tionality factors involved should have nearly the same magnitude. Taking into account the existence of a vacancy concentration factor in $\kappa(D)$, not present in $\kappa(r^2)$, we found the ratio

$$\Gamma_{\mathrm{FM}}/\Gamma_{\mathrm{EX}} \simeq \kappa(D)/\kappa(r^2) = 3.6 \qquad (9)$$

was constant on the interval $0.8 \leq \phi/\phi_c \leq 2$. This calculation was based on Girifalco's theoretical expressions for tracer diffusion coefficients and the vacancy concentration in ordered and disordered β brass. The result shown in Eq. (9) was determined using his numerical results for the diffusion of Cu. As was stated before, Girifalco's theory is in excellent agreement with the data of Kuper *et al.* This rough approximation suggests that no gross difference between the two jump frequencies exists, and that the Flinn-McManus method gives the correct ratio of jump frequencies for two different temperatures.

As shown here, the type of results one can obtain from a computer simulation experiment are clearly of interest in the study of transient states. However, these results cannot be fully utilized without knowing the associated absolute time scale. A sampling method in which an absolute time scale could be defined would be very useful in general kinetics studies of systems involving the migration of two or more interacting species in a crystal. In an *operational* sense, however, this method should be no more complicated than the Flinn-McManus sampling method, in order to be a practicable method with respect to present day computers. An enormous number of sampling events must be performed in a full-scale simulation. The present study, for example, constitutes a meager beginning in kinetic process simulation of order-disorder transitions. One really needs to follow at least 10^6 jumps per vacancy in order to describe a sufficiently large part of the vacancy lifetime for the results to be immediately useful in the design and interpretation of experiments.

ACKNOWLEDGMENTS

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Electron and Phonon Scattering in GaAs at High Temperatures

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The electrical resistivity ρ, the Seebeck coefficient Q, and the thermal conductivity κ, were measured in a series of GaAs samples in the temperature range 300–900°K. Values of Q were combined with room-temperature values of the Hall coefficient in order to derive the relative weights of the polar scattering ($\tau \sim E^r$, $0 \leqslant r \leqslant 0.5$) and the ionized-impurity scattering ($\tau \sim E^{3/2}$) in a self-consistent manner. The partial mobilities μ_P (polar mobility) and μ_I (ionized-impurity mobility) were then derived from the measured ρ. The Brooks-Herring formula for μ_I was found to overestimate screening effects. The temperature dependencies of these mobilities were $\mu_P \sim T^{-2.3}$ and $\mu_I \sim T^{3/2}$. Knowledge of the Fermi levels and of the degree of "mixing" of the two scattering mechanisms made it possible to assess exactly the electronic contributions to κ. It was found that $\kappa_{\mathrm{lattice}}$ was proportional to $T^{-1.25}$, and that it decreased as the free-carrier concentrations in the samples increased, thus showing the influence of scattering of phonons by electrons. The value of $\kappa_{\mathrm{lattice}}$ at the Debye temperature in the undoped material is used to confirm the contribution due to scattering of acoustical by optical phonons.

I. INTRODUCTION

THE electric[1–3] and thermoelectric[4–6] properties of GaAs at elevated temperatures have been measured by many investigators. Measurements of thermal conductivity, on the other hand, have been reported for room temperature[7–11] and below[10–12]; and there is only a single reference to their extension to elevated

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temperatures.[13] The present study was undertaken to extend the previous measurements to higher temperatures and to relate the results to the type and concentrations of charge carriers.

Measurements of the Hall and Seebeck coefficients are used in order to derive, in a self-consistent way,[14] the effects of both polar and ionized-impurity scattering as well as the positions of the Fermi levels. This makes it possible to determine the Lorentz number and the ratio of polar to ionized-impurity mobilities. The measurements of the electrical resistivity are then used to calculate the absolute values of the polar and ionized-impurity mobilities and also the electronic contributions to the thermal conductivity. The resulting values of the lattice thermal conductivities are shown to indicate the effects of two scattering mechanisms which had been seen in previous work: acoustical phonon-optical phonon scattering,[15,16] and phonon-electron scattering.[17,18]

II. THEORY

The most important[19,20] electron-scattering mechanism in undoped polar semiconductors, and even their alloys,[21] is the scattering of the electrons (or holes) by the polar optical modes of the lattice vibrations. This has been shown to be the case near room temperature as well as at elevated temperatures.[16] When the polar semiconductors are doped, then the effects of electron scattering by the ionized impurities have to be added to those[21,22] due to the polar modes.

