# Photoconductive and Photoelectromagnetic Lifetime Determination in Presence of Trapping. I. Small Signals*

A. AMITH
*RCA Laboratories, Princeton, New Jersey*

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Impurities which are located in the forbidden energy gap of a semiconductor are classified as traps or as recombination and generation levels, according to their capture cross sections and their proximity to the quasi-Fermi levels of the carriers. Their influence upon the photoconductance and the photoelectromagnetic effect is considered; noted in particular are their effects on the values of carrier lifetimes deduced from these photosignals. The lifetimes deduced are always too high for that type carrier of which some are trapped, and they are too small for the other type carrier. In extrinsic material the photoeffects are augmented by trapping of minority carriers, and diminished by trapping of majority carriers. In general the effects of minority carrier trapping are more severe than those of majority carrier trapping. Furthermore, the photoelectromagnetic effect is much less sensitive to trapping than is the photoconductance and may often yield the correct minority carrier lifetime in extrinsic material. Consequently, the method of deducing carrier lifetimes by combining the photoconductance and the photoelectromagnetic effects may lead to very misleading results indeed. Yet separate measurements of the two effects over a range of temperatures will yield the carrier lifetimes, the energy level of the traps, and their density. Moreover, concomitant measurements of the spectral dependence of photoconductance and the photoelectromagnetic effect in an extrinsic semiconductor would serve to classify the impurity centers which are found, because an impurity photoelectromagnetic effect occurs only if the carriers generated from the centers are minority carriers.

## INTRODUCTION

THE purpose of this note is the assessment of the effects of traps, located in the forbidden energy gap, upon the steady state photoconductance and the photoelectromagnetic (PEM) effect.[1] Of particular interest is the influence of such traps upon the values of the carrier lifetimes deduced from measurements of these photoeffects.

A simple geometrical consideration of the motion of an excess free carrier during its lifetime under the action of an electric or a magnetic field, will indicate that the short-circuit PEM current is proportional to the square root of the lifetime whereas the photoconductance is proportional to the lifetime itself. The reason why the PEM current depends upon a lower power of the carrier lifetime than does the photoconductance is that the prime requisite for the PEM effect is the existence of a density gradient in the direction of illumination, and that gradient is proportional to $\partial n/\partial y$. The photoconductance, on the other hand, is proportional to $n$ itself. It is this fact which makes the combination of photoconductance with the PEM effect so attractive a means for the determination of carrier lifetimes, in particular when they are so short as to render useless the many transient methods extant. Such a combination eliminates the dependence on the intensity of illumination and on the electrical properties of the front surface.

The situation becomes complicated as soon as the steady-state densities of the optically generated electrons and holes are not equal. Such is the case when a single type of carriers is excited from an impurity center, or when the phenomenon of trapping occurs; one may no longer assign a single lifetime to both kinds of carriers.

The differing natures of the photoconductance and the PEM effect lead one to expect that the effects of trapping would manifest themselves differently in the two cases.

The photoelectromagnetic PEM effect arises from the action of an external magnetic field in the $z$ direction upon carrier pairs which have been generated by illumination on the $y=0$ face of a rectangular semiconductor parallelepiped, and which diffuse into the body of the semiconductor in the $y$ direction. Consequently the holes and electrons are deflected into the $+x$ and the $-x$ directions, respectively. There ensues a current along the $x$ axis which has the following value per unit width (along the $z$ axis) of the illuminated sample:

$$I^{sc}=\int_0^t J_x dy, \tag{1}$$

where the superscripts indicate that it is measured under short-circuit conditions. $J_x$ is the total current density flowing in the $x$ direction, and $t$ is the sample's thickness (in the direction of illumination). The effect depends upon the availability of carrier pairs to diffuse along the $y$ axis in order to avoid any net electrical current in that direction. In sufficiently extrinsic material it would be primarily a minority-carrier affair.

The photoconductance, on the other hand, is due to the availability of the optically generated excess carriers to drift in the electric field which is applied along the $x$ axis. The change in conductance due to illumination is:

$$\Delta G=\int_0^t e\mu(n_f+p_f/b)dy, \tag{2}$$

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[1] For a thorough treatment and extensive bibliography see W. van Roosbroeck, Phys. Rev. **101**, 1713 (1956).

where $G$ is the conductance along a unit length per unit width of the sample, $e$ is the absolute value of the electronic charge, $\mu$ is the mobility of electrons and $\mu/b$ is that of holes, $n_f$ and $p_f$ are the excess densities of free electrons and holes which are excited optically in the conduction and the valence bands, respectively. Photoconductance results then from the drift of excess carriers of either kind under the influence of the applied electric field; the requirement of charge neutrality in the bulk of the semiconductor will affect the number of carriers of either type which are free to enhance the conduction.

It will be seen that for extrinsic materials and small signals the presence of traps always reveals itself in the expression for photoconductance, but it enters into the PEM effect only if the density of traps is large.

## THEORY

The analysis which follows treats the case of small magnetic fields, neglecting second-order terms and using the Hall angles rather than their tangents. Furthermore, all carriers of one type are assumed to have the same mobility.

No reference to the nature of the impurity centers in the forbidden gap will be made at the outset; they will be characterized only by their energy levels and by their capture cross sections for holes and for electrons. Subsequently the circumstances will be noted under which these impurity centers would act as traps for either type of carrier. These traps, which contribute to the accumulation of holes or electrons in them,[2] will be distinguished from centers through which electrons transit from the conduction band to the valence band.[3] The kinetics and statistics of all the impurity centers (noninteracting) in the forbidden energy gap are the same regardless of the function which they perform. As a result of the dynamic classification of the centers which will be developed, their function will depend upon the surrounding circumstances.

Following the derivations in Appendix A, we obtain these relationships among the free carriers for the case of small signals

$$n_f=\frac{C_n(n_0+n_1)+C_p(p_0+p_1)+C_pn_t^0}{C_n(n_0+n_1)+C_p(p_0+p_1)+C_nn_t^0n_1/n_0}n_f\equiv\Gamma p_f, \quad (3)$$

where $n_t^0$ is the density of electrons which are in the impurity centers at thermal equilibrium; $C_n$ is the product of the density of impurity centers and the probability per unit time that a center will capture an electron, averaged over all electrons in the conduction band; $C_p$ is an analogous quantity for holes; and $\Gamma$ is a proportionality factor defined by Eq. (3).

