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Photo-Hall-effect measurements of ionized impurity scattering in GaAs

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We use the photo-Hall effect in the ionized-impurity scattering conduction regime in GaAs to determine the effects of illumination on the carrier mobility μ. By employing low-level ac light pulses we are able to investigate the quasistatic case and can isolate those effects due to illumination. We find that the μ enhancement observed upon illumination may be understood in terms of: (i) the screening of ionized donors by electrons, (ii) carrier freeze out in the Brooks-Herring formalism, and (iii) photoinduced carrier heating.

I. INTRODUCTION

We have used the photo-Hall effect to investigate charge transport in the ionized-impurity scattering conduction regime in GaAs. The effect is particularly powerful in studying transport mechanisms in that it yields information on both charge-carrier concentration n and mobility μ. In the following we present results which make it possible to extend the traditional Brooks-Herring[1] treatment of carrier scattering by ionized impurities to the case of an illuminated sample.

The mobility of charge carriers in an unilluminated semiconduction in a temperature regime where ionized-impurity scattering dominates the conduction process, is given in the classical treatment[2] as

$$\mu = \left(\frac{C_1 T^{3/2}}{N_I}\right) B \tag{1}$$

where T is the sample temperature and N_1 is the number of ionized impurities. The effect of screening of a free-carrier density n enters through the screening factor B where

$$B = [\ln(1+b) - b/(1+b)]^{-1} \tag{2}$$

and

$$b = C_2 T^2 n^{-1} . \tag{3}$$

The constants

$$C_1 = 3.3 \times 10^{15} \left(\frac{\kappa_s^{\,2}}{(m^*/m)^{1/2}}\right) \tag{4a}$$

$$= 2.1 \times 10^{18} \mathrm{V}^{-1}\,\mathrm{sec}^{-1}\,\mathrm{cm}^{-1}\,\mathrm{K}^{-3/2} \text{ for GaAs,} \tag{4b}$$

and

$$C_2 = 1.3 \times 10^{14}\ (m^*/m)\kappa_s \tag{5a}$$

$$= 1.1 \times 10^{14}\ \mathrm{K}^{-2}\,\mathrm{cm}^{-3} \text{ for GaAs} \tag{5b}$$

incorporate the effective mass $m^* = 0.07m$ and static dielectric constant $\kappa_s = 12.9$ of GaAs. The free-electron mass is m. The free-carrier density n enters in that it screens the N_I scattering centers. An increase in n results in an increase in μ.

What we treat in the following is the effect upon μ of photons with energy near the band gap in a temperature regime where the above expressions for mobility are applicable. Since one of the principal effects of such illumination is to increase the free-carrier density, one might *ab initio* expect an enhanced mobility. Just such a photoinduced mobility enhancement has not been directly reported in the literature, but is indeed what we observe and discuss below.

References to an enhancement of mobility caused by an increase in free-carrier screening appear in several places in the literature. Queisser discusses how an increase in n might lead to an increase in μ for several different scattering mechanisms.[3] In a series of articles[4] Crandall discusses how an increase in n due to the impact ionization caused by high fields results in an increase in the free-electron screening of the electron-impurity interaction in GaAs. Although the origin of this charge-carrier increase is unlike ours, nonetheless, the physical effect is identical. That is, he accounts for an increase of μ by assessing the role of additional charge carriers in screening ionized impurities.

By purely optical techniques, Bludau, Wagner, and Queisser[5] report a mobility enhancement in GaAs through screening by a free-carrier plasma. From luminescence line-shape analysis of the recombination of free electrons to acceptor-bound holes, these authors report a large increase in μ over the dark value. They attribute the rise to a change in the screening factor B in Eq. (1). Caution should be taken in comparing the present experiment to that of Bludau *et al.*, since in the latter experiment high-intensity light was focused onto samples held at 2 K. In the present experiment, much lower-intensity light and much higher sample temperatures were employed.

Finally, the present authors reported earlier[6] of a dc photo-Hall experiment on GaAs in which an observed enhancement of μ was partially accounted for in terms of a screening of impurities by photo-generated carriers. The differences between this previous high light level dc experiment and the present low light level ac investigation must be considered, however, before making a direct comparison between the studies.