The scattering by ionized impurities can be represented by a relaxation time of the form[23]

$$\tau_I = C_I \eta^{3/2}, \tag{1a}$$

where η is the carriers' reduced energy in units of kT, and

$$C_I = \frac{(2m^*)^{1/2}\epsilon^2(kT)^{3/2}}{\pi N_I e^4 \alpha}. \tag{1b}$$

If one ignores the effects of screening of the ionized scattering centers by the free carriers (as was done by Conwell and Weisskopf[23]), then

$$\alpha = \ln\left[1+\left(\frac{3\epsilon kT}{e^2 N_I^{1/3}}\right)^2\right]. \tag{1c}$$

If the effect of screening is taken into account (as was done by Brooks and by Herring[23]), then the scattering is reduced and

$$\alpha = \ln(1+b) - b/(1+b),$$

where

$$b = \frac{24\pi\epsilon m^*(kT)^2}{ne^2h^2}. \tag{1d}$$

Here m^* is the effective mass, ϵ is the dielectric constant, and N_I and n are the concentrations of the ionized impurities and the carriers, respectively. The relaxation time of Eq. (1) is valid up to moderately high levels of doping.

The polar interaction between the carriers and the longitudinal optical modes cannot generally be represented in terms of a relaxation time, because the changes effected in the carriers' energies are not small in comparison with their total energy prior to collision.[24–26] However, Ehrenreich[2] found that when $T \geqslant \theta_l$, where θ_l is the Debye temperature for the longitudinal-optical phonons, then a relaxation time of the form

$$\tau_P = C_P \eta^{r(T)}, \tag{2a}$$

can be fitted to the variational solution of the transport equation for the mobility, the Hall and the Seebeck coefficients. Ehrenreich calculated the parameter r as a function of the reduced temperature, T/θ_l, and found that it varies from $r=0$ at $T=\theta_l$ to $r=0.5$ when $T \gg \theta_l$. He also determined the energy-independent coefficient of Eq. (2a) to be

$$C_P = \left(\frac{T}{\theta_l}\right)^r \left[v_a M (2\pi k\theta_l)^{5/2} / (4\pi(2m^*)^{1/2} e^2 e^{*2} kT)\right] \times \left[(e^{\theta_l/T}-1)\frac{T}{\theta_l}\right], \tag{2b}$$

where v_a is the volume of the unit cell, M is the reduced atomic mass and e^* is the effective ionic charge.

We assume that the reciprocal of the total relaxation time is given as the sum of the reciprocals of the relaxation times in Eqs. (1) and (2), which are taken to be independent of each other:

$$\tau^{-1} = (C_I \eta^{3/2})^{-1} + (C_P \eta^r)^{-1}. \tag{3}$$

Here C_I and C_P are energy-independent adjustable parameters which are calculated from the experimental data. Subsequently, they are compared to C_I and C_P of Eqs. (1) and (2). When the energy bands are spherical, then the various transport coefficients for low magnetic fields can be expressed in terms of integrals of the form[23]

$$K_\nu = \frac{4(kT)^\nu}{3m^*} \int_0^\infty \mathfrak{N}(\eta)\tau\eta^\nu \frac{\partial f_0}{\partial \eta} d\eta, \tag{4}$$

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where $\mathfrak{N}(\eta)$ is the density-of-states and f_0 is the Fermi-Dirac distribution function.

