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Impurity Photomagnetoelectric Effect: Application to Semi-Insulating GaAs

David C. Look
Wright State University - Main Campus, david.look@wright.edu

Impurity photomagnetoelectric effect: Application to semi-insulating GaAs†

D. C. Look
Physics Department, University of Dayton, Dayton, Ohio 45469
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The theories of the photomagnetoelectric (PME) and photoconductivity (PC) effects in semiconductors are extended to include unequal excitation rates of holes and electrons, as might be expected from impurity photo-excitation. The results are applied to two semi-insulating Cr-doped GaAs crystals, which exhibit mixed conductivity. It is seen that the PC and PME effects give complementary information on the holes and electrons. In the impurity excitation region the PME current responds strongly to changes in the absorption coefficient, and provides a convenient way to study this quantity.

I. INTRODUCTION

Semi-insulating GaAs, produced by doping with Cr and/or O is widely used as a substrate material for GaAs devices. Because of this it has been studied extensively by many techniques in recent years, including the photomagnetoelectric (PME) effect.[1,2] However, the PME effect varies strongly with the absorption constant (α) and, thus, as far as we know, has been experimentally applied to semiconductors only in the intrinsic photoexcitation region, where α is large. This is true of the available theoretical treatments also, which are formulated under the condition that electrons and holes are excited at equal rates. For extrinsic (impurity, or defect) photoexcitation this condition may not hold, so the theory must be extended. In semi-insulating Cr-doped GaAs we have found that the PME response can be measured down to about 0.6 eV, much lower than the intrinsic response, which cuts off at about 1.42 eV, the room-temperature bandgap. In this paper we develop the theory of the impurity PME and photoconductivity (PC) effects and use the results to elucidate the nature of the Cr energy levels in GaAs:Cr.

II. THEORY

The theory of current-carrier transport in semiconductors has been developed rather extensively by van Roosbroeck, under a variety of conditions, including free-charge neutrality,[3] total-charge neutrality,[4] and non-neutrality (space charge).[5] The neutrality aspects applicable to this paper will be discussed later, although they are not specifically invoked in the theory which follows.

The continuity equations for holes and electrons may be written

$$-\frac{\vec{\nabla}\cdot\vec{J}_p}{e}=\frac{\partial\hat{p}}{\partial t}+r_p-g_p, \tag{1}$$

$$\frac{\vec{\nabla}\cdot\vec{J}_n}{e}=\frac{\partial\hat{n}}{\partial t}+r_n-g_n, \tag{2}$$

where $\vec{J}_p$ is the hole current density, g_p the hole generation rate, r_p the hole recombination rate, and $\hat{p}$ the "excess" hole density, i.e., $\hat{p}\equiv p-p_0$, where p_0 is the hole density in the dark. Similar definitions hold for the electrons, and e is the absolute value of the electronic charge. We will assume that the light propagation is in the $\vec{y}$ direction and that the generation rates are independent of x and z. Then we can write $g_p=\alpha\eta_p I_0 e^{-\alpha y}$ and $g_n=\alpha\eta_n I_0 e^{-\alpha y}$, where α is the absorption constant, η_p and η_n are the efficiencies, respectively, for hole and electron excitation, and I_0 is the light intensity (photons/cm^2 sec) incident at the surface. In reality, I_0 should be adjusted for reflections but we will not do so here. For interband (intrinsic) excitation, $\eta_n=\eta_p$, of course, so that $g_n=g_p$. If there are no sources or sinks of total current, then $\vec{\nabla}\cdot\vec{J}=\vec{\nabla}\cdot(\vec{J}_p+\vec{J}_n)=0$, and, at steady state, $r_p-g_p=r_n-g_n$. For intrinsic excitation then, $r_p=r_n$, but for extrinsic excitation this will not generally be the case. We will assume phenomenological expressions for the recombination rates: $r_p\equiv\hat{p}/\tau_p$ and $r_n\equiv\hat{n}/\tau_n$, where τ_p and τ_n are independent of sample coordinates. Such independence should hold if the sample is homogeneous and if the occupational levels of the dominant recombination centers do not change appreciably, such as for small-signal conditions.