When the centers communicate only with the valence band, acting as *hole traps*, then

$$n_f=[1+N_tp_1/(p_0+p_1)^2]p_f, \quad (4a)$$

and when they communicate only with the conduction band, acting as *electron traps*, then

$$p_f=[1+N_tn_1/(n_0+n_1)^2]n_f. \quad (4b)$$

$N_t$ is the density of the impurity centers, $n_0$ and $p_0$ are the thermal equilibrium densities of electrons and of holes, $n_1$ and $p_1$ are their respective densities which would obtain in the case when the Fermi level $E_F$ coincides with the centers' energy level $E_T$.

The development of the relationships between the free carriers in the two bands will be pursued until they are related to the external generating source and then to the photoeffects. But before proceeding it is well to scrutinize the performance of the impurity centers and to see in some detail what characterizes them as traps, which provide for accumulation of charge in them but not for the transit of carriers through them.

The answer to the last question lies in the relative magnitudes of the rates of the carriers' kinetics through these centers. Let $g_{tc}$ and $g_{tv}$ be the rates of electron release from the centers to the conduction band and to the valence band; $r_{ct}$ and $r_{vt}$ be the rates of capture of free electrons from the conduction band and from the valence band, respectively. These rates characterize the action of the impurity centers in the following fashion:

$$\begin{array}{lll} \text{generation centers} & g_{tc}>g_{tv}, & r_{ct}<r_{vt}, \\ \text{recombination centers} & g_{tc}<g_{tv}, & r_{ct}>r_{vt}, \\ \text{electron traps} & g_{tc}>g_{tv}, & r_{ct}>r_{vt}, \\ \text{hole traps} & g_{tc}<g_{tv}, & r_{ct}<r_{vt}. \end{array} \quad (5)$$

We shall avail ourselves of the concept of the steady-state quasi-Fermi levels for electrons and for holes:

$$\begin{aligned} E_F{}^n&=E_c+kT\ln\frac{n_0+n_f}{N_c}=E_i+kT\ln\frac{n_0+n_f}{n_i}, \\ E_F{}^p&=E_v-kT\ln\frac{p_0+p_f}{N_v}=E_i-kT\ln\frac{p_0+p_f}{n_i}. \end{aligned} \quad (6)$$

$E_c$ and $E_v$ are the edges of the conduction and of the valence bands, respectively; $N_c$ and $N_v$ are the densities of states in the two bands, and $E_i$ is the intrinsic energy level.

From these definitions and the developments in Appendix A we deduce the following conditions[4]:

$g_{tc}\gtrless g_{tv}$ whenever

$$E_c-E_T\lessgtr E_F{}^p-E_v-kT[\ln(N_v/N_c)+\ln(C_p/C_n)],$$

[2] H. Y. Fan, Phys. Rev. **92**, 1424 (1953).
[3] W. Shockley and W. T. Read, Jr., Phys. Rev. **87**, 835 (1952).
[4] A. Rose, in a similar manner speaks of demarcation levels. See *Progress in Semiconductors* (Meywood and Company, Ltd., London, 1957), Vol. 2.

i.e., whenever

$$E_T \gtrless 2E_i - E_F{}^p + kT \ln(C_p/C_n), \tag{7}$$

$r_{ct} \gtrless r_{vt}$ whenever

$$E_T - E_v \gtrless E_c - E_F{}^n + kT[\ln(N_v/N_c) + \ln(C_p/C_n)],$$

i.e., whenever

$$E_T \gtrless 2E_i - E_F{}^n + kT \ln(C_p/C_n).$$

We are now able to specify in more detail the parameters upon which depends the performance of the impurity centers located at an energy level $E_T$:

*Generation centers:*

$$2E_i + kT \ln(C_p/C_n) - E_F{}^n > E_T > 2E_i + kT \ln(C_p/C_n) - E_F{}^p; \tag{8}$$

this inequality can be satisfied only when $E_F{}^p > E_F{}^n$, or $n_0 p_f + p_0 n_f + n_f p_f < 0$, which represent extraction of carriers.

*Recombination centers:*

$$2E_i + kT \ln(C_p/C_n) - E_F{}^n < E_T < 2E_i + kT \ln(C_p/C_n) - E_F{}^p, \tag{9}$$

this can be satisfied whenever $E_F{}^n > E_F{}^p$, which is during ordinary excitation. We note that the very same centers will act as generation centers and as recombination centers when the roles of $E_F{}^n$ and $E_F{}^p$ are reversed.

*Electron traps:*

$$E_T > 2E_i + kT \ln(C_p/C_n) - E_F{}^p \quad (\text{or } -E_F{}^n \text{ whenever } E_F{}^p > E_F{}^n); \tag{10a}$$

note that a center would act as an electron trap regardless of where it is located in the forbidden gap if

$$C_p \lesssim C_n N_c N_v{}^{-1} \exp\{-(E_c - E_F{}^p)/kT\}. \tag{10b}$$

*Hole traps:*

$$E_T < 2E_i + kT \ln(C_p/C_n) - E_F{}^n \quad (\text{or } -E_F{}^p \text{ whenever } E_F{}^p > E_F{}^n); \tag{11a}$$

a center will act as a hole trap regardless of where it is located in the forbidden gap if

$$C_n \lesssim C_p N_v N_c{}^{-1} \exp\{-(E_F{}^n - E_v)/kT\}. \tag{11b}$$

In the special case when

$$C_p = C_n \exp\{(E_T - E_F)/kT\}, \tag{12}$$

the impurity centers do not cause any further accumulation of charge in them, over that which has already existed in thermal equilibrium; in this case $n_t = 0$ and $n_f = p_f$.