The electrical conductivity is

$$\sigma = ne\mu_c = e^2 K_1 , \tag{5}$$

where μ_c is defined as the conductivity mobility, and n is the carrier concentration.

$$n = \frac{4}{\sqrt{\pi}} \left(\frac{2\pi m^* kT}{h^2} \right)^{3/2} F_{1/2}(\eta^*) . \tag{6}$$

Here F is a Fermi integral and η^* is the reduced Fermi level in units of kT. The Seebeck coefficient is

$$Q = \mp (k/e)(-\eta^* + B) , \tag{7a}$$

in which B is a parameter which is a function of the Fermi level and of the energy dependence of the scattering:

$$B = (1/kT)(K_2/K_1) . \tag{7b}$$

The Lorentz number is

$$L_0 \equiv \left(\frac{k}{e} \right)^2 A = \left(\frac{k}{e} \right)^2 \left[\frac{1}{(kT)^2} \frac{K_3}{K_1} - B^2 \right] , \tag{8}$$

and the zero-field Hall coefficient is

$$R_H = \mathfrak{r}_H \frac{1}{nec} , \tag{9a}$$

in which

$$\mathfrak{r}_H = \frac{n}{m^* c} \frac{K_1''}{K_1^2} . \tag{9b}$$

The coefficient $\mathfrak{r}_H$ is the ratio of the Hall mobility, defined as $R_H\sigma$, to the conductivity mobility μ_c; c is the velocity of light and K_1'' is the integral K_1 in which τ^2 has been inserted instead of τ.

The equations listed above provide the basis for evaluating the various transport coefficients in terms of C_I, C_P, and η^*. However, since C_I and C_P each vary from zero to infinity, it is convenient to introduce another variable q, which would vary only from zero to one:

$$q = \mu_P / (\mu_P + \mu_I) , \tag{10}$$

in which

$$\mu_I = \frac{6e}{m^*} C_I \frac{F_2}{F_{1/2}} , \quad \mu_P = \frac{2e}{m^*} C_P \frac{(\frac{3}{2}+r) F_{\frac{1}{2}+r}}{F_{1/2}} . \tag{11}$$

Here μ_I and μ_P are the partial mobilities which are determined by ionized-impurity scattering and by polar scattering, respectively. The relation between the coefficients C_I and C_P and the parameter q is

$$C_P/C_I = \frac{q}{1-q} \frac{3F_2}{(\frac{3}{2}+r) F_{\frac{1}{2}+r}} . \tag{12}$$

When the scattering is due solely to ionized impurities, then $q = 1$ and C_P/C_I goes to infinity; when it is due solely to polar modes, then $q = 0$ and $C_P/C_I = 0$.

The Seebeck coefficient, the Hall coefficient and the Lorentz number depend only on the ratio C_P/C_I (or q), and on η^*; they are functions of the energy dependence of the relaxation time but not of its absolute value. The conductivity mobility, on the other hand, depends on the absolute values of C_I and C_P as well as on η^*. Since the coefficient r is known[2] at all values of T/θ_l, measurements of R_H and of Q on a single sample are sufficient to determine q and η^* uniquely; this, then, also fixes the value of the Lorentz number, and also enables us to convert the Hall mobility to the conductivity mobility. We can proceed to deduce the absolute values of μ_P and μ_I in the following manner: Define μ_{11} by

$$\mu_{11}^{-1} = \mu_P^{-1} + \mu_I^{-1} . \tag{13}$$

Upon combining Eq. (13) with Eqs. (5) and (11), we deduce the ratio,

$$\mathfrak{F} \equiv \frac{\mu_c}{\mu_{11}} = \frac{2}{3} \left[\frac{1}{3C_I F_2} + \frac{1}{(\frac{3}{2}+r) C_P F_{\frac{1}{2}+r}} \right] \int_0^\infty \eta^{3/2} \tau \frac{\partial f_0}{\partial \eta} d\eta . \tag{14}$$

The ratio $\mathfrak{F}$ is a function of q and of η^*. Consequently, having determined q and η^* from measurements of R_H and of Q, we know the appropriate values of $\mathfrak{F}$. We are now able to derive the values of μ_{11} from μ_c, and thus determine the absolute values of μ_I and μ_P from Eqs. (10) and (13).

Thus, from measurements of R_H and of Q we derive q and η^* and determine the values of L_0 and of $\mathfrak{F}$. Using the measured electrical conductivity, we deduce the electronic thermal conductivity as well as μ_I and μ_P. The values of the coefficients C_I and C_P can then be derived according to Eq. (11). We have tabulated the various transport coefficients as functions of q and of η^* for various values of the parameter r. (These tables are available from the authors upon request.)

