Electron mobility in compensated GaAs and $Al_xGa_{1-x}As$

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The dependence of electron mobility μ on temperature T in GaAs and $Al_xGa_{1-x}As$ indicates that for compensated material a term having $\mu \propto T^{-1/2}$ causes a significant reduction in the mobility measured at high temperatures. The magnitude of the $T^{-1/2}$ term in mobility, denoted μ_{CA}, is found to be linearly proportional to the compensating acceptor concentration over a range' of more than two orders of magnitude in samples with no intentional doping where carbon is the major compensating acceptor. Intentional compensation using Ge and Zn is found to have no effect on μ_{CA}. Illumination ($h\nu > E_G$) has no effect on μ_{CA}. Such illumination is demonstrated to significantly reduce the size of space-charge layers at the *n-i* interface. Thus, the $T^{-1/2}$ mobility is *not* due to scattering by space-charge regions as has been previously assumed. The acceptor C, or an associate involving C, is concluded to be the scattering center responsible for μ_{CA}. The effect may be due to the short-range central-cell potential resulting from the large electronegativity difference between C and the As for which it substitutes in the lattice.

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I. INTRODUCTION

The low electron mobility measured at room temperature in some samples of GaAs and other semiconductors has remained a puzzle for over 20 years. The mobility calculated for ionized impurity and phonon scattering describes satisfactorily the mobility in high-purity relatively uncompensated samples.[1,2] However, particularly for highly compensated samples, the measured room-temperature mobility is considerably lower than calculated.[3-5]

Early workers invoked unspecified mobility "killer centers" to explain the reduced mobility. At relatively high temperatures, where ionized impurity scattering is negligible, the mobility limited by these killer centers was found to be proportional to T^{-n} where $\frac{1}{2} < n < 1$. Weisberg[3] proposed that an inhomogeneous distribution of either donors or acceptors would cause small *p*-type regions, each surrounded by a space-charge region, in otherwise *n*-type material. Such space-charge regions would be most likely to be formed in highly compensated material where $N_A \simeq N_D$.

Weisberg[3] showed that the mobility limited by scattering from these space-charge regions should indeed be proportional to $T^{-1/2}$, based on the idea that the local perturbation of the conduction band by the formation of the space-charge region could be thought of as forming impenetrable obstacles. Conwell and Vassel[6] later calculated the mobility to be

$$\mu_{SC} = \frac{2.4\times 10^9}{N_S Q (Tm^*/m_0)^{1/2}} \text{ (cm}^2\text{/V s)}, \qquad (1)$$

where $N_s Q$ is the density–cross-section product for the space-charge regions and m^* and m_0 represent the effective mass and free mass for electrons.

Many reports of such space-charge scattering have been made, based solely on the observation of the $T^{-1/2}$ dependence of mobility. Space-charge scattering has been invoked not only for GaAs, InAs, and InP,[3-5] but also for II/VI compounds such as CdTe, CdSe,[7-9] and also for SiC.[10]

Electron mobility has been studied in some detail for both high-purity and compensated GaAs and the closely related alloy $Al_xGa_{1-x}As$. Thus these results will be summarized in more detail. High-purity ($N_D + N_A \leqslant 10^{14}$ cm^{-3}) GaAs epitaxial layers can be grown by both liquid-phase epitaxial (LPE) and $AsCl_3$ vapor epitaxial (VPE) growth techniques. These yield room-temperature electron mobilities of ~ 9000 cm^2/V s and 77 K mobilities of 2×10^5 cm^2/V s.[11,12] However, in many samples of nominally undoped (hereafter referred to as simply undoped) GaAs grown from the melt,[13] by LPE[14] and by $AsCl_3$ VPE,[3,15] considerably lower 300 K mobilities are reported. In all cases the temperature dependence of mobility shows that the reduction is not due to ionized impurity scattering, which is proportional to $T^{3/2}$, but is due to a mechanism where $\mu \propto T^{-1/2}$. With no further evidence, the reduction in mobility was attributed to space-charge scattering. Katoda and Sugano[4] made the significant observation that the space-charge-scattering factor $N_s Q$ is proportional to the compensation, although Stringfellow[16] later showed that the results could better be understood as $N_s Q$ being proportional to N_A for both GaAs and $Al_xGa_{1-x}As$ in the direct band gap region ($x \leqslant 0.35$).

This brief introduction indicates that this scattering which results in $\mu \propto T^{-1/2} N_A^{-1}$ severely affects the electron mobility in compensated GaAs and $Al_xGa_{1-x}As$. Since the scattering mechanism has not been firmly established to be due to space-charge regions, this contribution to the mobility will be referred to here as μ_{CA}, the electron mobility due to the acceptors in compensated semiconductors.

This work will be devoted to developing a better understanding of the physical origin of μ_{CA}. In highly compensated samples of GaAs and $Al_xGa_{1-x}As$ grown by LPE, organometallic VPE (OMVPE), and molecular beam epitaxy (MBE), the temperature dependence of mobility will be reported. In addition, the effect of illumination ($h\nu > E_G$) on the temperature dependence of mobility will be described.