The hole and electron current densities may be written, for small Hall angles ($\tan\mu^H B\simeq\mu^H B$), as

$$\vec{J}_p=\sigma_p\vec{E}-eD_p\vec{\nabla}p+\mu_p^H\vec{J}_p\times\vec{B}, \tag{3}$$

$$\vec{J}_n=\sigma_n\vec{E}+eD_n\vec{\nabla}n-\mu_n^H\vec{J}_n\times\vec{B}, \tag{4}$$

where for holes, σ_p is the conductivity, D_p the diffusion constant, and μ_p^H the Hall mobility, and similarly for electrons, $\vec{E}$ is the electric field, and $\vec{B}$ the magnetic field strength. For $\mu_p^H B\ll 1$, we can approximate $\vec{J}_p$ in the third term of Eq. 3 by the first two terms, and, for $\mu_n^H B\ll 1$, we can do the same in Eq. (4). Then, by adding Eqs. (3)

and (4) the total current density is found:

$$\vec{J} = (\sigma_n + \sigma_p)\vec{E} + e(D_n\vec{\nabla}_n - D_p\vec{\nabla}p) + (\mu_p^H\sigma_p - \mu_n^H\sigma_n)\vec{E}\times\vec{B} - e(\mu_n^H D_n\vec{\nabla}n + \mu_p^H D_p\vec{\nabla}p)\times\vec{B}. \quad (5)$$

Here the four terms on the right-hand side represent drift, Dember, Hall, and PME contributions, respectively.[3]

Again, for $\mu^H B \ll 1$, we can use Eq. (5) to approximate

$$\vec{E} \simeq [\vec{J} - e(D_n\vec{\nabla}n - D_p\vec{\nabla}p)]/(\sigma_n + \sigma_p) \quad (6)$$

and substitute this into the third and fourth terms of Eq. (5). After some manipulation the result is

$$\vec{J} = (\sigma_n + \sigma_p)\vec{E} + e(D_n\vec{\nabla}n - D_p\vec{\nabla}p) + \frac{\mu_p^H\sigma_p - \mu_n^H\sigma_n}{\sigma_n + \sigma_p}\vec{J}\times\vec{B} - e(\mu_n^H + \mu_p^H)\frac{\sigma_p D_n\vec{\nabla}n + \sigma_n D_p\vec{\nabla}p}{\sigma_n + \sigma_p}\times\vec{B}. \quad (7)$$

The fourth term on the right-hand side is the PME contribution to the current density. Note that $\vec{\nabla}n = \vec{\nabla}\hat{n}$, $\vec{\nabla}p = \vec{\nabla}\hat{p}$, and if we assume that these are collinear with the light vector ($\vec{I}_0 = I_0\hat{j}$), and that $\vec{B}$ is in the z direction ($\vec{B} = B\hat{k}$), then, under short-circuit conditions ($E_x = 0$), the PME current density will be

$$\vec{J}_{\rm PME} = -eB(\mu_n^H + \mu_p^H)\left[\left(\sigma_p D_n\frac{\partial n}{\partial y} + \sigma_n D_p\frac{\partial p}{\partial y}\right)\Big/(\sigma_n + \sigma_p)\right]\hat{i}. \quad (8)$$

We next develop the differential equations for n and p. Substitution of Eqs. (3) and (4) into Eqs. (1) and (2), respectively, yields

$$-\frac{\vec{\nabla}\cdot\vec{J}_p}{e} = -\frac{\vec{\nabla}\sigma_p}{e}\cdot\vec{E} - \frac{\sigma_p}{e}\vec{\nabla}\cdot\vec{E} + D_p\nabla^2 p = \frac{\partial\hat{p}}{\partial t} + r_p - g_p, \quad (9)$$

$$\frac{\vec{\nabla}\cdot\vec{J}_n}{e} = \frac{\vec{\nabla}\sigma_n}{e}\cdot\vec{E} + \frac{\sigma_n}{e}\vec{\nabla}\cdot\vec{E} + D_n\nabla^2 n = \frac{\partial\hat{n}}{\partial t} + r_n - g_n, \quad (10)$$

where we have assumed that $\vec{\nabla}D_p = \vec{\nabla}D_n = 0$. ($D = kT\mu/e$, by the Einstein relation.) Multiplication of Eq. (9) by σ_n, and Eq. (10) by σ_p, and then adding the results, yields

$$r_p - g_p = r_n - g_n = \frac{\sigma_n D_p\nabla^2 p + \sigma_p D_n\nabla^2 n}{\sigma_n + \sigma_p} + \frac{1}{e}\frac{\sigma_p\vec{\nabla}\sigma_n - \sigma_n\vec{\nabla}\sigma_p}{\sigma_n + \sigma_p}\cdot\vec{E}, \quad (11)$$

where we have now assumed steady-state conditions. Again, we approximate $\vec{E}$ by Eq. (6), and, after lengthy manipulation, can show that

$$r_p - g_p = r_n - g_n = \vec{\nabla}\cdot\frac{\sigma_p D_n\vec{\nabla}n + \sigma_n D_p\vec{\nabla}p}{\sigma_n + \sigma_p} + \frac{\mu_n^H\sigma_p\vec{\nabla}n - \mu_p^H\sigma_n\vec{\nabla}p}{(\sigma_n + \sigma_p)^2}\cdot\vec{J}. \quad (12)$$

Here it may be noted that the argument of the first term on the right-hand side is the same as one of the factors in the PME term of Eq. (7). The second term in Eq. (12) will vanish, because no total current will flow in the direction of $\vec{\nabla}n$ and $\vec{\nabla}p$, i.e., the light propagation direction.