III. EXPERIMENTAL

The samples used in this study were cut from single-crystal ingots which had been grown by the horizontal Bridgman technique. The electrical resistivity ρ, the Seebeck coefficient Q, and the thermal diffusivity κ/c_p (wherein κ is the total thermal conductivity and c_p is the specific heat at constant pressure) were all measured on the same bar-shaped samples, 6×6×50 mm. The Hall coefficients were measured on thin bridge-shaped samples, which were cut from the same ingot, adjacent to the bar samples. The Seebeck coefficient and the thermal diffusivity were measured by an ac method which had been discussed in detail earlier.[27] The electrical resistivity was measured on the same sample, *in situ*, by a standard potentiometric dc method. The

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Table I. Measured electrical properties of GaAs samples.

Sample	Doping	Type	$R_H^{-1}\times10^{-17}$ (cm^{-3})		$\rho\times10^3$ (Ω cm)		$R_H/\rho\times10^{-3}$ (cm^2/V sec)		Q (μV/deg)	κ(W/cm deg)
			77°K	300°K	77°K	300°K	77°K	300°K	300°K	
1	Undoped	n	2.26	2.7	8.35	7	3.3	3.3	−310	0.435
2	Te	n	67.0	72.0	0.327	0.44	2.85	2.0	−80	0.400
3	Zn	p	300	540	1.48	2.1	0.14	0.055	+185	0.370
4	Undoped	n	0.42	0.50	38.4	31	3.9	4.0	···	0.445

manner in which the chromel-alumel thermocouples were mounted on the samples was described elsewhere.[28] In the present case, however, platinum-clad molybdenum wires were used for the probes and the thermocouple bases. The measurements were taken in vacuum of 5×10^{-6} Torr and better. The Seebeck coefficient measurements were not extended above 750°K, at which temperature the arsenic vapor pressure was sufficient[29] to cause rapid contamination of the thermocouples. Thermal diffusivity measurements were extended to 950°K. It was also found that when a sample's temperature was raised above 800°K, considerable changes took place in the room temperature values of ρ after cycling the temperature. This was attributed to annealing effects[30] which occurred at the high temperatures. Consequently, no values for ρ are given above 800°K.

The ac method of measuring the thermal diffusivity has many advantages[15,16,27,28] over direct methods of measuring thermal conductivity. However, in order to derive the thermal conductivity from values of the diffusivity one needs to know the specific heat c_p. Published values of c_p for GaAs do not extend above 273°K.[31] It was noted previously[15] that when the reduced specific heats c_p/c_{DP} are plotted as a function of the reduced temperature T/θ_D, then similar materials fall on a single curve; c_{DP} is the DuLong-Petit specific heat for the material (1.83 J/cm^3 deg for GaAs) and θ_D is the Debye temperature (344°K for GaAs[32]). Recently published data on InSb and[31,33] GaSb fall[34] on a curve represented by

$$c_p/c_{DP}=0.88+0.0675T/\theta_D, \quad \text{when} \quad T/\theta_D \gtrsim 1. \qquad (15)$$

We assume that the specific heat values for GaAs fall on the same curve. This has been confirmed experimentally.[35]

The electrical properties of the four samples used in the present study are listed in Table I. The increase in the value of R_H^{-1} from 77 to 300°K is not attributed to any change in the concentration of free carriers, but rather to the fact that, as the temperature is lowered, the relative importance of ionized impurity scattering is increased [see Eq. (1)]. This results in an increase of the coefficient $\mathfrak{r}_H$ [see Eq. (9)].