II. EXPERIMENTAL DETAILS

Samples of liquid-phase epitaxy n-GaAs(Si) with $\mu_{\text{dark}} = 6.7 \times 10^3$ cm^2/V sec, $n_{\text{dark}} = 1.5 \times 10^{15}$ cm^{-3}, and a dark resistivity of 0.7 Ω cm at room temperature were cut into cloverleaf patterns[7] and measured in a variable temperature (4 K $\leq T \leq$ 300 K) cryostat fitted with light pipe optical access. Compensation of the samples was determined to within 20% by Schottky-barrier profiling and Hall analysis. Ohmic contacts (made by alloying with pure tin) were attached in a Van der Pauw configuration[7,8] and were shielded against illumination leaving a central active region of approximately 0.3 mm^2. Light from a tungsten-halogen lamp was chopped at 300 Hz, passed through a Jarrel-Ash $\frac{1}{4}$-meter monochromator and transmitted through the quartz light pipe onto the sample. Typical light intensities at the sample were 2×10^{15} photons/cm^2 sec. The full width at half-maximum of the incident radiation was 28 meV, and since our samples were on the order of 5–10 μm thick, we calculate the ratio of volume to surface absorbed light to be of the order of unity. (A very broad line would have its high-energy tail absorbed more in the surface than the bulk.) Currents passed through the sample were dc while the measured voltages were detected synchronously with the chopped incident light.

III. RESULTS AND DISCUSSION

We have restricted our investigation to a regime where ionized impurities dominate the scattering process. This regime can be isolated in GaAs by investigating the T dependence of the mobility. In previously reported work[9] a $T^{3/2}$ temperature dependence of the mobility has been identified as signifying ionized impurities as the major scattering centers for 4 K $\leq T \leq$ 40 K. Here the upper limit of T depends strongly upon total impurity concentration.

To verify experimentally that we are indeed in such a regime, we determined the temperature dependence of the mobility in the dark. Our results are shown in Fig. 1. For 80 K $\leq T \leq$ 200 K, μ is limited by scattering with polar optical phonons. As expected, μ here is a decreasing function of T. For 15 K $\leq T$ 60 K, μ is an increasing function of T and fits fairly well the analytical expression [Eq. (1)] for ionized impurity scattering. Between 60 and 89 K, μ may be limited by a combination of piezoelectric and deformation potential scattering as well as those mechanisms already mentioned. Below 15 K, the contacts of the sample no longer appear Ohmic, so the problem becomes quite complicated. We restrict ourselves to a discussion of the region between 15 and 60 K where ionized impurity scattering dominates the conduction process. Although there are further difficulties[10] concerning the applicability of the Brooks-Herring theory at very low T, these problems are obviated by our choice of 15 K as the minimum measuring temperature.

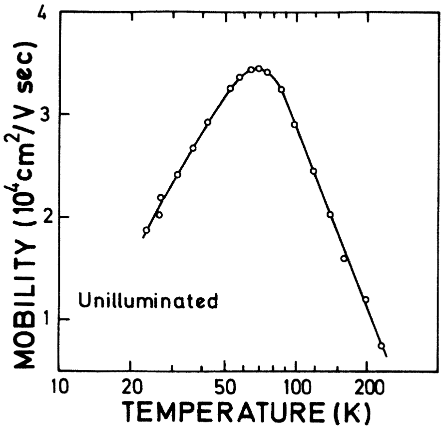

FIG. 1. Temperature dependence of the mobility of unilluminated GaAs. For temperatures between approximately 15 and 60K, scattering is dominated by ionized impurities, and Eq. (1) of the text is applicable.

The carrier freeze-out curve, i.e., carrier density versus inverse temperature, $n(T^{-1})$, can be used as a measure of the inhomogenity and nonuniformity of our samples.[11] We find in the regime of interest determined above a lack of any bowing up of $n(T^{-1})$ at low T, and thus conclude that we may consider our samples to be uniform and homogeneous for the purpose of our studies.