The preceding characterization of the impurity centers, which has specified their performance as one of four types, is not exclusive. In the strictest sense, a center will be an electron trap alone only when both $r_{vt}$ and $g_{tv}$ vanish, that is when $C_p = 0$. So long as $r_{vt}$ and $g_{tv}$ have finite values, carriers may transit through that center from one band to another. What is implied is that there already exists an efficient mechanism for transit of carriers between the bands, either directly or, more likely, through another group of centers which are the recombination (or generation) centers. Thus a particular group of impurity centers may be the sole recombination agent in a material, until another impurity is added through which the transit of carriers is so much more efficient that the original group become traps. The efficient recombination of carriers is indicated by recombination rates $\mathfrak{R}_n$ and $\mathfrak{R}_p$ in the continuity equation. If the centers under study provide for an equally efficient transit of carriers then the lifetime for carriers in the material will be a combination in parallel of that lifetime characteristic of these centers and the lifetime included in the terms $\mathfrak{R}_n$ and $\mathfrak{R}_p$. It is thus important to bear in mind that an impurity which acts as a trap in one case may act as a recombination center in another case, in the same semiconductor material.

We proceed to discuss the photoeffects. In a material where the centers under study are traps, the continuity equation for holes under small-signal conditions assumes the following form [see Eq. (B.2)]:

$$e^{-1} \operatorname{div} \mathbf{J}^+ = -p_f/\tau_p + \mathfrak{G}_p. \tag{13}$$

where $\mathbf{J}^+$ is the hole current density and $\mathfrak{G}_p$ is the optical generation rate of holes. As derived in Appendix B, the hole current in the direction of illumination is

$$J_y{}^+ = -\frac{\mu kT}{b(n_0+n_f)+p_0+p_f} \times [(n_0+n_f)dp_f/dy + (p_0+p_f)dn_f/dy],$$

which becomes

$$J_y{}^+ = -eD_T dp_f/dy; \tag{14b}$$

where $D_T$ is the ambipolar diffusivity in the presence of trapping—it reduces to the ordinary ambipolar diffusivity $D_0$ when there is no trapping (in that case $\Gamma = 1$):

$$D_T = \frac{n_0 + \Gamma p_0}{(n_0/D_p) + (p_0/D_n)} = D_0[1 + (\Gamma - 1)p_0/(n_0 + p_0)]. \tag{15}$$

The behavior of the PEM short-circuit current is reflected in the behavior of $J_y{}^+$, since

$$I^{sc} = \int_0^t J_x dy = \theta \int_0^t J_y{}^+ dy,$$

where $\theta$ is the total Hall angle.

In the case when all carrier generation takes place right near the illuminated surface, the density of free holes is

$$p_f = \frac{Q[s_2 \sinh\lambda(t-y) + \lambda D_T \cosh\lambda(t-y)]}{(s_1 s_2 + \lambda^2 D_T{}^2) \sinh\lambda t + (s_1 + s_2)\lambda D_T \cosh\lambda t}, \tag{16}$$

the PEM short-circuit current is

$$I^{sc}=\frac{eD_TQ\theta}{(s_1s_2+\lambda^2D_T^2)\sinh\lambda t+(s_1+s_2)\lambda D_T\cosh\lambda t \times[s_2\sinh\lambda t+\lambda D_T(\cosh\lambda t-1)]}, \quad (17)$$

and the photoconductance is

$$\Delta G=\frac{e\mu(b^{-1}+\Gamma)Q\lambda^{-1}}{(s_1s_2+\lambda^2D_T^2)\sinh\lambda t+(s_1+s_2)\lambda D_T\cosh\lambda t \times[s_2(\cosh\lambda t-1)+\lambda D_T\sinh\lambda t]}. \quad (18)$$

$s_1$ and $s_2$ are the surface recombination velocities on the front (illuminated) and the back surface, respectively; $Q$ is the intensity of illumination, and

$$\lambda=(\tau_pD_T)^{-\frac{1}{2}}.$$

Let us dwell upon the implication of Eqs. (16), (17), and (18), which describe the steady state excess carrier density, the PEM short-circuit current and the photoconductance—all under small signal conditions. When trapping is absent, then $D_T=D_0$, where $D_0$ is the ordinary ambipolar diffusivity and $\lambda$ is the reciprocal of the ambipolar diffusion length—because in that case the hole lifetime and the electron lifetime are one and the same. If the material is extrinsic, say $n$ type, and the trapping is small enough so that $|\Gamma p_0|\ll n_0$, then $D_T=D_p$ and $\lambda=L_p^{-1}$—both referring to the minority carriers. Under these conditions one may look upon the PEM effect as solely a minority carrier affair. The traps do not appear in the continuity equations and the density of the excess free minority carriers $p_f$ is then related to their lifetime and the external excitation alone—regardless of the presence of traps (it is to be borne in mind, however, that distinction has to be made between minority carrier lifetime and majority carrier lifetime). The expression for the PEM short-circuit current is likewise independent of trapping in this case. Not so the photoconductance, wherein the influence of the traps is always prominent through the parameter $\Gamma$.

It is worth noting an interesting corollary under the same circumstances, when the material is extrinsic and trapping moderate enough so as not to affect the PEM signal. Should the optical excitation generate majority carriers alone (e.g., from an impurity level) there would be no PEM effect although there would be photoconductance.[5] Consequently, concomitant measurements of the spectral dependence of photoconductance and PEM signal would serve to find impurity levels and classify them. This would be of particular interest when the impurity photoeffects occur at photon energies larger than the energy separation of the Fermi level from the band edge of the carriers thus generated.

[5] Thermodynamic arguments are invoked in J. Tauc, Czechoslov. J. Phys. **5**, 178 (1955).