The measured values of the Seebeck coefficient for samples 1, 2, and 3 are shown in Fig. 1. For each of the three samples there are also drawn lines marked I and P, they represent the calculated values of Q for the cases of pure ionized-impurity and of pure polar scattering, respectively. We note that in all three cases the relative weight of the polar scattering in the measured values of Q increases with increasing temperature, whereas the relative weight of the ionized-impurity scattering decreases. This is due to the fact that polar scattering becomes stronger at higher temperatures

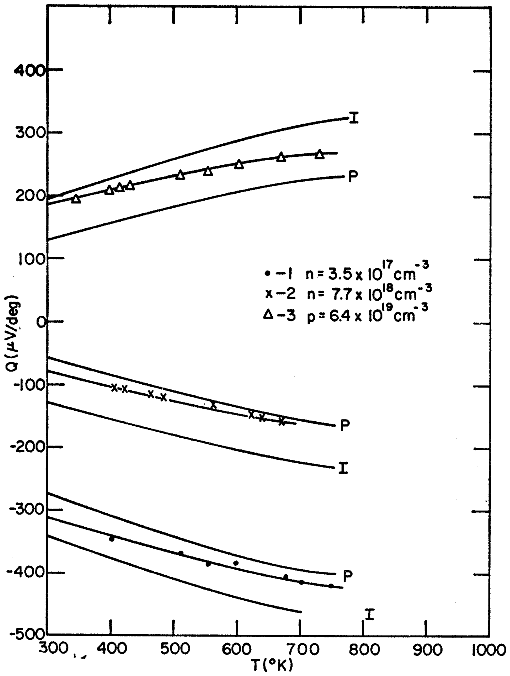

Fig. 1. The Seebeck coefficients of GaAs samples 1, 2, and 3 as functions of the temperature. Curves designated by P and I are the theoretical values of Q based on pure polar and ionized-impurity scattering, respectively.

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TABLE II. Derived electrical properties of GaAs samples at 300°K.

Sample	Doping	Type	$n\times10^{-17}$ (cm^{-3})	$\mu_c\times10^{-3}$ (cm^2/V sec)	κ_{lattice} (W/cm deg)	$\kappa_{\text{el}}\times10^2$ (W/cm deg)
1	Undoped	n	3.5	2.54	0.435	...
2	Te	n	76.5	1.88	0.385	1.53
3	Zn	p	640	0.046	0.367	0.307
4	Undoped	n	0.5	4.0	0.445	...

[Eq. (2)], while ionized-impurity scattering decreases as the temperature rises [Eq. (1)]. The electrical resistivities of the samples 1, 2, and 3 are shown in Fig. 2, which shows an increase with rising temperature. Sample 4 exhibited strong annealing effects when its temperature was raised, so that measurements of Q and of ρ on that samples are not reported. The thermal resistivities of all four samples are shown in Fig. 3. The reason for the behavior of the thermal resistivity of sample 4 is that, owing to its small carrier concentration, there was very little free-carrier absorption of radiation; and the photon contribution to the thermal conductivity (see below) was considerable. A much smaller contribution of the photons to thermal conductivity is seen in the case of sample 1, which has a higher carrier concentration than sample 4. In Fig. 3 are also included values of thermal conductivities near room temperature which have been reported in the literature; the agreement between those values and the results of the present work is satisfactory.

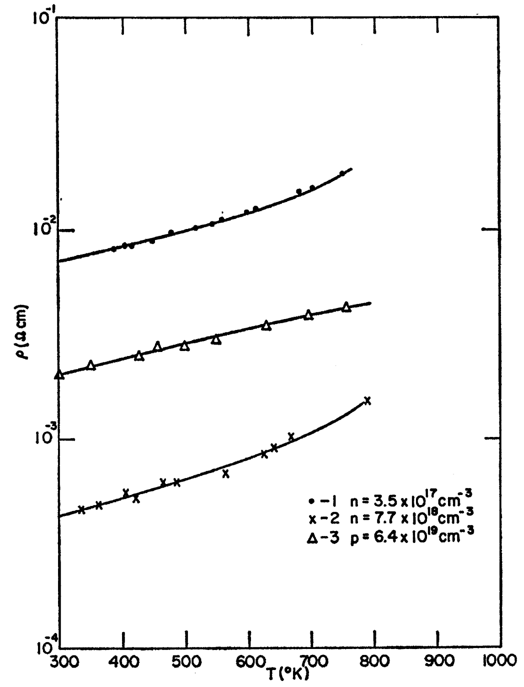

FIG. 2. The electrical resistivities of GaAs samples 1, 2, and 3 as functions of T.