For a sample at $T = 29$ K under illumination with 800-nm light, we find an increase in the carrier density as shown in Fig. 2. We plot here the relative increase in carrier concentration, $\delta n/n$, as a function of incident light intensity. The highest-intensity datum on this figure corresponds to approximately 2×10^{15} photons/cm^2 sec. The straight line through the points represents a least-squares fit to a straight line on this log-log plot. For these data (as well as for all others taken at different T) we find that $\delta n/n \;\alpha\; I^a$ where $a = 0.6 \pm 0.1$. We are therefore assured that the recombination is predominantly bimolecular.

The spectral dependence of the relative light-

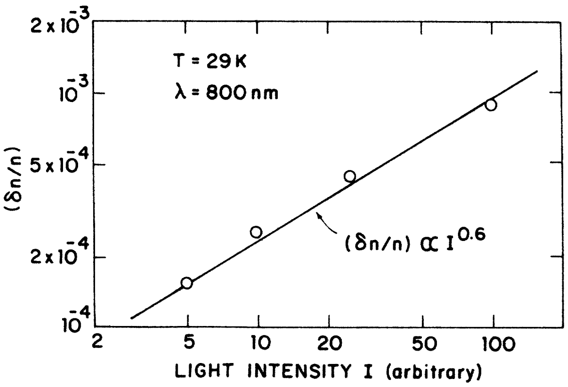

FIG. 2. Light-intensity dependence of the relative change in charge-carrier concentration of GaAs at a temperature of 29 K under illumination by light of wavelength 800 nm. The power-law intensity dependence implies that recombination is predominantly bimolecular.

induced changes in conductivity, carrier concentration, and mobility ($\delta\sigma/\sigma$, $\delta n/n$, and $\delta\mu/\mu$, respectively), are shown in Fig. 3. Here we observe a sharp rise of the photoconductive response as we approach band-gap excitation from the red end of the spectrum. The oscillatory behavior of the photoconductivity often seen[12] in such a plot is presumably not observable due to the low resolution of our optical system. As shown in Fig. 3, the changes induced by our illumination were small (in all cases $\delta n/n < 10^{-2}$), and for all cases we found σ, n, and μ to be *enhanced* upon illumination. Because of the low light level chosen in our work, the analysis of the data may be treated quasistatically. That is, since $\delta n/n \ll 1$, equilibrium statistics may be assumed.

Although it is difficult to determine precisely the electric field E in our sample, we believe that E is well below that for which one would expect impact ionization to be operative.[13] From our best estimates of the exact geometry of the sample and its electrodes, we calculate the fields to be below 1 V/cm. We can experimentally determine if impact ionization is playing a role by measuring $n(E)$. Since the field is proportional to the direct current i applied to the sample, a plot of $n(i)$ can lend insight into the role of impact ionization in our studies. We show such a plot in Fig. 4. Here we see that n is independent of i provided $i < 0.1$ mA. Above 0.1 mA, impact ionization comes into play, and n is an increasing function of i. In our studies, we kept $i < 0.1$ mA so to avoid the complication of impact ionization.

Simple extension of the above treatment [Eqs. (1)–(3)] to the case where n is increased by an amount δn leads to a calculated change in mobility given by

$$\delta\mu/\mu = C_3(\delta n/n)\,, \tag{7}$$

where

$$C_3 = B[b/(1+b) + 1/b]\,,$$

provided

$$\delta n/n \ll 1\,. \tag{8}$$

Such an extension is, of course, too simple in the case where illumination is the cause of the in-

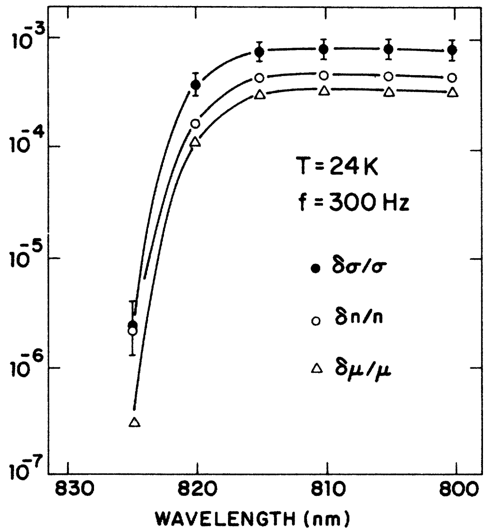

FIG. 3. Spectral dependence of the relative changes in conductivity σ, charge-carrier concentration n, and mobility μ of GaAs under illumination. Typical error bars are shown on the conductivity data. Sample temperature is 24 K and the light is chopped at a frequency of 300 Hz.