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TABLE I. Effect of illumination on the electron scattering in GaAs and $Al_xGa_{1-x}As$.

Run	Growth	Thickness			n(300 K)	Dark		Illuminated				
No.	technique	(μm)	x	Dopant	(cm^{-3})	$N_D + N_A$ (cm^{-3})	$\mu_{CA}^{-1} T^{-1/2}$ (V s/cm^2 K$^{1/2}$)	$\mu_{CA}^{-1} T^{-1/2}$ (V s/cm^2 K$^{1/2}$)	$(N_D + N_A)$ (cm^{-3})	λ (nm)	$\Delta t/t_d$ (77 K)	$2W_D/t_0$
1033A	MBE	1.8	0	Ge	1.46×10^{16}	1.30×10^{17}	1.19×10^{-5}	1.16×10^{-5}	1.15×10^{17}	800	0.25	0.28
M040	LPE	6.0	0	U	5.1×10^{15}	1.00×10^{16}	2.80×10^{-6}	2.80×10^{-6}	1.00×10^{16}	800	0.12	0.15
LS96	OMVPE	5.0	0.06	U	2.1×10^{16}	1.87×10^{17}	7.77×10^{-6}	7.77×10^{-6}	1.87×10^{17}	750	0	0.08
1401	MBE	1.5	0.25	U	7.5×10^{16}	5.30×10^{17}	1.24×10^{-5}	1.24×10^{-5}	5.00×10^{17}	650	0	0.15
LS147	OMVPE	2.0	0.35	U	1.47×10^{16}	3.70×10^{17}	1.83×10^{-5}	1.83×10^{-5}	3.20×10^{17}	650	0.26	0.25

Illumination would be expected to shrink the space-charge regions and hence cause a major increase in the mobility limited by space-charge scattering. In addition, the relationship between μ_{CA} and N_A over a large range of N_A will be reported. Finally, the results of an effort to identify the effects of various compensating acceptors on μ_{CA} will be presented.

II. EXPERIMENTAL

The GaAs and $Al_xGa_{1-x}As$ epitaxial layers studied were grown on Cr-doped semi-insulating GaAs substrates by LPE, OMVPE, and MBE techniques. The LPE samples (supplied by Bauser and Linnebach of the Max-Planck-Institut fur Festkorperforschung) were grown in a standard graphite apparatus from Ga-rich solution[17] at a substrate temperature of 760 °C. The OMVPE samples were grown in an SiO_2 cold-wall apparatus[18] with the substrate sitting on an rf-heated graphite pedestal at temperatures between 700 and 750 °C. The Ga, Al, and As were transported to the growing surface using volatile organometallic compounds $[Ga(CH_3)_3$ and $Al(CH_3)_3]$ and AsH_3, respectively. The growth was carried out in a flowing Pd-purified H_2 ambient.

The MBE GaAs samples were grown in an UHV apparatus without sample exchange interlock or cold shroud.[19] With this technique, molecular beams of Ga and As are directed from resistence-heated graphite containers onto the substrate held at between 520 and 620 °C. All samples were Ge doped from a third Ge oven. In Table I the growth conditions are listed along with the materials properties for important samples referred to in Sec. III.

Hall effect and conductivity measurements were performed on standard cloverleaf-shaped van der Pauw samples. Contacts were alloyed In or Sn balls. The measurements were performed at currents of between 10^{-4} and 10^{-6} A using a magnetic field of 5 kG. The samples were illuminated with monochromatic light with a very low intensity of $\leqslant 10^{13}$ photons /cm^2 s. The contacts were shielded from the light. The data were analyzed considering ionized impurity, polar optical, piezoelectric, deformation potential, and compensating acceptor scattering described in detail in Ref. 16 with N_A and the compensating acceptor scattering amplitude ($\mu_{CA}^{-1} T^{-1/2}$) used as adjustable parameters to give a best fit of the calculation to the experimental μ-vs-T data.

Photoluminescence (PL) was used to identify the acceptors in the GaAs[20] and $Al_xGa_{1-x}As$.[21] The measurements were performed with the sample immersed in liquid He at 2 K and irradiated with the 6471-Å line of a Kr laser focused to a spot of area $\sim 10^{-3}$ cm^2. The power was typically 1–10 mW. The PL was collected through a Spex monochromator with better than 1 Å resolution and detected using a cooled GaAs photocathode photomultiplier.

III. EXPERIMENTAL RESULTS

Several highly compensated specimens of GaAs and $Al_xGa_{1-x}As$ were chosen for the study of the effect of illumination on the compensating acceptor, CA, scattering. The important parameters for these specimens are shown in Table I. For MBE specimen 1033A the electron-mobility–vs–temperature data can be fit very well by the calculation which includes ionized impurity, polar optical phonon, piezoelectric, deformation potential, and CA scattering, as shown in Fig. 1. This sample is seen to be highly compensated, $(N_D + N_A)/(N_D - N_A)$ is determined to be 8.9, and CA scattering to be quite strong. Since $\mu_{CA} \propto T^{-1/2}$, it is convenient to indicate the magnitude of the scattering due to acceptors in the space-charge region as $S_{CA} = \mu_{CA}^{-1} T^{-1/2}$, which is tabulated in Table I.