To relate $\vec{\nabla}n$ to $\vec{\nabla}p$ we use the fact that $r_p - g_p = r_n - g_n$ to get

$$\vec{\nabla}\hat{p}/\tau_p = (\vec{\nabla}\hat{n}/\tau_n) - \alpha^2(\eta_p - \eta_n)I_0 e^{-\alpha y}\hat{j}. \quad (13)$$

This expression can be substituted into Eq. (12), but the resulting differential equation, after taking the divergence, becomes rather cumbersome. For intrinsic excitation, $\eta_p = \eta_n$, and the second term on the right-hand side vanishes; furthermore, for extrinsic excitation, α will be small and we may be able to ignore this term here also. We will see later that a condition for this is $\alpha L \ll 1$, where L is a diffusion length, about 10^{-4} cm. Typical measured values of α in the extrinsic region are 1–10 $\rm cm^{-1}$, so that indeed, $\alpha L \ll 1$. At any rate, we will solve Eq. (12) under the approximation $\vec{\nabla}\hat{p}/\tau_p = \vec{\nabla}\hat{n}/\tau_n$, giving the following differential equations for $\hat{p}$ and $\hat{n}$:

$$\vec{\nabla}\cdot D_n^*\vec{\nabla}\hat{n} - \hat{n}/\tau_n = -\alpha\eta_n I_0 e^{-\alpha y}, \quad (14)$$

$$\vec{\nabla}\cdot D_p^*\vec{\nabla}\hat{p} - \hat{p}/\tau_p = -\alpha\eta_p I_0 e^{-\alpha y}, \quad (15)$$

where

$$D_n^* = \frac{\sigma_p D_n + \sigma_n D_p\tau_p/\tau_n}{\sigma_n + \sigma_p}, \quad (16)$$

$$D_p^* = \frac{\sigma_p D_n\tau_n/\tau_p + \sigma_n D_p}{\sigma_n + \sigma_p}. \quad (17)$$

If $\tau_n = \tau_p$, then $D_n^* = D_p^* \equiv D^*$, the familiar ambipolar diffusion constant.[3] Note that the effective diffusion length is the same for both electrons amd holes; i.e., $L = (D_n^*\tau_n)^{1/2} = (D_p^*\tau_p)^{1/2}$.

At this point it is perhaps worthwhile to discuss the concept of the "relaxation" semiconductor, introduced by van Roosbroeck,[5] which differs from the more commonly encountered "lifetime" semiconductor. The latter has a dielectric relaxation time τ_d shorter than the carrier lifetimes, so that local charge neutrality obtains. Then, $\hat{n} = \hat{p}$ (and $\tau_n = \tau_p$) in the absence of trapping, or $\hat{n}/\tau_n = \hat{p}/\tau_p$ in the more general case. For steady-state photoconductivity in the relaxation semiconductor, how-

ever, $\tau_d \gg \tau$, and an approximate state of overall charge neutrality is maintained by equal volume capture rates of holes and electrons, i.e., $n/\tau_n = p/\tau_p$. A special case of this is Schetzina's "conductivity-locked" transport[6] which holds if τ_n, τ_p, μ_n and μ_p do not vary with the light irradiation, thus keeping the ratio σ_n/σ_p constant. Since $\vec{\nabla}\hat{n}/\tau_n = \vec{\nabla}\hat{p}/\tau_p$ in all of these cases (for constant τ) the resulting differential equations are essentially the same, and our expressions for $\hat{n}$ and $\hat{p}$ are the same as Schetzina's,[6] with the substitution $n/\tau_n = p/\tau_p$. For 10^8 Ωcm material, with a dielectric constant of 10, we can calculate $\tau_d \simeq 10^{-4}$ sec, which is certainly longer than the carrier lifetimes (10^{-8}–10^{-7} sec) normally encountered in GaAs:Cr at room temperature. At higher light levels, however, it is possible to have $\tau_d \simeq \tau$. Although there is evidence for conductivity locking in some of our samples this is not a major point in the analysis which follows, and thus the distinction between the lifetime and relaxation cases will not be dealt with further in this paper.