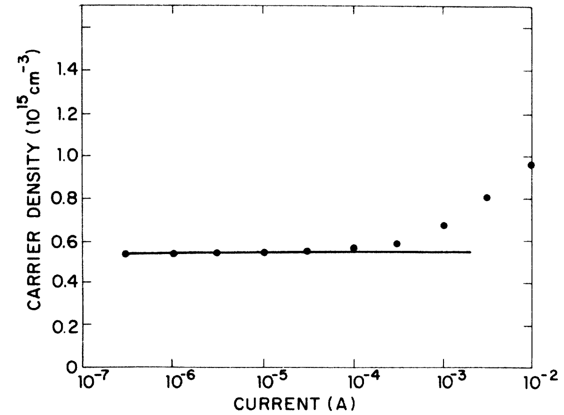

FIG. 4. Charge-carrier concentration n as a function of sample current i for dark samples of GaAs. Above currents of approximately 0.1 mA, n is an increasing function of i, implying that impact ionization is operative for currents larger than 0.1 mA. We restrict our study to currents below 0.1 mA and thus to fields low enough so that we need not consider impact ionization.

crease in n, since further complications may be expected upon illumination. Nevertheless, it is instructive to adapt Eq. (6) to the more complicated case of a sample under illumination by writing

$$\delta\mu/\mu = FC_3(\delta n/n)\,, \tag{9}$$

where we have introduced a dimensionless enhancement factor F which we expect might differ from unity in the presence of light. If screening by free electrons were the only illumination-induced effect, then we would expect $F = 1$ at all T. Any deviation from this behavior implies that an explanation in terms of other mechanisms is in order.

A rigorous treatment of the effects of illumination would involve inclusion of any changes in the number of scattering centers in the derivation of Eq. (6). [These would be N_I of Eq. (1) or, e.g., ionized acceptors N_A^- in our n-type samples.] An additional expansion, for example, in terms of a factor of $[1+\delta N_A^-/N_A^- + \cdots]$ might more accurately describe the effects of illumination, but such an expansion is, for our samples and experiment, unnecessary for a relatively complete understanding of the effects of illumination. We have chosen lightly compensated samples so as to minimize the effects of ionized acceptor scattering. Furthermore, we find that by proper consideration of all mechanisms contribution to the enhancement factor F, we can account fairly accurately for almost all of the mobility enhancement observed upon illumination. Thus in Eq. (9) we choose not to include changes in N_A^- due to illumination and thereby avoid a rather cumbersome expansion in terms of $\delta N_A/N_A^-$.

As merely one example from our data, we show in Fig. 5 the temperature dependence of the enhancement factor F for the sample described in Sec. II. The ionized impurity scattering conduction regime is spanned by the four experimental points shown, and these data are typical of all samples measured. As might have been expected, we see $F \neq 1$. We will next investigate causes for this deviation of F from unity.

The above analysis assumes no carrier freeze-out and essentially employs the model of Dingle.[14] The contribution of Brooks and Herring[1] is the introduction of the proper charge-carrier density n' into the theory in the case where carrier freeze-out increases the density of charge carriers in the vicinity of an impurity of opposite charge. Brooks and Herring expand Poisson's equation in powers of the departure of local impurity densities from their average values as well as in powers of $e\Phi/k_BT$ and retain only linear terms for both expansions to obtain[15]

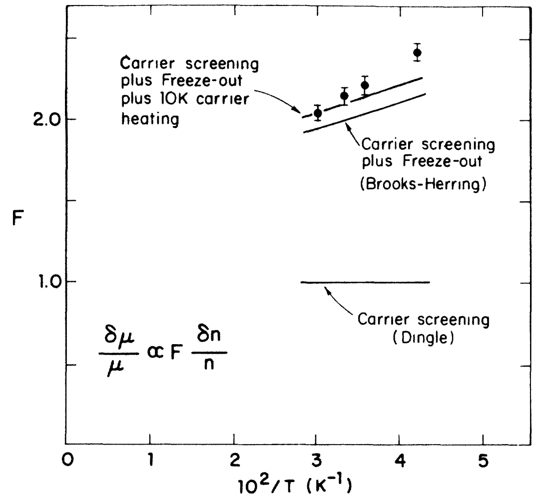

FIG. 5. Enhancement factor F versus inverse temperature for GaAs illuminated with 800-nm radiation chopped at 300 Hz. The factor F defined by Eq. (9) of the text provides a measure of the role of various mechanisms to the optically-induced mobility enhancement.