Illumination at a wavelength of 800 nm is seen in Fig. 1 to cause a considerable increase in mobility at lower tem-

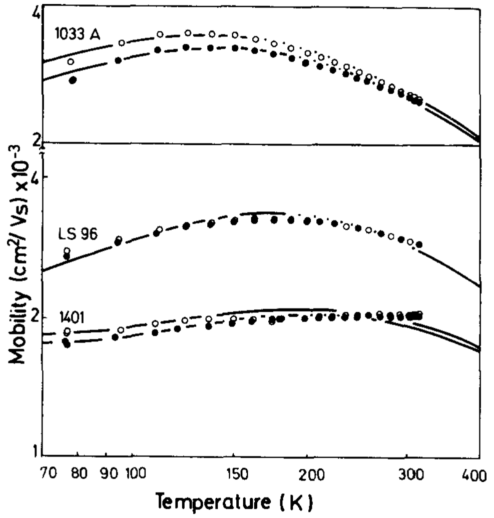

FIG. 1. Effect of illumination on the electron-mobility–vs–temperature behavior for three samples of GaAs and $Al_xGa_{1-x}As$ having a strong $T^{-1/2}$ component of mobility. Solid data points were measured in darkness and open points with illumination.

peratures but little change at higher temperatures. The values of $N_D + N_A$ and S_{CA} under illumination were determined by making a best fit of the calculated curve to the experimental data. The effect of illumination on ionized impurity scattering is already well documented.[22] The increase in mobility is due mostly to a combination of increased screening by the photoexcited carriers and to the neutralization of some of the acceptors by the movement of the quasi-Fermi level for holes. Since both effects are lumped into a change in the concentration of ionized impurities, $N_D + N_A$ is placed in parenthesis in Table I. Optical phonon scattering is not affected by illumination.[22] The most important observation is that S_{CA} does not change appreciably with illumination. The increase in mobility is due almost entirely to the decrease in ionized impurity scattering.

At these low excitation levels the concentration of photoexcited carriers in a homogeneous sample is rather low. Assuming $\tau \sim 10^{-9}$ s, $\Delta n \sim 10^{8}$ cm^{-3}. For n-i multilayer structures with a thin n layer, Queisser and Theodorou[23] found that the values of Δn can be somewhat larger than for a homogeneous sample. This effect is reflected in the results for 1033A where the n-layer thickness is 1.8 μm. The change in the ionized impurity scattering is much larger than expected for $\Delta n \sim 10^{8}$ cm^{-3}. For thicker specimens, such as M040 and LS96, the effect of the multilayer structure is small. Thus, as seen in Fig. 1 for LS96 the mobility even at low temperatures is affected very little by illumination. The values of $N_D + N_A$ and S_{CA}, as listed in Table I are both unaffected by illumination for these thick samples.

For the $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ samples 1401 and LS147, the compensation ratio is rather high and the results are the same; namely, the ionized impurity scattering is decreased slightly, but the magnitude of the CA scattering is absolutely unchanged. The $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ specimens are, of course, illuminated at shorter wavelengths (650–750 nm) to allow the production of hole-electron pairs.

Because we are interested in the effect of light on space-charge scattering, it is important to demonstrate the effect of light of the selected wavelengths and intensities on observable space-charge regions. Queisser and Theodorou[23] have demonstrated that the space-charge region produced at the interface between an n-type epitaxial layer and the semi-insulating substrate can be substantially altered by illumination. The change in the width of the space-charge layer induced by the illumination, which it should be noted has virtually no effect on μ_{CA}, is illustrated in Fig. 2 for the n-i structure 1033A. The measured quantity is the Hall effect voltage (V_H) which is inversely proportional to the product of carrier concentration, n, and the conducting layer thickness, t. The magnitude of the effect of illumination is conveniently expressed as the change in V_H^{-1} induced by illumination normalized by V_H^{-1} measured in the dark which may also be written $\Delta(nt)/(nt)_d$.

At low temperatures the effect is rather large for sample 1033A, with $\Delta(nt)/(nt)_d = 0.25$. This is approximately what would be expected if n remained unchanged and the space-charge layers at the top surface and at the interface, which act to decrease the thickness of the conducting layer,[24] were totally eliminated by the illumination. For $n = 1.5 \times 10^{16}$ cm^{-3} the combined widths of the two regions would be ~ 0.50 μm.[25] The values of twice the depletion layer width at zero bias divided by the metallurgical thickness of the epitaxial layer, t_0, are tabulated for comparison with $\Delta(nt)/(nt)_d$ in Table I. The conclusion that the effect of illumination is mainly due to the decrease in the space-charge layer width is in agreement with recent observations of Queisser and Theodorou.[23] For thick samples, the reduction of the space-charge width produces a smaller value of $\Delta t/t_0$ as seen in Table I. It is also observed that even for the relatively thin MBE sample 1401, no change in nt is observed. This could be caused by a large interfacial recombination velocity due to a poor substrate-epilayer interface.