IV. DISCUSSION OF RESULTS

The measurements of R_H and of Q at 300°K were analyzed in a self-consistent manner, as described in Sec. II. The effective masses for samples 1, 2, and 3 were taken to be 0.07 m_0, 0.083 m_0, and 0.7 m_0, respectively. The values for samples 1 and 3 are at the band edges,[22] whereas, in the case of sample 2 with its high doping,[36] the density-of-states effective mass was integrated from the band edge to the Fermi level. From the values of the reduced Fermi level η^* and the scattering parameter q [see Eqs. (7) and (9)] which were thus derived, it was possible to determine the carrier concentration, the conductivity mobility, the Lorentz number and the factor $\mathfrak{F}$ [Eq. (14)] at 300°K. Table II lists the values of the transport parameters at 300°K which were deduced from the measured R_H and Q.

It was assumed that in these three samples, the carrier concentrations at higher temperatures remain the same as at 300°K. Since all impurities are fully

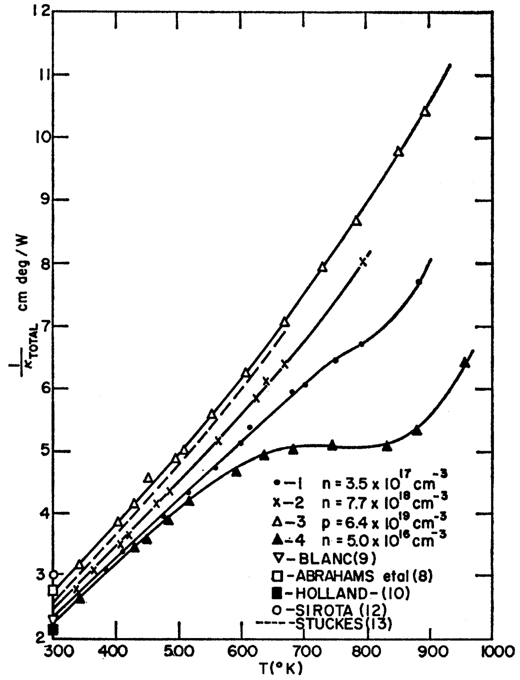

FIG. 3. The thermal resistivities of GaAs samples 1, 2, 3, and 4 as functions of T. Other workers' data included for comparison.

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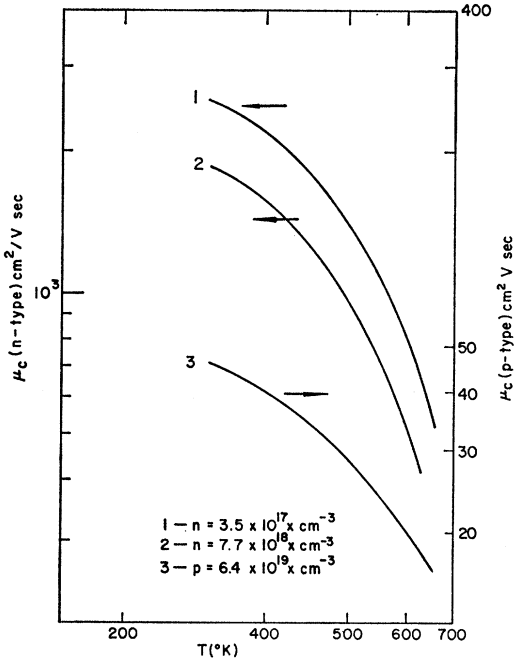

FIG. 4. The conductivity mobilities deduced for samples 1, 2, and 3 as functions of T.

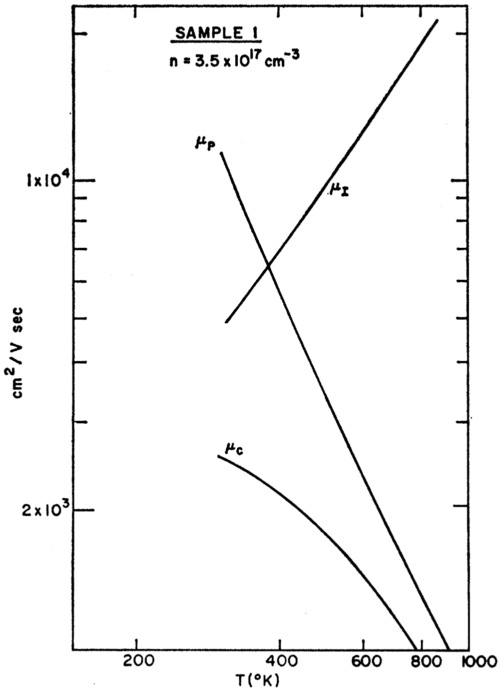

FIG. 5. The conductivity mobility of samples 1, together with the polar mobility μ_P and the ionized-impurity μ_I, as functions of T.