We return now to the expressions for the photoeffects, which assume the following forms[6] when the sample's thickness $t$ is large in comparison with $\lambda^{-1}$:

$$I^{sc}=\frac{eQ\theta(D_T\tau_p)^{\frac{1}{2}}}{1+s_1(\tau_p/D_T)^{\frac{1}{2}}}, \quad (19)$$

$$\Delta G=\frac{eQ\mu(b^{-1}+\Gamma)\tau_p}{1+s_1(\tau_p/D_T)^{\frac{1}{2}}}. \quad (20)$$

In the case that $s_1(\tau_p/D_T)^{\frac{1}{2}}\ll 1$ it is instructive to rewrite the last two equations

$$I^{sc}=eQ\theta[1+Fp_0/(n_0+p_0)]^{\frac{1}{2}}(D_0\tau_p)^{\frac{1}{2}}, \quad (21)$$

$$\Delta G=eQ\mu[1+bF/(1+b)](b^{-1}+1)\tau_p, \quad (22)$$

in which a new parameter has been introduced:

$$F\equiv\Gamma-1. \quad (23)$$

It has thus been demonstrated that the lifetimes deduced from the PEM short-circuit current and from the photoconductance (PC) will differ from the hole lifetimes and the electron lifetimes according to the following relationships:

$$\tau_{PC}=[1+bF(1+b)^{-1}]\tau_p =[1-F(1+F)^{-1}(1+b)^{-1}]\tau_n, \quad (24a)$$

$$\tau_{PEM}=[1+Fp_0(n_0+p_0)^{-1}]\tau_p =[1-F(1+F)^{-1}(1+p_0/n_0)^{-1}]\tau_n. \quad (24b)$$

When the impurity centers act as *traps* for either type of carrier, the parameter $F$ is seen to have the following specific values [see Eqs. (3) and (4)]:

For *hole traps*

$$F=N_tp_1/(p_0+p_1)^2; \quad (25a)$$

for *electron traps*

$$F=-N_tn_1/[N_tn_1+(n_0+n_1)^2]. \quad (25b)$$

It is now possible to relate the photoconductive and PEM lifetimes to the hole and electron lifetimes in terms of the explicit parameters of the impurity centers: When the centers are *electron traps*,

$$\tau_{PC}=\left[1-\frac{b}{1+b}\frac{N_tn_1}{N_tn_1+(n_0+n_1)^2}\right]\tau_p =\left[1+\frac{1}{1+b}\frac{N_tn_1}{(n_0+n_1)^2}\right]\tau_n, \quad (26a)$$

$$\tau_{PEM}=\left[1-\frac{p_0}{n_0+p_0}\frac{N_tn_1}{N_tn_1+(n_0+n_1)^2}\right]\tau_p =\left[1+\frac{n_0}{n_0+p_0}\frac{N_tn_1}{(n_0+n_1)^2}\right]\tau_n;$$

[6] See also S. W. Kurnick and R. W. Zitter, J. Appl. Phys. **27**, 278 (1956).

when the centers are *hole traps*,

$$\tau_{PC}=\left[1+\frac{b}{1+b}\frac{N_t p_1}{(p_0+p_1)^2}\right]\tau_p$$
$$=\left[1-\frac{1}{1+b}\frac{N_t p_1}{N_t p_1+(p_0+p_1)^2}\right]\tau_n, \tag{26b}$$
$$\tau_{PEM}=\left[1+\frac{p_0}{n_0+p_0}\frac{N_t p_1}{(p_0+p_1)^2}\right]\tau_p$$
$$=\left[1-\frac{n_0}{n_0+p_0}\frac{N_t p_1}{N_t p_1+(p_0+p_1)^2}\right]\tau_n.$$

There is exact symmetry between the expressions for holes and electrons ($b$ has to be interchanged with $b^{-1}$!).

Both $\tau_{PC}$ and $\tau_{PEM}$ yield lifetime values which are too high for the carriers of the type which are trapped and too low for carriers of the type which are not trapped. Furthermore, as trapping becomes excessive the lifetimes deduced for carriers of the type which are not trapped reach a limiting value which depends upon $b$; on the other hand the lifetimes deduced for the type of carriers which are trapped keep on increasing. Most significant are the very different sensitivities of $\tau_{PC}$ and $\tau_{PEM}$ to trapping. This becomes of particular importance in extrinsic material, say $n$ type, in which holes, the minority carriers, are being trapped. The PEM short-circuit current will yield the correct value of the minority carrier lifetime so long as $N_t p_1/(p_0+p_1)^2 \ll[p_0/(n_0+p_0)]^{-1}$, which may be a rather extensive range of trapping. The photoconductance, however, will yield a very erroneous value for the lifetime of holes. On the other hand, as trapping becomes heavy the latter will yield a value close to that of the majority carrier lifetime: $\tau_{PC}\approx\tau_n b/(1+b)$. Note further that the PEM current will be linear with increasing illumination as long as $n_0+n_f\gg p_0+p_f$, whereas the photoconductance would begin to saturate at high levels of illumination before that. This can be seen easily by referring to Appendix A from which we note that

$$n_t=-n_t^0 p_f/(p_0+p_1+p_f) \quad \text{for } \textit{hole traps},$$

and

$$n_t=n_t^0 n_f(n_1/n_0)/(n_0+n_1+n_f) \quad \text{for } \textit{electron traps}.$$

We return now to the expressions for the PEM short-circuit current and the photoconductance. As noted previously, both the intensity of illumination and the surface recombination velocity of the front surface are eliminated upon dividing Eq. (17) by Eq. (18):

$$\frac{I^{sc}}{\Delta G}=\frac{\lambda D_T\theta}{\mu(b^{-1}+\Gamma)}\frac{\delta_2+\tanh\frac{1}{2}\lambda t}{1+\delta_2\tanh\frac{1}{2}\lambda t}, \tag{27}$$

where

$$\delta_2=s_2/(\lambda D_T).$$

It is of some interest to note the limiting forms which the above ratio assumes under certain conditions:

for large $s_2$,

$$\frac{I^{sc}}{\Delta G}=\frac{\lambda D_T\theta}{\mu(b^{-1}+\Gamma)}\coth\tfrac{1}{2}\lambda t,$$

for a thin sample,

$$\frac{I^{sc}}{\Delta G}=\frac{\lambda D_T\theta}{\mu(b^{-1}+\Gamma)}\frac{\delta_2+\frac{1}{2}\lambda t}{1+\frac{1}{2}\delta_2\lambda t},$$

for a thin sample and large $s_2$,

$$\frac{I^{sc}}{\Delta G}=\frac{2D_T\theta}{\mu(b^{-1}+\Gamma)}t^{-1},$$

for a thick sample,

$$\frac{I^{sc}}{\Delta G}=\frac{\lambda D_T\theta}{\mu(b^{-1}+\Gamma)}.$$

From Eq. (27) we derive this expression for the lifetime of holes:

$$\tau_p=D_T\left[\frac{\Delta G\theta}{I^{sc}\mu(b^{-1}+\Gamma)}\frac{\delta_2+\tanh\frac{1}{2}\lambda t}{1+\delta_2\tanh\frac{1}{2}\lambda t}\right]^2. \tag{28}$$