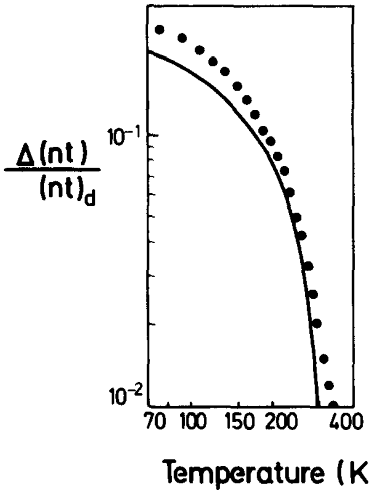

FIG. 2. Change in the product of n (cm^{-3}) and conducting layer thickness, t (cm), with illumination normalized by the value measured in darkness for sample 1033A. The solid line was calculated as described in the text.

The effect of light on the space-charge layer width is dramatically reduced with increasing temperature, as seen in Fig. 2. This data demonstrates a significant point. Namely, the hypothesis that μ_{CA} is due to space-charge scattering is not disproven by the observation of no change in the 300 K mobility with illumination. The size of the space-charge region changes very little with illumination at 300 K. We must examine the effect of illumination on mobility in the entire range from 77 to 300 K. From such an analysis it becomes clear that μ_{CA} could not be due to space-charge scattering, as will be discussed in more detail in Sec. IV.

The final topic to be presented in this section is the wavelength dependence of $\Delta\mu$ and Δt. For sample 1033A (GaAs), the band gap varies between 1.424 and 1.508 eV in the temperature range 300–77 K.[26] The photon energy of the illumination, 1.549 eV, is higher than the band-gap energy but is in the region where α is approximately[27] 10^4 cm^{-1} for the doping levels considered here. Thus the excitation is relatively uniform for 1–2-μm-thick epitaxial layers. For the $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ alloys the wavelengths of 650 nm ($x = 0.25$–0.35) and 750 nm ($x = 0.06$) were chosen to give $\alpha \simeq 10^4$ cm^{-1} between 77 and 300 K.

For several specimens the Hall effect and conductivity measurements were made at several wavelengths between 600 and 900 nm. The effects were qualitatively independent of wavelength, but the magnitude of $\Delta\mu$ and $\Delta(nt)$ changed. For $\lambda = 900$ nm, very few electron hole pairs are produced and both $\Delta\mu$ and $\Delta(nt)$ were observed to be small. At $\lambda = 800$ nm for the $Al_xGa_{1-x}As$ samples, significant electron-hole pair production occurs only in the substrate. In this case the measured effects of illumination were again very small. For $\lambda = 600$ nm only the surface of the epitaxial layers is excited. This increases the amount of surface recombination and hence reduces the magnitude of both $\Delta\mu$ and $\Delta(nt)$ somewhat. In general, the magnitudes of the two quantities $\Delta\mu$ and $\Delta(nt)$ scaled together as λ was changed. The effects were exactly the same for all wavelengths, namely, μ_{CA} was not affected by illumination. These results are conclusive evidence that the effects measured are not artifacts due to photoconductivity in the substrate. The excitation of the substrate is not significant because of the weak excitation intensity used.

IV. DISCUSSION OF RESULTS

A. Model of temperature dependence of μ_{SC} with illumination

The experimental results show quite clearly that illumination nearly eliminates space-charge regions at 77 K, but at higher temperature little change is observed. The effect of illumination on the electron mobility appears to be limited to a small increase in the ionized impurity limited mobility due to a combination of increased screening and a reduction in the concentration of ionized acceptors. By contrast, space-charge scattering is thought to be due to perturbations in the conduction band by the space-charge regions distributed throughout the sample. Photoexcited minority holes would be collected at these space-charge regions and excess electrons would be repelled. As the result, a field would be built up which would reduce the size of the space-charge region and the magnitude of the perturbation in the conduction band. Our data shows that the CA scattering is unchanged by illumination. This strongly suggests that space-charge scattering is *not* the mechanism for the component of the total mobility which is proportional to $T^{-1/2}$. However, the conclusion could be strengthened by modeling the complex temperature dependence of the space-charge width, using this to derive an expression for μ_{SC} versus T under illumination, and comparing the results with experimental data.

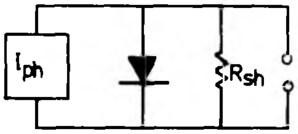

FIG. 3. Schematic diagram of the equivalent circuit for the solar-cell model of the open-circuit voltage induced in a *n-i* junction by illumination.