Equations (14) and (15) are readily solved only if D_n^* and D_p^* are independent of coordinates. This will occur under the following conditions: (i) small signal strengths, for which $\sigma_n \to \sigma_{n0}$, $\sigma_p \to \sigma_{p0}$; (ii) predominant electron conductivity, for which $D_n^* = D_p\tau_p/\tau_n$, $D_p^* = D_p$; (iii) predominant hole conductivity, for which $D_n^* = D_n$, $D_p^* = D_n\tau_n/\tau_p$; or (iv) equality of n and p, for which

$$D_n^* = D_n D_p(1+\tau_p/\tau_n)/(D_n+D_p),$$

$$D_p^* = D_n D_p(1+\tau_n/\tau_p)/(D_n+D_p).$$

From Eq. (7) it is seen that only $D_p^* = D_p$ is important for case (ii), and only $D_n^* = D_n$ for case (iii); i.e., the hole diffusion is important for n-type samples, and the electron diffusion for p-type samples, and the electron diffusion for p-type samples.

$$\nabla^2\hat{n} - \hat{n}/L^2 = -(D_n^*)^{-1}\alpha\eta_n I_0 e^{-\alpha y}, \tag{18}$$

$$\nabla^2\hat{p} - \hat{p}/L^2 = -(D_p^*)^{-1}\alpha\eta_p I_0 e^{-\alpha y}, \tag{19}$$

where $\nabla^2\hat{n} = \partial^2\hat{n}/\partial y^2$ and $\nabla^2\hat{p} = \partial^2\hat{p}/\partial y^2$. These equations can be readily solved by standard techniques to yield

$$\hat{n} = A_n e^{y/L} + B_n e^{-y/L} + C_n e^{-\alpha y}, \tag{20}$$

$$\hat{p} = A_p e^{y/L} + B_p e^{-y/L} + C_p e^{-\alpha y}, \tag{21}$$

where

$$C_n = \alpha\eta_n I_0 L^2/D_n^*(\alpha^2L^2-1) = \alpha\eta_n I_0\tau_n/(\alpha^2L^2-1) \tag{22}$$

and

$$C_p = \alpha\eta_p I_0\tau_p/(\alpha^2L^2-1). \tag{23}$$

It must be remembered here that Equations (20)–(23) are valid only for small α, if $\eta_n \neq \eta_p$.

The boundary conditions are given by the perpendicular currents at the surfaces, which may be obtained from Equations (3), (4), and (6):

$$D_n^* \left.\frac{\partial\hat{n}}{\partial y}\right|_0 = S_{0n}\hat{n}(0), \tag{24a}$$

$$-D_n^* \left.\frac{\partial\hat{n}}{\partial y}\right|_d = S_{dn}\hat{n}(d), \tag{24b}$$

$$D_p^* \left.\frac{\partial\hat{p}}{\partial y}\right|_0 = S_{0p}\hat{p}(0), \tag{24c}$$

$$-D_p^* \left.\frac{\partial\hat{p}}{\partial y}\right|_d = S_{dp}\hat{p}(d), \tag{24d}$$

where the illuminated surface is at $y=0$ and the back surface at $y=d$. The quantities S_p and S_n are surface recombination velocities for holes and electrons, respectively. Then the constants in Eqs. (20) and (21) become

$$A_n = C_n\frac{(S_{dn}-D_n^*/L)(S_{0n}+\alpha D_n^*)e^{-d/L} - (S_{0n}+D_n^*/L)(S_{dn}-\alpha D_n^*)e^{-\alpha d}}{(S_{dn}+D_n^*/L)(S_{0n}+D_n^*/L)e^{d/L} - (S_{0n}-D_n^*/L)(S_{dn}-D_n^*/L)e^{-d/L}}, \tag{25a}$$

$$B_n = -C_n\frac{(S_{dn}+D_n^*/L)(S_{0n}+\alpha D_n^*)e^{d/L} - (S_{0n}-D_n^*/L)(S_{dn}-\alpha D_n^*)e^{-\alpha d}}{(S_{dn}+D_n^*/L)(S_{0n}+D_n^*/L)e^{d/L} - (S_{0n}-D_n^*/L)(S_{dn}-D_n^*/L)e^{-d/L}}. \tag{25b}$$

The expressions for A_p and B_p are the same, except with $n \to p$.

The short-circuit PME current *per unit width* I_{PME} will now be given by Eq. (8), integrated over y,

$$\begin{aligned} I_{PME} &= \int_d^0 J_x\,dy = -e(\mu_n^H+\mu_p^H)BD_n^*\int_d^0\frac{\partial\hat{n}}{\partial y}\,dy \\ &= e(\mu_n^H+\mu_p^H)BD_n^*[\hat{n}(d)-\hat{n}(0)] \\ &= e(\mu_n^H+\mu_p^H)B\tfrac{1}{2}\{D_n^*[\hat{n}(d)-\hat{n}(0)] \\ &\qquad + D_p^*[\hat{p}(d)-\hat{p}(0)]\}, \end{aligned} \tag{26}$$

where the last expression is written to maintain a symmetry with respect to $\hat{n}$ and $\hat{p}$.