ionized at 300°K, and the intrinsic carrier concentrations remain completely negligible up to the highest temperatures reported, this is a valid assumption. Consequently, the temperature dependencies of the mobilities are inverse of those of the measured electrical resistivities. The conductivity mobilities of samples 1, 2, and 3 are shown in Fig. 4; these mobilities represent the combined effects of polar and ionized impurity scattering. Since it was assumed that the carrier concentrations remain constant, values of η^* at all temperatures could be deduced from Eq. (6); and the corresponding values of q were then derived according to Eq. (7). The appropriate values of the parameter r [Eq. (2a)] were calculated by Ehrenreich.[2] In the case of sample 1, which has the lowest carrier concentration, the deduced values of Q and η^* were then combined with the measured resistivity [see Eqs. (10), (13), and (14)] in order to derive the partial mobilities μ_P and μ_I. The conductivity mobility of sample 1 is shown in Fig. 5, together with the partial mobilities, polar (μ_P) and ionized-impurity (μ_I), which were derived from it. It is thus possible to compare the values of μ_P and μ_I at all temperatures and to note the temperature dependence of each. The partial mobilities deduced at 300°K are $\mu_P = 11\,500$ cm^2/V sec and $\mu_I = 4900$ cm^2/V sec. The value of μ_P is in fairly good agreement with that deduced by other workers,[37,38] but is higher than the theoretical value of 9300 cm^2/V sec.[22] The value deduced for μ_I is considerably lower than the theoretical value of 1.18×10^4 cm^2/V sec calculated according to the Brooks-Herring formula [see Eqs. (1) and (11)]. The dielectric constant used[39] was $\epsilon = 12.5$. It is difficult to find the reason for this discrepancy, because even if we take into account the theoretical polar mobility, this would increase the value of μ_I deduced from the experimental data by very little. It could be that the Brooks-Herring formula overestimates the amount of screening in polar semiconductors. The ionized-impurity mobility predicted by the Conwell-Weisskopf formula,[23] which neglects screening effects, is 6370 cm^2/V sec; this is in better agreement with our results. It could also be that the low[38] measured mobility is due to impurity compensation in the sample. The temperature dependence of μ_I deduced from our measurements is $\mu_I \sim T^{1.5}$, which is in good agreement with the predictions of the Brooks-Herring and the Conwell-Weisskopf formulas. The temperature dependence of μ_P is $\mu_P \sim T^{-2.3}$ over the range from 300 to about 900°K. This is a slightly steeper slope than that predicted from theory. The slope of μ_P should be determined by the slope of C_P of Eq. (2b):

$$C_P \sim T^r (e^{\theta_l/T} - 1) . \qquad (16)$$

The statistical factor in Eq. (11b) is almost temperature-independent. Near the optical Debye temperature,

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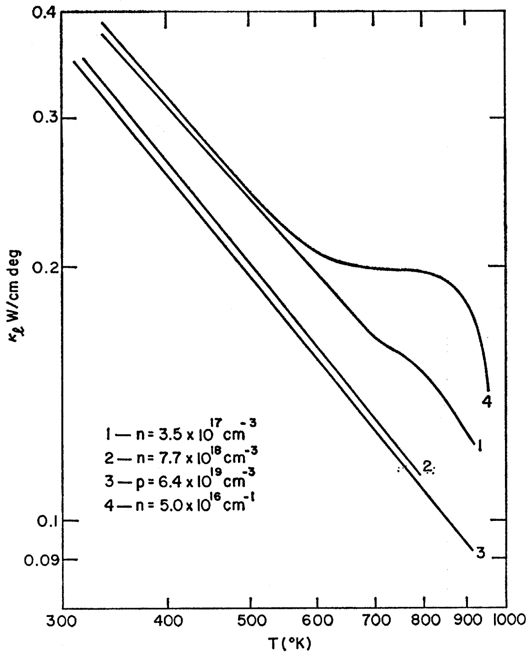

FIG. 6. The lattice thermal conductivities of samples 1, 2, 3, and 4 as functions of T.

where $r=0$, this yields a slope of T^{-x} where $+2>x>+1$. The slope should decrease with increasing temperature.