A first-order model for the effect of illumination on the space-charge layer width will be based on a model developed for solar cells. The space-charge layer width may be written

$$W = [2\epsilon_S(V_{bi} + V)/q(N_D - N_A)]^{1/2} \tag{2}$$

for n-type material with a potential V applied across the space-charge layer. V_{bi} is the built-in potential, ϵ_s is the low-frequency dielectric constant, and q is the electron charge. In the dark, W changes very little with temperature. The effect of light is to produce a voltage V which reduces the space-charge width. The simplest model to predict V versus temperature is the solar-cell model[28] for the open-circuit voltage illustrated in Fig. 3. We assume that every photon which enters the crystal produces an electron-hole pair which is then separated by the field, giving rise to a current J_{ph}. In the open-circuit condition this produces a forward voltage which at steady state produces an equal and opposite current. From the behavior of p-n junctions we know that the forward current has two components, given by[29]

$$J_{df} = J_S[\exp(qV/kT) - 1] + \tfrac{1}{2}qW\sigma N_r v_{th} n_i \exp(qV/2kT), \tag{3}$$

where

$$J_s \cong q(D_p/\tau_p)^{1/2} n_i \tag{4}$$

when $p_{n0} \ll n_{p0} \approx n_i$.

In these equations σ and N_r are the cross section and density of recombination centers in the space-charge region, v_{th} is the thermal velocity, n_i is the intrinsic carrier concentration, D_p and τ_p are the hole diffusion length and lifetime in n-type material, and p_{n0} and n_{p0} are the hole concentration on the n side and the electron concentration on the p side of the junction, respectively. Simplifying and taking $J_{df} = J_{ph}$ we obtain

$$J_{ph} = J_s[\exp(qV/kT) + K\exp(qV/2kT)], \tag{5}$$

where K is a constant for a given diode which determines the relative magnitude of the $2kT$ recombination current compared with the $1kT$ ideal diode current. Since we do not know the parameters for the recombination centers, the value of K is adjusted to fit the experimental data. Equation (5) can be solved at a given light intensity to yield V versus temperature. Using Eq. (2) we can easily calculate $W(T)$, which can then be used to calculate $\Delta t/t_d$:

$$\Delta t/t_d = [(t_0 - W_l) - (t_0 - W_d)](t_0 - W_d)^{-1}, \tag{6}$$

where the subscripts l and d refer to the space-charge layer width with and without illumination.

The calculation is performed using parameters for sample 1033A. V_{bi} is taken to be $\frac{1}{2}E_G$ for the n-i junction considered here, with[26]

$$E_G = 1.519 - 5.405\times10^{-4}T^2(204 + T)^{-1}. \tag{7}$$

The value of n_i is calculated from

$$n_i = 4.9\times10^{15}(m_e^* m_h^*)^{3/4}T^{3/2}\exp\left(-\frac{E_G}{2kT}\right). \tag{8}$$

The calculated dependence of $\Delta t/t_0$ is compared with the experimental data in Fig. 2. This simple theory gives a good explanation of the temperature dependence of the space-charge width. The value of 16 000 for K seems reasonable, being equivalent to a current of 2.6×10^{-9} A at which the $1kT$ and $2kT$ currents are equal. The physical significance of K could also be thought of in terms of the density of recombination centers N_r, which for $K = 16\,000$ would be $\sim10^{16}$ cm^{-3} for $\sigma = 10^{-14}$ cm^2.

We have now a simple model describing the size of a space-charge region under illumination versus T. This sim-

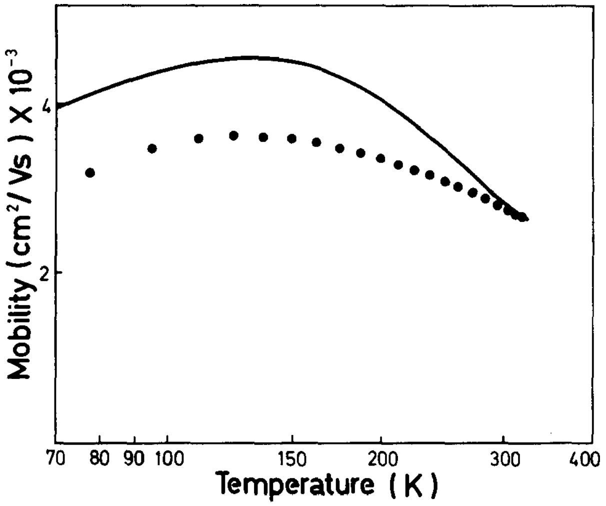

FIG. 4. Mobility, with illumination at $\lambda = 800$ nm, versus temperature for sample 1033A. The solid line was calculated using the model described in the text for the temperature dependence of scattering from space-charge regions during illumination.

