ± 0.01	-0.62 ± 0.09	0.139 ± 0.001	0.21 ± 0.05^a	-0.1 ± 0.3^c

^a Assuming density of states, $N_V = 1.7 \times 10^{21} \text{ T}^{3/2} \text{ m}^{-3} \text{ } ^\circ\text{K}^{3/2}$.

^b Assuming $g_1/g_0 = 4/3$.

^c Assuming $g_1/g_0 = 1/4$.

The present samples have low carrier densities and yet show low mobilities; thus impurity scattering is expected to be dominant. Bulk-grown crystals often show space-charge scattering, especially in crystals with low carrier concentrations.^{14,23} We thus have considered ionized-impurity and space charge as the impurity-scattering mechanisms for the two samples. For sample 781/9, N_I was assumed to have the form $N_I = 2N_{AS} - p$. Here N_{AS} is the concentration of shallow acceptors, which compensate donors (including Cr donors in this case, i.e., $\text{Cr}^{3+} \rightarrow \text{Cr}^{4+}$). For sample H550, we assumed $N_I = 2N_{DS} + p$, where N_{DS} is the compensating donor concentration. The values of N_{AS} and N_{DS} as well as the $N_s Q_s$ values are shown in Table II(a). The quoted errors reflect the uncertainties in finding the proper mix of these two scattering mechanisms in the given temperature ranges. Space-charge scattering is predominant for the unintentionally-doped sample H550.

To illustrate the relative importance of the various scattering mechanisms, drift-mobility values for each band are calculated for sample 781/9 and shown in Figs. 3 and 4. Except at low temperatures where impurity scattering prevails, the dominant scattering mechanisms for both bands are those due to deformation-potential acoustic and optical

FIG. 3. Variation with temperature of the calculated drift mobility values corresponding to the separate scattering mechanisms in the heavy-hole band, for sample 781/9; μ_{Dh} , combined; μ_{npo} , nonpolar optical; μ_{ac} , acoustic; μ_{hlo} , interband optical; μ_{po} , polar optical; μ_{pe} , piezoelectric; μ_I , ionized impurity; μ_{sc} , space charge.

FIG. 4. Variation with temperature of the calculated drift mobility values corresponding to the separate scattering mechanisms in the light-hole band for sample 781/9; notations are the same as those in Fig. 3.

phonons (through intraband and interband scattering for the heavy holes and light holes, respectively). Interband scattering into the splitoff band was also included in the analysis, but found to be negligible for both bands. In fact, the splitoff band is far below the other two valence bands and thus the carrier concentration in this band is $\leq 0.04\%$ of the total concentration, even at 660 °K, the maximum temperature of measurement.

Figure 5 shows the Hall-factor variation with temperature determined for the two cases in this work. The values for the heavy holes are lower than unity for the whole temperature range, because of the anisotropy effect. For light holes, on the other hand, the Hall factor ranges from 1.06 to 1.42. However, the effective Hall factor varies over a much wider range, 1.2–2.18, with temperature. A high value of r , 2.66, has been obtained by Gouskov *et al.*,²⁴ but they have considered only polar optical scattering. On the other hand, r values similar in magnitude to those discussed here have been reported for holes in Ge²⁵ and Si.^{25,26} The high effective r value is not due to any particular band, but is rather due to the presence of two-band conduction.

We have calculated μ_H and r as a function of impurity compensation $(N^+ + N^-)/p$ for a large range of carrier concentrations at room temperature, and the results are shown

FIG. 5. Hall factor variation with temperature for samples 781/9 (solid line) and those shown in Fig. 2 (dashed line): r , effective Hall factor; r_h , heavy hole; r_l , light hole.

in Fig. 6. It is noted that most of the common samples would have r values in the range 1.2–2.15, at room temperature. To see the effects of space charge, we have calculated r and μ_H for the case $N_s Q_s = 5 \times 10^8 \text{ m}^{-1}$, with no ionized impurity scattering; the results are also shown in Fig. 6. This $N_s Q_s$ value is similar to that of sample H550. It is noteworthy that the space-charge scattering is also very effective in reducing μ_H and r values for samples with low carrier density. Therefore, it would be difficult to identify the dominant impurity-scattering mechanism simply by looking at the room temperature value of μ_H ; a detailed transport analysis is needed.