The electronic contributions to the total thermal conductivities of samples 1, 2, and 3 are given simply by the Lorentz contribution of a single type of carrier [see Eq. (8)]:

$$\kappa_{\mathrm{el}}=(k/e)^2 A_{p}^{n}\sigma_{p}^{n}T. \tag{17}$$

Owing to the high band gap of GaAs and to the amount of ionized impurities present in all three samples, the contributions of the free minority carriers as well as the ambipolar contributions[15] were negligible. The appropriate values of the parameter A have been calculated on the basis of Eq. (8). The values of the lattice thermal conductivities κ_l are shown in Fig. 6; they were obtained by subtracting the electronic contributions from the total conductivities.[40] The electronic contribution to the thermal conductivity of sample 4 was not computed, because the measurements of the electrical resistivity and the Seebeck effect showed severe annealing effects. However, from the rather high room-temperature electrical resistivity, it can be deduced that the electronic thermal conductivity is negligible; so that for this one sample, κ_l is the same as κ_{total}. The temperature dependency of the lattice thermal conductivities is $\kappa_l \sim T^{-1.25}$. This is a stronger temperature dependence than that predicted for three-phonon processes, and probably indicates the presence of higher order processes.[15]

The lattice thermal conductivity of sample 2 is smaller than that of sample 1, and the latter is smaller than sample 4. This decrease of κ_l due to increase in the concentration of free carriers was observed in other materials[17,18] and was attributed to scattering of phonons by electrons. A calculation of the increase in thermal resistivity due to the mass differences of the added dopant showed that in no case was it in excess of 1%. Above 600°K, the thermal conductivity of sample 4 exhibits a strong photon effect,[41] which had been observed in other lightly doped semiconductors of low-lattice thermal conductivity.[42] This effect represents the transport of heat through the crystal by radiation emanating from the hotter end. It contributes significantly to the thermal conductivity when the background of the lattice thermal conductivity is small, and when free-carrier absorption is absent. The effect of increased carrier concentration on the photon contribution is evident for sample 1. The increased free carrier absorption causes a reduction in the photon effect.

Leibfried and Schlömann[43] derived a theoretical expression for the lattice thermal conductivity, assuming only 3-phonon scattering. Using this expression it is possible[15] to derive from the experimental results of $\kappa_{\mathrm{lattice}}$, a reduced thermal conductivity or an effective anharmonicity parameter γ. The behavior of this anharmonicity parameter in the III-V compounds, as well as in Ge and Si, was found to reflect the effect of a significant contribution of optical-acoustical phonon-phonon scattering to the total thermal resistivity in some of these materials. The value $\gamma^2=0.98$ was derived for GaAs at $T=\theta_D$. The results for GaAs, therefore, suggest a considerable amount of optical-acoustical phonon-phonon scattering to be involved in this material.

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[40] There is some question about the relative importance of acoustical phonon as compared to polar scattering of the holes in the case of p-type GaAs. See, for example, O. V. Emel'yanenko, D. N. Nasledov, and P. V. Petrov, Fiz. Tverd. Tela **2**, 2455 (1960) [English transl.: Soviet Phys.—Solid State **2**, 2188 (1960)]; D. N. Nasledov, J. Appl. Phys. Suppl. **32**, 2140 (1961); also footnote 25 in Ref. 22. In the present work, the analysis of Q and R_H is a phenomenological one, and Eq. (3) is simply a trial function in which C_I and C_P are adjustable parameters. The assumption is that the ratio C_P/C_I (or q) determined from Q and R_H pertains to the Lorenz number as well.

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