Equation (28) is the correct expression for the hole lifetime in terms of the measured photoconductance and the short-circuit PEM current. The trapping is accounted for by $D_T$, by $\Gamma$, and by $\lambda$. If, however, we fail to include the trapping effects and make use of the ordinary expression for the lifetime which is valid only when $n_f=p_f$, then we would deduce from the measurements an apparent lifetime $\tau_a$, which is erroneous

$$\tau_a=D_0\left[\frac{\Delta G\theta}{I^{sc}\mu(b^{-1}+1)}\frac{\delta_2+\tanh\frac{1}{2}\lambda t}{1+\delta_2\tanh\frac{1}{2}\lambda t}\right]^2. \tag{29}$$

We are now in position to assess the magnitude of the error that would be associated with the lifetime which is deduced from the PEM-PC ratio method, without proper inclusion of the effects of trapping. This error is the ratio

$$\tau_p/\tau_a=[1+Fp_0/(n_0+p_0)][1+bF/(1+b)]^{-2}; \tag{30}$$

or

$$\tau_a=\tau^2_{PC}/\tau_{PEM}. \tag{31}$$

Depending upon whether the traps, in an extrinsic semiconductor, are for majority carriers or minority carriers, our error in deducing the lifetime would be in opposite directions. When majority trapping occurs, then the apparent minority carrier lifetime which we deduce is too low. Under ordinary conditions, however, the error would remain rather small, for even as $N_t$ increases, $\tau_p/\tau_a$ tends to the limit $(1+b)^2$ in sufficiently extrinsic $n$-type material. In the presence of minority carrier trapping the apparent lifetime would be too

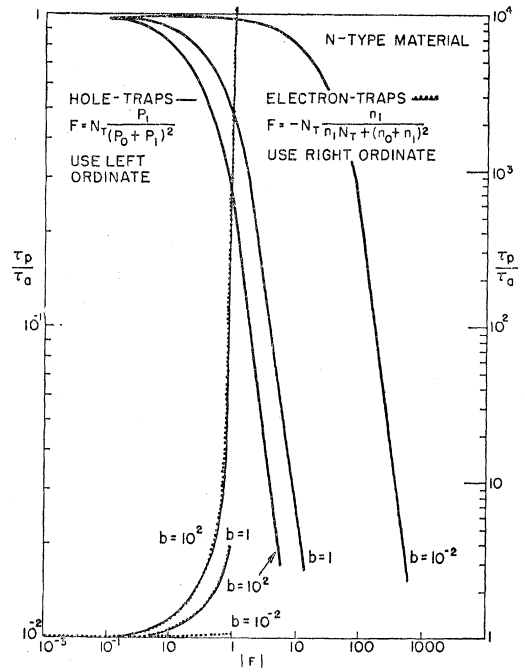


FIG. 1. The error in the PC-PEM lifetime in the case of majority carrier trapping or minority carrier trapping.

large and the error keeps increasing with the square of the density of traps.

These relationships are shown in Fig. 1, wherein $\tau_p/\tau_a$ is plotted as a function of the trapping parameter $F$ for various values of the mobilities' ratio $b$ (when the condition $Fp_0/(n_0+p_0)<1$ is fulfilled). In order to relate $\tau_p/\tau_a$ to the properties of a particular semiconductor, germanium was chosen to illustrate the dependence.[7] Figure 2 applies to minority carrier traps (holes in $n$-type material) whereas Fig. 3 applies to majority carrier traps. The traps may be anywhere in the forbidden gap, as specified in Eqs. (10b) and (11b), so long as $Fp_0/(n_0+p_0)<1$. Both figures enable us to deduce the value of $F$ for any carrier concentration, and any density and position of traps. In Fig. 2 the curves start crossing as $E_T-E_v$ increases, because $p_0$ exceeds $p_1$ as soon as the impurity centers are above the Fermi level. We note that a given density of minority carrier traps would cause a more serious error in the lifetime determination as $E_T-E_v$ increases—until $E_T$ is above the Fermi level, when the traps' influence diminishes rapidly. For example, traps located 0.5 ev above the valence band and which have density of $10^{13}$ cm$^{-3}$ would give $F\sim10^3$ in highly $n$-type material ($p_0=10^7$), thus causing a large error in the estimation of the lifetime (see Fig. 1). Yet for a material where $p_0=10^{11}$ the very same traps would give $F\sim1$ with but little effect on the lifetime deduced from the measurements. In Fig. 3 the curves cross for an analogous reason as in Fig. 2, reflecting changes in the relative magnitudes of $n_0$ and $n_1$. Thus the majority carrier traps are more effective the closer they lie to the Fermi level, between the latter and the band of the majority carriers (the conduction band, in the present example). Note further that when the traps lie between the Fermi level and the band of the type of carriers which are trapped, the value of $F$ is independent of $n_0$ and $p_0$ for a given energy level and density of traps. When the traps lie on the other side of the Fermi level, $F$ depends quite strongly upon the thermal equilibrium carrier densities. This is why the range over which majority carrier traps are effective in an extrinsic material is rather small.

[7] At 300°K $\Delta E_G=0.67$ ev, $N_c=10.2\times10^{18}$, $N_v=5.65\times10^{18}$, $m_n=0.55m_e$, $m_p=0.37m_e$.