The excess conductance, *per unit width*, is given by

$$\begin{aligned} \hat{G} &= \int_d^0 \hat{\sigma}\,dy = e\int_d^0(\mu_n\hat{n}+\mu_p\hat{p})\,dy \\ &= eL[(\mu_n A_n+\mu_p A_p)(1-e^{d/L}) \\ &\qquad -(\mu_n B_n+\mu_p B_p)(1-e^{-d/L}) \\ &\qquad -(\alpha L)^{-1}(\mu_n C_n+\mu_p C_p)(1-e^{-\alpha d})], \end{aligned} \tag{27}$$

where μ_n and μ_p, without superscript H, are conductivity mobilities. We will evaluate these expressions in the limit $d/L \gg 1$, since, for typical GaAs wafers, $d \approx 500$ μm, and we expect $L \simeq 1$–10 μm. Then terms in $e^{d/L}$ will dominate terms in $e^{-d/L}$ and $e^{-\alpha d}$, and Eqs. (26) and (27) can be written

$$I_{\mathrm{PME}} = \frac{eI_0 B(\mu_n^H + \mu_p^H)\alpha L}{2}\left[\eta_n\left(\frac{L_{0n}}{1+\alpha L} - \frac{L_{dn}e^{-\alpha d}}{1-\alpha L}\right) + \eta_p\left(\frac{L_{0p}}{1+\alpha L} - \frac{L_{dp}e^{-\alpha d}}{1-\alpha L}\right)\right], \tag{28}$$

$$\hat{G} = [eI_0/(1-\alpha^2 L^2)]\{\eta_n\mu_n\tau_n[(1+\alpha L)(1-\alpha L_{dn})(1-e^{-\alpha d}) + \alpha(L_{dn}+L_{0n}-2L) + \alpha^2 L(L_{dn}-L_{0n})] + \eta_p\mu_p\tau_p[(1+\alpha L)(1-\alpha L_{dp})(1-e^{-\alpha d}) + \alpha(L_{dp}+L_{0p}-2L) + \alpha^2 L(L_{dp}-L_{0p})]\}, \tag{29}$$

where $L_{0n} = L/(1+S_{0n}\tau_n/L)$, and L_{dn}, L_{0p}, and L_{dp} have similar definitions. The L_{ij}'s are "effective" diffusion lengths, conforming to the general notation of, for example, Adduci, *et al.*[7]

For intrinsic excitation, well above the band gap, we would expect $\eta_n = \eta_p \equiv \eta$, and $\alpha d \gg 1$, since $\alpha \gtrsim 10^4$ cm^{-1}. Then

$$I_{\mathrm{PME}} = eI_0 B\eta(\mu_n^H + \mu_p^H)\alpha L L_0/(1+\alpha L), \tag{30}$$

$$\hat{G} = eI_0\eta(\mu_n\tau_n + \mu_p\tau_p)(1+\alpha L_0)/(1+\alpha L), \tag{31}$$

where $L_0 \equiv L/(1+S_{0n}\tau_n/L) = L/(1+S_{0p}\tau_p/L)$ since, in this case, $\eta_n = \eta_p$, which, by the boundary conditions, leads to $S_n\tau_n = S_p\tau_p$. Equations (30) and (31) are essentially the same as those developed by Adduci, *et al*,[7] except that in their expressions, $\tau_n = \tau_p$. For $\alpha L_0 \gg 1$, and $S\tau/L \ll 1$, these equations become

$$I_{\mathrm{PME}} = eI_0 B\eta\mu_n(1+b^{-1})[D_n(1+c)\tau_{\mathrm{PME}}/(1+bc)]^{1/2}, \tag{32}$$

$$\hat{G} = eI_0\eta\mu_n(1+b^{-1})\tau_{\mathrm{PC}}, \tag{33}$$

where $b \equiv \mu_n/\mu_p$, $c \equiv n/p$, and $\tau_{\mathrm{PME}} = (\tau_n + c\tau_p)/(1+c)$, $\tau_{\mathrm{PC}} = (\tau_n + b^{-1}\tau_p)/(1+b^{-1})$, as defined by Zitter,[8] who considered the PME and PC effects in the presence of trapping. Here we have ignored differences in the Hall and conductivity mobilities. The individual lifetimes τ_n and τ_p can sometimes be determined from the values of τ_{PC} and τ_{PME}, as measured according to Eqs. (32) and (33). If $\tau_n = \tau_p \equiv \tau$, then a common technique for measuring the lifetime is based upon Eqs. (30) and (31):

$$\tau^{-1/2} = (I_{\mathrm{PME}}/B\hat{G}\sqrt{D^*})(1+1/\alpha L_0). \tag{34}$$

It should be remembered that all of the above expressions for I_{PME} and $\hat{G}$ have been derived under the assumption that D_n^*, D_p^*, and D^* are independent of coordinates, which is true if (i) $\hat{n}, \hat{p} \ll n_0, p_0$, respectively, (ii) $n \gg p$, (iii) $p \gg n$, or (iv) $n = p$. An additional assumption, of course, is that the individual D's, i.e., D_n and D_p, (or μ_n and μ_p) are independent of coordinates.