From the above analysis, we have obtained the carrier

FIG. 6. Variations of Hall mobility and Hall factor with impurity concentration at room temperature; the parameters in the figures denote $(N^+ + N^-)/p$. Here N^+ and N^- are singly ionized donor and acceptor concentrations. Space-charge effects, calculated with $Q_s N_s = 5 \times 10^8 \text{ m}^{-1}$, are denoted by sc.

FIG. 7. Carrier density variations with temperature for samples 781/9 and H550.

density variation with temperature, and the results for the two samples are plotted in Fig. 7. The solid lines are theoretical fits to the relevant charge-balance expressions, Eqs. (4) and (5). The parameters obtained from these fits are shown in Table II(b). For sample H550, the points above 340 °K are influenced by a deeper acceptor, and the points below 115 °K are influenced by impurity conduction. Thus, only data between 115 and 340 °K were considered for the fit to Eq. (5) for sample H550. It is seen from Table I that, for sample 781/9, the value of N_{AS} determined from the transport fit is not much different from the value of $N_{AS} - N_{DS}$ deduced from the statistical fit. At face value, these data would suggest that $N_{DS} \ll N_{AS}$, which might seem reasonable since the Cr atoms would be competing with the common shallow donor Si atoms for the Ga sites. However, intercompensating effects between the scatterings due to ionized impurities and space charge, as mentioned earlier, and also the approximations in the transport theory itself, are large enough that any such conclusions would be very speculative. The same reasoning holds in a comparison of N_{DS} for sample H550, deduced from transport theory, with $N_{DS} - N_{AS}$ for that sample deduced from the statistical considerations.

Finally, we compare the previous statistical fit of the data for sample 781/9, which assumed that $r = 1$, with that obtained from the present study. As seen in Table II(b), the

$\text{Cr}^{4+}/\text{Cr}^{3+}$ energy at $T = 0$ has not changed significantly, but the temperature coefficient has. Thus, the old energy value (with $r = 1$) at 296 °K was 0.28 eV, while the present value is 0.26 eV. Also, the calculated Cr concentration has changed significantly, from $0.9 \times 10^{23} \text{ m}^{-3}$ to $1.8 \times 10^{23} \text{ m}^{-3}$, a factor two. However, the conclusions of the original study are not invalidated because, within error, the analytical measurements of the Cr concentration still agree with the electrical measurements.

The heat-treated sample H550 was originally n type, before the 550 °C anneal. The acceptor produced at 0.14 eV is in the energy region commonly observed for heat-treated GaAs crystals.^{4,27} Several impurities, including Cu, Ag, Au, Pb, Mn, and Co, are believed to produce acceptor centers within 0.05 eV of this energy,²⁸ and furthermore, in Ref. 27 it is argued that V_{Ga} -related states may exist in this region. Unfortunately, we were unable to carry out analytical measurements on this sample, which might have shed further light on the matter. Because of the importance of the conversion problem, however, detailed transport analyses are worthwhile in order to accurately determine the electrical parameters. Note, incidentally, that the temperature coefficient α is quite small for this sample if the degeneracy factor is given by the commonly assumed value, $g_1/g_0 = 1/4$. A small α is not inconsistent with the fact that the relevant energy is much closer to the valence band than the conduction band edge.

The reasonable agreement between the present transport calculation and the experimental data seems to justify the simplified analysis employed here, and the basic assumptions involved. A rather important conclusion is that the presence of the light hole band significantly effects the resultant transport parameter values, and thus cannot be neglected, even though the light hole concentration is only about 8% of the heavy-hole concentration. Therefore, the same detailed considerations used for the heavy-hole band must be applied to the light hole band. Some of the important parameters, such as the acoustic deformation potential and the coupling coefficient for the interband scattering, bear further study based on more sophisticated theoretical and experimental considerations.

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