## CONCLUSION

A theory has been presented which takes into account the specific statistics of trapping and its influence upon photoconductance and the PEM effect. Photoconductance and PEM effect are influenced by trapping, and so are the carrier lifetimes deduced from them. Yet the PEM effect is in general much less sensitive to trapping than is the photoconductance; indeed in extrinsic material there is a wide range of trapping which has no influence upon the PEM effect. The PEM-PC ratio method for the determination of lifetimes will lead to erroneous values, unless the exact nature of the trapping extant is known and accounted for. Yet independent measurements of photoconductance and the PEM effect over a range of temperatures can be analyzed to yield densities and levels of traps as well as of recombination centers.

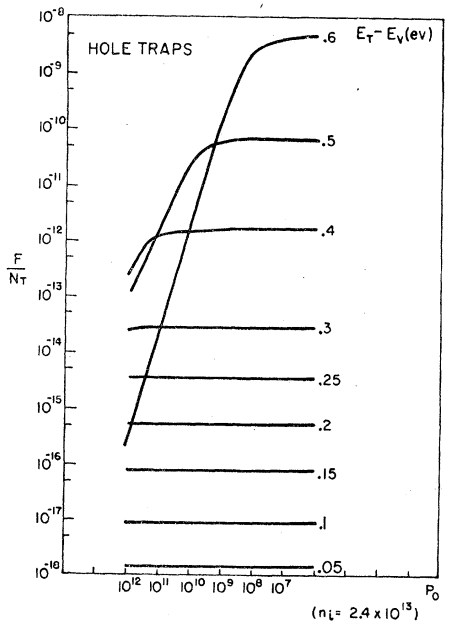


FIG. 2. The effect of the carrier density on the trapping parameter $F$ for various locations of minority carrier traps.

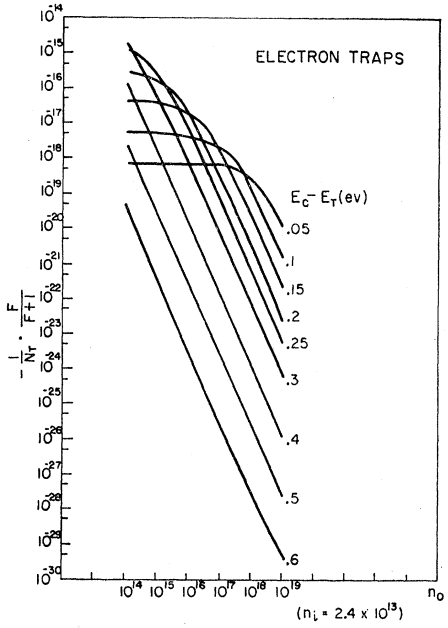


FIG. 3. The effect of the carrier density on the trapping parameter $F$ for various locations of majority carrier traps.

These considerations are of paramount significance in the case of the wide band gap compound semiconductors, wherein the extremely short carrier lifetimes make the use of steady state methods almost inescapable, yet wherein trapping effects are particularly large. Preliminary measurements[8] on GaAs did indeed bear out the predictions of this theory and they lent themselves to analysis as described above. These results will be reported in full in a later publication.

It is also noted that concomitant measurements of the spectral dependence of photoconductance and the PEM effect would aid in classifying the impurity centers, because an impurity PEM effect will occur in an extrinsic material only if the carriers thus generated from those centers are minority carriers.

## ACKNOWLEDGMENTS

The author is indebted to Mr. M. A. Lampert of these laboratories for valuable discussions, and to Dr. W. van Roosbroeck of the Bell Telephone Laboratories for many helpful comments which led to clarification and extension of certain aspects in the original manuscript.

[8] A. Amith, Bull. Am. Phys. Soc. 4, 28 (1959). In these experiments, the photoconductance and the PEM short-circuit current were measured in GaAs with $10^{10}$ electrons per cc, between 300°K and 90°K. As the temperature was lowered, the PEM signal decreased whereas the photoconductance increased. The apparent lifetime increased from $10^{-6}$ sec at room temperature to a few seconds at 90°K. However, when the PEM effect alone was used to deduce the lifetime of holes, it was found to decrease from $10^{-7}$ sec at room temperature to $10^{-10}$ sec at 90°K. Recombination centers of density of $10^{15}$ per cc lying 0.65 ev below the conduction band were derived by applying the Shockley-Read analysis. The value of the hole lifetime thus obtained was then substituted into the expression for the photoconductance, whence it was found that the number of hole traps located 0.23 ev above the valence band was $10^{16}$ per cc.

## APPENDIX A. GENERAL RELATIONSHIPS AMONG CARRIER DENSITIES

The continuity equations for the *excess* densities of free electrons, free holes, and trapped electrons, are

$$\begin{aligned}\partial n_f/\partial t &= -\mathfrak{R}_n+\mathfrak{G}_n+g_{tc}-r_{ct}+e^{-1}\,\mathrm{div}\mathbf{J}^-,\\ \partial p_f/\partial t &= -\mathfrak{R}_p+\mathfrak{G}_p-g_{tv}+r_{vt}-e^{-1}\,\mathrm{div}\mathbf{J}^+,\\ \partial n_t/\partial t &= -g_{tv}-g_{tc}+r_{vt}+r_{ct},\end{aligned} \tag{A.1}$$

note that the excess density of trapped electrons is negative in case that holes are trapped: $n_t=-p_t$. $\mathfrak{R}_n$, $\mathfrak{R}_p$ and $\mathfrak{G}_n$, $\mathfrak{G}_p$ are, respectively, the rates of recombination and rates of generation of excess electrons and holes. Other terms are defined in the text.

The rates of capture and of release of the carriers assume the following forms:

$$\begin{aligned}r_{ct}&=C_n(n_0+n_f)(N_t-n_t^0-n_t),\\ g_{tc}&=C_n n_1(n_t^0+n_t),\\ r_{vt}&=C_p p_1(N_t-n_t^0-n_t),\\ g_{tv}&=C_p(p_0+p_f)(n_t^0+n_t).\end{aligned} \tag{A.2}$$

$C_n$ and $C_p$ are the probabilities per unit time that a free electron or hole be captured in an impurity center when all centers are empty of that type of carrier (i.e., traps are all filled with electrons for the case of $C_p$). $n_t^0$ is the thermal equilibrium density of electrons trapped in the impurity centers the density of which is $N_t$.