We now consider extrinsic excitation, for which $\alpha L \ll 1$, but $\eta_n \neq \eta_p$, necessarily. First, as discussed earlier, we must be able to ignore the second term on the right-hand side of Eq. (13) in order for Eqs. (20) and (21) to be valid. This term $\lesssim \alpha(\hat{n}/\tau_n + \hat{p}/\tau_p)$, whereas $\vec{\nabla}n/\tau_n$ and $\vec{\nabla}_p/\tau_p$ are on the order of $\hat{n}/L\tau_n$ and $\hat{p}/L\tau_p$, by Eqs. (20) and (21), if $\alpha L \ll 1$. Thus, if $\alpha L \ll 1$, the relevant term can be ignored, and Eqs. (28) and (29) can be solved, in this limit, to yield,

$$I_{\mathrm{PME}} = \tfrac{1}{2} eI_0 B(\mu_n^H + \mu_p^H)\alpha L\,[\eta_n(L_{0n} - L_{dn}e^{-\alpha d}) + \eta_p(L_{0p} - L_{dp}e^{-\alpha d})]. \tag{35}$$

If $L_{0n} = L_{dn} \equiv L_n$, $L_{0p} = L_{dp} \equiv L_p$, then

$$I_{\mathrm{PME}} = \tfrac{1}{2} eI_0 B(\mu_n^H + \mu_p^H)\alpha L(1-e^{-\alpha d})(\eta_n L_n + \eta_p L_p) \tag{36}$$

$$= \tfrac{1}{2} eI_0 B(\mu_n^H + \mu_p^H)\alpha(1-e^{-\alpha d}) \times \left(\frac{\eta_n}{1+S_n\tau_n/L} + \frac{\eta_p}{1+S_p\tau_p/L}\right)\frac{p\tau_n + n\tau_p}{n/D_p + p/D_n}, \tag{37}$$

where, again, $D_n = kT\mu_n/e$ and $D_p = kT\mu_p/e$. Similarly, for $\alpha L \ll 1$, $\hat{G}$ becomes

$$\hat{G} = eI_0(1-e^{-\alpha d})(\eta_n\mu_n\tau_n + \eta_p\mu_p\tau_p) = eI_0(1-e^{-\alpha d})\mu_n(1+b^{-1})\tau'_{\mathrm{PC}} \tag{38}$$

where $\tau'_{\mathrm{PC}} = (\eta_n\tau_n + b^{-1}\eta_p\tau_p)/(1+b^{-1})$, defined in analogy with Zitter's[18] τ_{PC}. For $\alpha d \ll 1$, it is noted that $I_{\mathrm{PME}} \propto \alpha^2$, while $\hat{G} \propto \alpha$, by Eqs. (37) and (38), respectively. The PME current depends upon α more strongly since it arises from the *gradients* of the carrier concentrations, whereas the photoconductivity is determined by the *totals* of the concentrations.

III. EXPERIMENT

The experiments were performed on a dc Hall-effect apparatus, designed for high-resistance (~10^{13} Ω) measurements, similar to the apparatus

described in Ref. 9. Sample resistances were about 10^{10} Ω or less. The monochromatic light intensity at the sample was estimated to be about 5×10^{14} photons/cm^2 sec, constant over the spectral range. Appropriate filters were used to minimize higher-order light in the diffraction pattern. Typical electric fields of about 1 V/cm were used for the PC measurements, and a magnetic field of 18 kG was used for the PME measurements. Nonlinear field effects were small.

The two samples were cleaved from Cr-doped GaAs ⟨100⟩ wafers to approximate dimensions of $10\times5\times0.4$ mm. Sample A was one of the most "n-type" of a large group of GaAs:Cr crystals which had been previously examined, and sample B one of the most "p-type." Their respective Fermi levels were 0.645 and 0.699 eV from the conduction band.[10] The assignment of carrier type is nebulous in most GaAs:Cr samples because of mixed conductivity.[11] In fact, nearly all such crystals have $p>n$, but yet have negative Hall coefficients. These phenomena are discussed in detail elsewhere.[10,11]

The data are presented in Fig. 1. Here $\hat{\sigma}=\hat{G}/d$ is the *additional* conductivity in the light. The dark conductivities are also noted in the figure. For convenience, we have plotted the measured PME current, $wI_{\rm PME}$, rather than $I_{\rm PME}$ itself, the normalized current *per unit width*. (Here $w_A\simeq4.8$ mm, and $w_B\simeq6.0$ mm, if normalization is desired.) The plot of α is crudely extracted from Fig. 2 of Ref. 12 and is meant only to approximate the spectral response of the absorption constant for "pure GaAs."