ple model can be used to calculate μ_{SC} versus T under illumination. The effect of light would be to reduce both the spatial extent and the magnitude of the conduction band fluctuation caused by the space-charge region. The calculation underestimates the effect of light by considering only the change in size of the space-charge region. Since the scattering cross section would be proportional to W^2, we can calculate the ratio of mobilities with and without illumination from Eq. (2):

$$\mu_l/\mu_d = [1 - 2V(T)/E_G(T)]^{-1}. \qquad (9)$$

The calculated mobility during illumination, μ_l, is plotted versus temperature for sample 1033A for comparison with the experimental data in Fig. 4. $N_D + N_A$ was taken to be 1.15×10^{17} cm^{-3} and the density–cross-section product, $N_s Q$, as 1.08×10^5 cm^{-1} (equivalent to $S_{\rm CA}$ of 1.16×10^{-5}V s/cm^2 K$^{1/2}$, the value obtained from the dark mobility). It is seen that the predicted temperature dependence of the space-charge scattering limited mobility with illumination is very different from the experimentally observed behavior. This contrasts sharply with the excellent fit to the same data, shown in Fig. 1, obtained by taking $\mu_{\rm CA}$ to be unchanged by illumination. It is now very clear that the experimental data cannot be consistent with the idea that the $T^{-1/2}$ term in mobility is due to space-charge scattering.

B. $\mu_{\rm CA}$ versus acceptor concentration

Data have recently become available which make worthwhile a reexamination of the magnitude of the scattering due to acceptors in compensated n-type GaAs and $\rm Al_x Ga_{1-x} As$. Chandra and Eastman[30] obtained low-N_A $\rm Al_x Ga_{1-x} As$ by LPE growth at 700 °C, considerably lower than the temperatures commonly used. From a careful study of electron mobility versus temperature they find that the $\mu \propto T^{-1/2}$ term must be included to explain their data. They believe the $T^{-1/2}$ term may be due to alloy scattering, though this requires the effect to be ~ 10 times larger than expected. Their data can also be interpreted to indicate that CA scattering is dominant at low x. On this basis we have used their data for $x < 0.1$ to obtain values of $\mu_{\rm CA}^{-1} T^{-1/2}$ which are plotted in Fig. 5 along with other data from the literature for undoped GaAs and $\rm Al_x Ga_{1-x} As$. It can be seen that $S_{\rm CA}$ is a linear function of N_A over a range of two orders of magnitude for nonintentionally doped samples.

Low-temperature photoluminescence studies of Ashen *et al.*[20] indicate that for undoped LPE GaAs, C is the major shallow acceptor. In $\rm Al_x Ga_{1-x} As$, grown by either LPE or OMVPE, Stringfellow[21] has shown that C is the only shallow acceptor observed using PL. OMVPE GaAs also contains only carbon.[21] Thus for the data for undoped GaAs and $\rm Al_x Ga_{1-x} As$ plotted in Fig. 5, C is the major shallow impurity. Therefore, we conclude that the value of $S_{\rm CA}$ is linearly related to the *carbon* concentration. The reason for the very low values of N_A and $S_{\rm CA}$ observed by Chandra and Eastman[30] is probably due to the reduced carbon solubility at the lower growth temperature.[31] In fact, PL measurements show a single weak conduction band to acceptor peak due to carbon, thus carbon is the *only* shallow acceptor present in this material and that its concentration is low.[32]

Samples of GaAs doped with acceptors other than C seem to behave differently. Included in Fig. 5 are data for Ge-doped MBE GaAs. The values of $S_{\rm CA}$ are somewhat lower than expected based on N_A. In fact, PL results indicate that both C and Ge are present. The C concentrations are approximately consistent with the observed values of $S_{\rm CA}$, i.e., C is in the $(1-2)\times10^{16}$-cm^{-3} range.[33] To gain additional data on this important point LPE GaAs specimens were grown doped with the donor Sn and the acceptor Ge to pro-

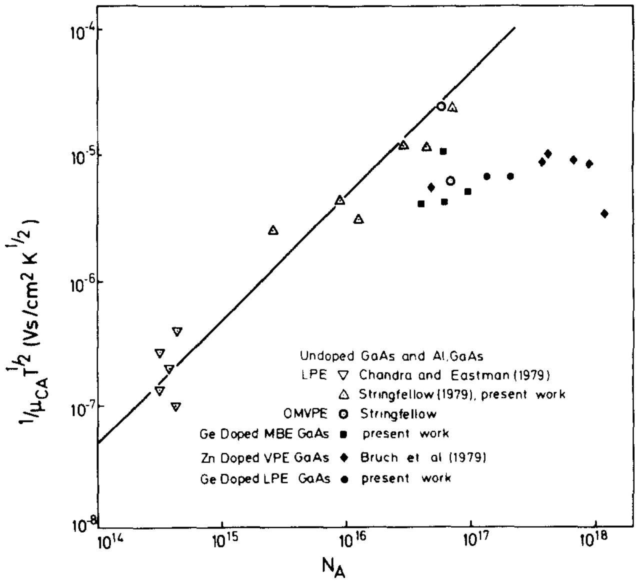

FIG. 5. Magnitude of the electron scattering for compensating acceptors $S_{\rm CA}$ versus acceptor concentration for samples of GaAs and $\rm Al_x Ga_{1-x} As$ with C as the major shallow acceptor (open data points) and with intentional compensation with additional Ge or Zn (filled data points).

duce heavily compensated n-type material with $n < 10^{17}$ cm^{-3}. From the mobility-vs-T data, values of S_{CA} and $N_D + N_A$ were determined which are included in Fig. 5. We conclude that Ge simply does not act to increase the value of S_{CA}.