At thermal equilibrium $r_{ct}=g_{tc}$ and $r_{vt}=g_{tv}$, hence

$$(N_t-n_t^0)/n_t^0=n_1/n_0=p_0/p_1. \tag{A.3}$$

The ratio of empty impurity centers to filled ones is

$$(N_t-n_t^0)/n_t^0=\exp[(E_T-E_F)/kT], \tag{A.4}$$

thus the proportionality constants $n_1$ and $p_1$ are

$$\begin{aligned}n_1&=n_0\exp\left(\frac{E_T-E_F}{kT}\right)\\ &=2(2\pi m_e kTh^{-2})^{\frac{3}{2}}\exp\left(\frac{E_T-E_c}{kT}\right),\\ p_1&=p_0\exp\left(\frac{E_F-E_T}{kT}\right)\\ &=2(2\pi m_h kTh^{-2})^{\frac{3}{2}}\exp\left(\frac{E_v-E_T}{kT}\right).\end{aligned} \tag{A.5}$$

In the steady state, all time derivatives in the continuity equation vanish, so that

$$g_{tc}-r_{ct}=-(g_{tv}-r_{vt}), \tag{A.6}$$

and consequently

$$g_{tc}-r_{ct}=C_n[n_1(n_t^0+n_t)-(n_0+n_f)\times(N_t-n_t^0-n_t)],$$
$$g_{tv}-r_{vt}=C_p[(p_0+p_f)(n_t^0+n_t)-p_1(N_t-n_t^0-n_t)], \quad (A.7)$$

from which follows the expression for the fraction of impurity centers which are occupied during illumination:

$$\frac{n_t^0+n_t}{N_t}=\frac{C_n(n_0+n_f)+C_pp_1}{C_n(n_0+n_1+n_f)+C_p(p_0+p_1+p_f)}. \quad (A.8a)$$

The fraction of impurity centers which are occupied at thermal equilibrium is, of course, dependent only on their energy level:

$$\frac{n_t^0}{N_t}=\frac{C_nn_0+C_pp_1}{C_n(n_0+n_1)+C_p(p_0+p_1)}=\frac{n_0}{n_0+n_1}=\frac{p_1}{p_0+p_1}, \quad (A.8b)$$

and the excess density of trapped electrons is

$$n_t=n_t^0\frac{C_nn_1n_f/n_0-C_pp_f}{C_n(n_0+n_1+n_f)+C_p(p_0+p_1+p_f)}. \quad (A.8c)$$

Equation (A.7) can now be rewritten in the following form:

$$g_{tc}-r_{ct}=-C_nC_pN_T\times\frac{n_0p_f+p_0n_f+n_fp_f}{C_n(n_0+n_1+n_f)+C_p(p_0+p_1+p_f)}. \quad (A.9)$$

The condition of local electrical neutrality is

$$n_f+n_t=p_f. \quad (A.10)$$

This condition would be fulfilled regardless of the magnitudes of the various carrier densities, provided that the semiconductor's dielectric relaxation time is much shorter than the sundry time constants associated with the return to equilibrium of the perturbed carriers. It is also implied that end effects are of no consequence, that is that the carriers' *Schubweg* is smaller than the crystal dimension in the direction of any applied bias.

Equations (A.8c) and (A.10) are combined to obtain relations among the carrier densities and the impurity centers's parameters. Whenever $C_n\neq 0$, we have

$$2n_f=-N_tn_1(n_0+n_1)^{-1}-(n_0+n_1)+p_f-C_pC_n^{-1}(p_0+p_1+p_f)+\{[N_tn_1(n_0+n_1)^{-1}+(n_0+n_1)+p_f+C_pC_n^{-1}(p_0+p_1+p_f)]^2+4N_tp_f(n_0C_pC_n^{-1}-n_1)(n_0+n_1)^{-1}\}^{\frac{1}{2}}, \quad (A.11a)$$

and when $C_p\neq 0$ then

$$2p_f=-N_tp_1(p_0+p_1)^{-1}-(p_0+p_1)+n_f-C_nC_p^{-1}(n_0+n_1+n_f)+\{[N_tp_1(p_0+p_1)^{-1}+(p_0+p_1)+n_f+C_nC_p^{-1}(n_0+n_1+n_f)]^2+4N_tn_f(p_0C_nC_p^{-1}-p_1)(p_0+p_1)^{-1}\}^{\frac{1}{2}}. \quad (A.11b)$$

Note that $n_f=p_f$ whenever

$$C_p=C_nn_1/n_0=C_n\exp\{(E_T-E_F)/kT\}.$$

If the impurity centers in question fulfil the conditions, defined in the text, under which they may be classified as *hole traps*, then

$$n_t=-N_tp_1p_f/(p_0+p_1)(p_0+p_1+p_f), \quad (A.12a)$$
$$n_f=p_f[1+N_tp_1/(p_0+p_1)(p_0+p_1+p_f)], \quad (A.12b)$$
$$p_f=\tfrac{1}{2}(p_0+p_1)^{-1}[-N_tp_1+(p_0+p_1)(n_f-p_0-p_1)+\{(p_0+p_1)^2(p_0+p_1+n_f)^2-N_tp_1\times[-N_tp_1+2(p_0+p_1)(n_f-p_0-p_1)]\}^{\frac{1}{2}}], \quad (A.12c)$$

if they are *electron traps*, then

$$n_t=N_tn_1n_f/(n_0+n_1)(n_0+n_1+n_f), \quad (A.13a)$$
$$n_f=\tfrac{1}{2}(n_0+n_1)^{-1}[-N_tn_1+(n_0+n_1)(p_f-n_0-n_1)+\{(n_0+n_1)^2(n_0+n_1+p_f)^2-N_tn_1\times[-N_tn_1+2(n_0+n_1)(p_f-n_0-n_1)]\}^{\frac{1}{2}}], \quad (A.13b)$$
$$p_f=n_f[1+N_tn_1/(n_0+n_1)(n_0+n_1+n_f)]. \quad (A.13c)$$