$$n' = n + (n+N_A)[1-(n+N_A)/N_D]\,. \tag{10}$$

Here N_A (N_D) is the number of acceptors (donors) per unit volume, e is the electronic charge, Φ is the scattering potential, and k_B is Boltzmann's constant. Assuming freeze-out for all data points shown in Fig. 5, we can incorporate the Brooks-Herring treatment into our analysis by absorbing the effects of using n' instead of the measured n into the factor F in Eq. (9).

We show in Fig. 5 the values of F expected for our data using the Dingle theory [$F = 1 \neq F(T)$], and the Brooks-Herring theory where freeze-out is incorporated into the model.

Since we are using greater than band-gap excitation, we must consider the effect of carrier heating upon the mobility. Under illumination the measured mobility is that of electrons up to one LO phonon (36 meV) from the conduction-band minimum, while in the dark one measures the mobility of carriers only within k_BT of the band minimum. Because μ is an increasing function of T, the effect of this carrier heating upon illumination is to cause an enhancement of the observed mobility. The effect is diminished at higher lattice temperatures where the increased phonon population relaxes the free-electron distribution further towards thermal equilibrium. Thus the effect of light-induced carrier heating is to cause a greater increase in F above unity at lower T than at higher T.

Although we cannot accurately determine the effect of carrier heating upon the electron distribution in the conduction band, we can incorporate a reasonable estimate of carrier heating into our analysis. We simply assume that an average electron temperature can be defined as being 10 K above the lattice temperature and incorporate the effects of carrier heating into the value of F of Eq. (7). Having done so, we show what value of F is expected for this 10-K carrier heating in the uppermost solid line of Fig. 5.

The reasonable agreement between the experimentally determined data points and the theoretical treatment incorporating impurity screening into the Brooks-Herring formalism with a small amount of carrier heating is seen in Fig. 5. Clearly, these simple but not unreasonable considerations of screening, freeze-out, and carrier heating result in a good fit between the data and our model.

Two second-order effects might improve the fit slightly. The fact that one expects more light-induced carrier heating at lower temperatures would result in a slightly higher F at lower T. Also because the highest-temperature data points are on the border of the freeze-out regime, one would expect these points to have a slightly lower F value than those obtained using the Brooks-Herring theory under the assumption of complete freeze-out.

The several effects of photoexcited holes upon μ do not play a major role in our experiment for several reasons. Because our n-type samples are so lightly compensated, the screening of ionized acceptors by photoexcited holes does not strongly affect carrier mobility. Because the Hall-effect weights the contributions of electrons and holes to μ by a factor proportional to the square of their respective mobilities, the more mobile electrons strongly dominate the μ measurement. Furthermore, the recombination rate of holes in GaAs is much faster than that of electrons. Finally, this same feature minimizes the effects of heavy hole scattering.

In order to deconvolute the various contributions to mobility enhancement more quantitatively, the experiment should be performed with improved spectral resolution. In particular, with a dye laser tuned to the band gap, one could photoexcite carriers to the band minimum thus avoiding free-carrier heating. Such a laser experiment is in preparation.

IV. CONCLUSIONS

A complete quantitative mobility theory must incorporate further complications such as static charge screening and the change in ion energy with varying dopant. However, by considering the light-induced *changes* in mobility in the quasistatic limit under the condition that $\delta n/n \ll 1$, we are able to isolate those effects due to illumination. Having done so, we conclude that our experimental data on the photo-Hall effect can be understood for the most part by proper consideration of three mechanisms: (i) a screening of ionized donors by electrons, (ii) carrier freeze-out in the Brooks-Herring formalism, and (iii) photoinduced carrier heating.

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