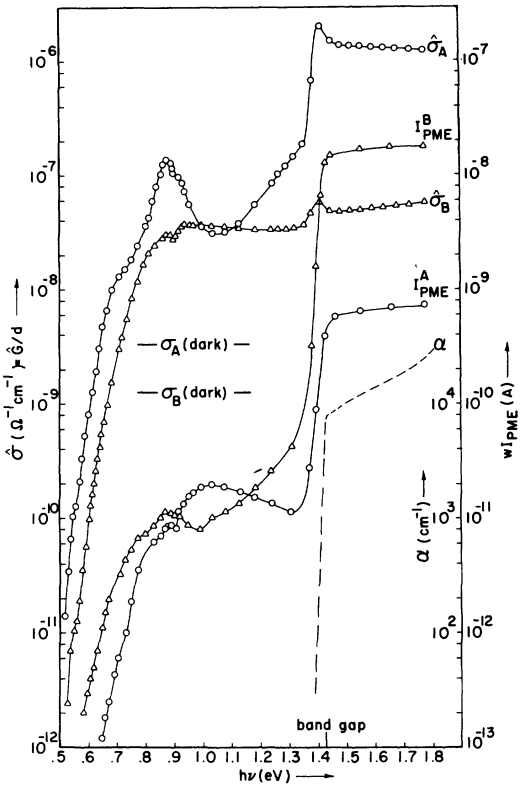

FIG. 1. Spectral dependence of photoconductivity $\hat{\sigma}$ and the photomagnetoelectric current $wI_{\rm PME}$ for two Cr-doped GaAs samples, A and B. The data for the absorption constant α are taken from Ref. 12.

IV. ANALYSIS

We first consider the intrinsic (above-band-gap) PC and PME responses, for which Eqs. (30) and (31) should apply. Suppose we *hypothesize* that $\tau_n=\tau_p$. Since $\eta_n\simeq\eta_p$ in this region, it follows that $n\simeq p$, because $n,\ p\gg n_0,\ p_0$, respectively (i.e., $\hat{\sigma}\gg\sigma_{\rm dark}$). Then $D_n^*=D_p^*\equiv D^*=2D_nD_p/(D_n+D_p)\simeq18.1$ cm^2/sec for sample A, and 18.8 cm^2/sec for sample B. (The mobilities were calculated by means of a mixed-conductivity analysis[10]). Now, it is apparent from Fig. 1 that $\hat{G}$ and $I_{\rm PME}$ do not vary with light energy nearly as strongly as α, which suggests, according to Eqs. (30) and (31), that $\alpha L_0\gg1$. (This condition necessarily makes $\alpha L\gg1$, since $L\geq L_0$). Then Eq. (34) gives $\tau_A\simeq6.6\times10^{-4}$ and $\tau_B\simeq5.9\times10^{-9}$ sec, which leads to $L_A\simeq(D_A^*\tau_A)\simeq1.1\times10^3$ μm, and $L_B\simeq3.3$ μm. We can check these results directly from Eqs. (30) and (31) by using our approximate value of I_0 and assuming that $\eta=1$. The results of this are $L_{0A}\simeq0.29$ μm, $\tau_A\simeq1.8\times10^{-7}$ sec, and $L_{0B}\simeq4.1$ μm, $\tau_B\simeq7.2\times10^{-9}$ sec. A comparison of these calculations reveals that an assumption of $\tau_n\simeq\tau_p$ is probably correct for sample B, but almost certainly not correct for sample A, since the above results for sample A are inconsistent.

A second, presumably more precise, analysis can be carried out by relaxing the assumption, $\alpha L_0\gg1$, and then plotting $I_{\rm PME}^{-1}$ vs α^{-1}, and $\hat{G}/I_{\rm PME}$ vs α^{-1}. The first plot has an x axis intercept of $-L$, and the second, $-L_0$, according to Eqs. (30) and (31). For sample A, the results are $L\simeq2.2$ μm, $L_0\simeq1.1$ μm which leads to $S_n\tau_n/L=S_p\tau_p/L\simeq1$, or $S_n\tau_n\simeq S_p\tau_p\simeq2.2$ μm. The extraction of L and L_0 from such plots is valid, however, only if the mobilities and lifetimes are independent of $h\nu$, which may not be the case at our light intensity. At any rate, this value of L differs considerably from our first estimate and thus the correct value is in doubt. It is still possible to get an approximate value of τ_n for this sample from Eq. (31) by realizing that $\mu_n\gg\mu_p$ for GaAs, and, for an "n-type" sample, $\tau_n\gtrsim\tau_p$, giving $\mu_n\tau_n\gg\mu_p\tau_p$; then $\tau_n=2\times10^{-7}$ sec.