The final set of data plotted in Fig. 5 are from Bruch *et al.*[34] for Sn-doped VPE GaAs specimens intentionally compensated during growth with Zn. Mobility data were reported only at ~77 and ~300 K, but these are sufficient to obtain S_{CA} and N_A. For these samples, S_{CA} is seen to be a factor of 100 lower than expected based on the behavior of specimens where C is the major acceptor. Again, the values of S_{CA} are consistent with the C concentration which might be expected.

These data taken together form a clear picture. C is the acceptor which causes the CA scattering. Ge and Zn produce a reduction in the ionized impurity mobility but have no effect on the value of μ_{CA}.

The actual identity of the scattering center is not entirely clear. The simplest hypothesis would be that it is carbon substituting on the As site, C_{As}. However, we should also consider possible complexes. A complex between the acceptor C_{As} and a donor could produce an isoelectronic center with a concentration proportional to that measured for C_{As}.

C. Impurity scattering

The data presented in Sec. IV B indicate that we should look more closely at the scattering due to ionized acceptor impurities. C is distinctive in comparison with other common acceptors such as Ge and Zn by its size. It is much smaller than the As for which it substitutes in the lattice, and it is also much more electronegative. The large electronegativity is evidenced in the central-cell correction to the ionization energy. The ionization energy for C is considerably less than the effective mass value[35] due to the fact that C is attractive to electrons (large electronegativity) and repulsive to holes. In this sense C in GaAs is analogous to N in GaP where N is much more electronegative than P. In the latter a strong electron scattering due to this short-range (central-cell) potential has been predicted[36,37] and experimentally observed.[38]

The localized central-cell potential is neglected in the standard ionized impurity calculations. Brooks[39] suggested that the impurity-cell potential would tend to increase the magnitude of the scattering, particularly at high temperatures, and make it less dependent on energy. If the scattering cross section were totally independent of energy, the mobility would, indeed, be proportional to $T^{-1/2}$.

The zeroth-order approach to understanding scattering at an impurity which has a long-range screened Coulomb potential and a large short-range central-cell potential would be to treat the two components of the potential separately and to sum the two scattering terms. Thus we would combine with the Brooks-Herring mobility a term due to the short-range potential. Faulkner calculated the electron-scattering cross section for isoelectronic N in GaP to be [36,37]

$$\sigma(E) = (4\pi/3)\,(2m^*E + 2m^*E_I)^{-1}, \tag{10}$$

where the quantity E_I is the ionization energy for the electron bound to the isoelectronic center. For elastic scattering where the cross section is isotropic we calculate the relaxation time[40]

$$\frac{1}{\tau} = \left(\frac{8\sqrt{2}\pi^2}{3}\right)\frac{N_I\hbar^2}{m_e^{3/2}}\,\frac{E^{1/2}}{E + E_I}\,. \tag{11}$$

The Hall mobility can then be calculated as

$$\begin{aligned}\mu_I &= \frac{e}{m^*}\,\frac{\langle\tau^2\rangle}{\langle\tau\rangle}\\ &= \frac{3}{16(2\pi^{3/2})}\,\frac{qm^{*1/2}}{N_I\hbar^2}\,\frac{15}{8}(kT)^{1/2} + \frac{E_I}{(kT)^{1/2}}\,.\end{aligned} \tag{12}$$

For GaAs Eq.(12) yields

$$\mu_I = \frac{3.4\times10^{20}}{N_I}\,\frac{15}{8}(kT)^{1/2} + \frac{E_I}{(kT)^{1/2}}\left(\frac{\mathrm{cm}^2}{\mathrm{V\,s}}\right). \tag{13}$$

The scattering by N in GaP is the only case for which this isoelectronic scattering has been experimentally observed.[38] In this case, Eq.(13), using the experimental value of E_I (8 meV) gives good agreement with the experimental data. The calculated values of E_I are much larger than 8 meV, presumably because the lattice relaxation around the N, which is not included in the calculations, acts to strongly reduce E_I. The value appropriate for the central-cell part of the C potential is not clear. Complicating the situation is the fact that the scattering might be due to a genuine isoelectronic center formed by a nearest-neighbor complex between a donor and a carbon acceptor. This complex would be electrically neu-

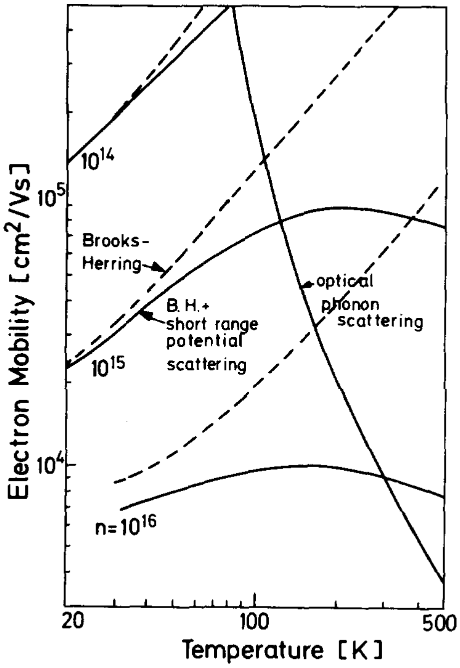

FIG. 6. Illustration of the effect of scattering by the short-range potential of the acceptor C in GaAs. Calculated curves are for the Brooks-Herring treatment of Coulombic scattering with $(N_D + N_A)/(N_D - N_A) = 3$ (broken curves) and a combination of this with the scattering from the central-cell potential as described in the text (solid curves). The mobility limited by optical phonon scattering in GaAs is also included.

tral and would have a concentration proportional to the concentration of isolated carbon acceptors. To explain the experimental data, E_I would have to exceed kT at room temperature, i.e., ~ 25 meV. This would make the second term in Eq.(13) dominant and would give $\mu_I \propto T^{-1/2}$. The magnitude of μ_I from Eq. (13) would also be approximately correct to explain the experimental results. As discussed above, we do not know how large E_I might be, but any value in the range of < 1000 meV is possible, depending on the degree of lattice relaxation around the point defect. The suggestion that $\mu_I \propto T^{-1/2}$ is qualitatively reasonable in light of the earlier discussion. The scattering due to a central-cell potential might be thought of as a type of alloy scattering, which also gives $\mu \propto T^{-1/2}$ for scattering from fluctuations in the local potential. In the present case the scattering is strong because of the large difference in electronegativity between C and As.

To summarize, it appears that the CA mobility, which is proportional to $T^{-1/2}$, is related to the acceptor C. C is the dominant compensating acceptor in GaAs grown by MBE, OMVPE, and LPE and is also found to be the dominant acceptor in nominally undoped $Al_xGa_{1-x}As$. The carbon is thought to produce the $T^{-1/2}$ mobility term because of electron scattering from its short-range central-cell potential. This type of electron scattering should be quite effective, particularly for high-energy electrons and would not be affected by illumination. Thus the mobility limited by ionized C acceptors would be quite complex, namely, μ increasing with increasing T at low temperature and being proportional to $T^{-1/2}$ at high temperatures. For example, in Fig. 6 we plot the calculated mobility-vs- T behavior for a combination of the Brooks-Herring expression for the Coulombic term [with $(N_D + N_A)/(N_D - N_A) = 3$] and μ_I from Eq.(13) (with $E_I = 100$ meV) for the scattering from the short-range potential. All of the compensating acceptors are considered to be carbon, with concentrations of 10^{14}, 10^{15}, and 10^{16} cm^{-3} for the three curves plotted. ($n = N_A$ for a compensation ratio of 3.)

For high-purity GaAs ($n \leqslant 10^{14}$ cm^{-3}), the effect of the short-range potential would not be observed experimentally because the scattering by optical phonons dominates the mobility at high temperatures. However, the effects of the central-cell scattering become visible at 10^{15} cm^{-3}, especially for $50 < T < 150$ K. At 10^{16} cm^{-3} and above, the central-cell scattering is important over the entire temperature range.

V. CONCLUSIONS

The temperature dependence of electron mobility in GaAs and $Al_xGa_{1-x}As$ shows the emergence of a term with μ proportional to $T^{-1/2}$ in compensated material. This mobility, designated μ_{CA}, is found to be proportional to N_A^{-1} in nominally undoped samples, where C is the major shallow impurity. Intentional compensation with Ge or Zn is found to have no effect on μ_{CA}. The effect of illumination ($h\nu > E_G$) was found to increase the mobility due to ionized impurity scattering, but to have no effect on μ_{CA}. Such illumination destroys space-charge regions as evidenced by the collapse of the space-charge layer at the n-epilayer/semi-insulating substrate interface with illumination which was clearly observed from Hall effect measurements.Thus, the mobility μ_{CA} cannot be due to scattering from space-charge regions distributed throughout the semiconductor, as was previously thought.

The acceptor C, or an associate involving C, is concluded to be the scattering center giving rise to μ_{CA}. The effect is thought to be due to the short-range central-cell potential due to the large electronegativity of C relative to the As which it replaces. Earlier calculations of Faulkner for isoelectronic impurities indicate that such a central-cell potential could produce an electron scatttering of the correct magnitude and temperature dependence.

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