For sample B, a plot of $I_{\rm PME}^{-1}$ vs α^{-1} gives $L=4$ μm, in good agreement with the previous values.

Unfortunately, $\hat{G}$ does not decrease as α increases, making a plot of $\hat{G}/I_{\mathrm{PME}}$ vs α^{-1} virtually meaningless. The problem here may again be a spectral dependence of one or more of the quantities τ_n, τ_p, μ_n, and μ_p. However, the previous analyses gave consistent values for τ and L, i.e., $\tau_B \simeq 6\times10^{-9}$ sec and $L_B \simeq 3$–4 μm. To the accuracy of this experiment, $L_{0B} \simeq L_B$, suggesting that $S_B\tau_B/L_B \ll 1$.

We now turn to the extrinsic (below-band-gap) photoexcitation. Here the analysis must be more qualitative, because we no longer can assume $\eta_n = \eta_p$. A detailed discussion of the origins of the photoconductivity has been given elsewhere,[13] but one of the most interesting features of the present data is the seeming *complementary* nature of the PC and PME data. That is, the curves for I^A_{PME} and $\hat{\sigma}_B$ have many similar features, as do the curves for I^B_{PME} and $\hat{\sigma}_A$. This is not too surprising in view of the fact that the photoconductivity is generally thought of as a *majority* carrier effect, and the PME current as a *minority* carrier effect. For example, the PC spectrum for sample A, an n-type sample, has only a shoulder at 0.90 eV, but the PME spectrum for this sample has a sharp rise at this energy. This might suggest a *hole* excitation threshold at 0.90 eV and, indeed, this can be shown to be the case by a mixed-conductivity analysis.[10] Conversely, a known *electron* excitation threshold, near 1.1 eV, is not seen in the PC spectrum of sample B, a p-type sample, but is clearly seen in the PME spectrum of this sample. Such behavior would be predicted from Eqs. (37) and (38), because I_{PME} depends *directly* upon the excitation efficiencies η_n and η_p, whereas in $\hat{G}$ these efficiencies are weighted by the carrier lifetimes. In an n-type GaAs sample this effect is further enhanced because $\mu_n \gg \mu_p$.

In the small-signal region (i.e., $\hat{\sigma} \ll \sigma_{\mathrm{dark}}$) we expect variations in both I_{PME} and $\hat{G}$ to be mainly due to variations in the absorption, through the parameters α, η_n, and η_p, because μ_n, μ_p, τ_n, and τ_p should be approximately equal to their dark values. As α increases to the point at which $\alpha d > 1$, $\hat{G}$ loses its strong dependence upon α, but I_{PME} does not. Thus, the measurement of I_{PME} in the extrinsic region gives a convenient qualitative description of α. To determine α quantitatively, one may use Eq. (37) if the other parameters are known. For sample B we have calculated n, p, μ_n, and μ_p at a few values of $h\nu$ in the extrinsic region, and find that D^* varies only from about 66–71 cm^2/sec, for energies up to 1.3 eV, if τ_n is assumed equal to τ_p, as was found in the intrinsic region. Then, if $S_p\tau_p/L$, $S_n\tau_n/L \ll 1$, if τ is about the same as that in the intrinsic region, and if $\eta_n + \eta_p \simeq 1$ (i.e., all absorption due to the photoexcitation of holes and electrons), we find that $\alpha_B \simeq 9$ cm^{-1} at $h\nu \simeq 1.0$ eV. For sample A, if we assume that $\tau_n \gg \tau_p$, and if $\tau_n \simeq 2\times10^{-7}$ sec in the extrinsic as well as in the intrinsic regions, then, at 1.0 eV, $\alpha_A \simeq 5$ cm^{-1}. Although these values of α_A and α_B are only approximate, they are consistent with literature values, which range from 2–12 cm^{-1} for Cr-doped GaAs crystals.[14-16]

V. SUMMARY

We have calculated the photoconductivity and photomagnetoelectric effects in semiconductors under both intrinsic and extrinsic photoexcitation. The former case has already been thoroughly investigated and our results agree with those in the literature. The extrinsic case differs in that we must allow for different excitation rates of holes and electrons. The results are applied to semi-insulating Cr-doped GaAs and show that the impurity PME effect complements the impurity PC effect in this material, because the former responds to minority carrier excitation while the latter responds to majority carrier excitation.

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