The general relationships (A.11a) and (A.11b) assume a much simpler form in the case of small signals, when the products $n_fn_t$ and $p_fn_t$ in Eq. (A.7) may be neglected:

$$n_f=\frac{C_n(n_0+n_1)+C_p(p_0+p_1)+C_pn_t^0}{C_n(n_0+n_1)+C_p(p_0+p_1)+C_nn_t^0n_1/n_0}p_f\equiv\Gamma p_f. \quad (A.14)$$

## APPENDIX B. THE PHOTOEFFECTS

The steady state continuity equation for holes is

$$e^{-1}\operatorname{div}\mathbf{J}^+=-\mathfrak{R}_p+\mathfrak{G}_p-C_nC_pN_t\times\frac{n_0p_f+p_0n_f+n_fp_f}{C_n(n_0+n_1+n_f)+C_p(p_0+p_1+p_f)}, \quad (B.1)$$

where the last term on the right describes transit of carriers through the impurity centers under study, in addition to the recombination mechanism implied in the term $\mathfrak{R}_p$. We are interested only in that situation where the impurity centers are traps, in which case they disappear explicitly from the continuity equation which becomes (when the recombination $\mathfrak{R}_p$ is linear)

$$e^{-1}\operatorname{div}\mathbf{J}^+=-p_f/\tau_p+\mathfrak{G}_p. \quad (B.2)$$

The total current density is composed of three parts, due to the electric field, the concentration gradient and the magnetic deflection

$$\begin{aligned}
&\mathbf{J}=\mathbf{J}_E+\mathbf{J}_c+\mathbf{J}_B,\\
&\mathbf{J}_E{}^-=e\mathbf{E}\mu(n_0+n_f),\quad \mathbf{J}_c{}^-=eD_n\nabla n_f,\\
&\mathbf{J}_B{}^-=-\mu_{nH}(\mathbf{J}_E{}^-+\mathbf{J}_c{}^-)\times\mathbf{B}/c,\\
&\mathbf{J}_E{}^+=e\mathbf{E}\mu b^{-1}(p_0+p_f),\quad \mathbf{J}_c{}^+=-eD_nb^{-1}\nabla p_f,\\
&\mathbf{J}_B{}^+=\mu_{pH}(\mathbf{J}_E{}^++\mathbf{J}_c{}^+)\times\mathbf{B}/c.
\end{aligned}\tag{B.3}$$

$\mu_{nH}$ and $\mu_{pH}$ are the Hall mobilities of electrons and holes, respectively; $c$ is the velocity of light. The explicit spatial components are

$$\begin{aligned}
&J_x{}^-=e\mu E_x(n_0+n_f)+\mu kTdn_f/dx+\theta_nJ_y{}^-,\\
&bJ_x{}^+=e\mu E_x(p_0+p_f)-\mu kTdp_f/dx+b\theta_pJ_y{}^+,\\
&J_y{}^-=e\mu E_y(n_0+n_f)+\mu kTdn_f/dy-\theta_nJ_x{}^-,\\
&bJ_y{}^+=e\mu E_y(p_0+p_f)-\mu kTdp_f/dy-b\theta_pJ_x{}^+,
\end{aligned}\tag{B.4}$$

where the electron and hole Hall angles are defined in terms of the respective carriers' Hall mobilities

$$\theta_n=-\mu_{nH}B/c,\quad \theta_p=\mu_{pH}B/c.$$

Consistent with the assumption that the $x$ dimension is large and thus does not affect the behavior in the bulk, is the result that $E_y$ (which for small signals is the Dember field, due solely to the different electron and hole mobilities) is indeed independent of the $x$ coordinate under short circuit conditions. This follows immediately from the condition $E_x=0$ and the requirement $\nabla\times\mathbf{E}=0$. This field is

$$E_y=-\frac{kT}{e}\frac{bdn_f/dy-dp_f/dy}{b(n_0+n_f)+p_0+p_f}.\tag{B.5}$$

Another consequence is that

$$J_x{}^-=\theta_nJ_y{}^-\quad\text{and}\quad J_x{}^+=\theta_pJ_y{}^+,\tag{B.6}$$

and the condition of no net electrical current in the $y$ direction $\int_0^t J_ydx$ reduces to $J_y=0$.

Substitution of Eq. (B.5) into Eq. (B.4) results in the following expression for the hole current in the direction of illumination

$$J_y{}^+=-\frac{\mu kT}{b(n_0+n_f)+p_0+p_f}\times[(n_0+n_f)dp_f/dy+(p_0+p_f)dn_f/dy],\tag{B.7a}$$

under small signal conditions, when $n_f=\Gamma p_f$, the last expression becomes

$$J_y{}^+=-\mu kT(n_0+\Gamma p_0)(bn_0+p_0)^{-1}dp_f/dy.\tag{B.7b}$$

Equations (B.7b) and (B.2) yield the following differential equation for the holes' spatial distribution:

$$d^2p_f/dy^2-\lambda^2p_f=-\mathcal{G}_p/D_T,\tag{B.8}$$

where

$$\lambda^2=(\tau_pD_T)^{-1},\quad\text{and}\quad D_T=\frac{n_0+\Gamma p_0}{n_0/D_p+p_0/D_n}.$$

Let $\mathcal{G}_n=\mathcal{G}_p=kQe^{-ky}$, in which $Q$ is the amount of illumination which is absorbed and generates carriers in the semiconductor sample. The boundary conditions to which the differential equation (B.8) is subject are:

$$\begin{aligned}
&\text{at}\quad y=0,\quad D_Tdp_f/dy=s_1p_{f1},\\
&\text{at}\quad y=t,\quad D_Tdp_f/dy=-s_2p_{f2}.
\end{aligned}\tag{B.9}$$

$s_1$ and $s_2$ are the surface recombination velocities, $p_{f1}$ and $p_{f2}$ are the hole densities at the two surfaces. The solution for the density of free holes is

$$\begin{aligned}
p_f=&Ce^{-ky}+C\Lambda\lambda D_T{}^2\{e^{-kT}(k-s_2/D_T)\\
&\times(s_1\lambda^{-1}D_T{}^{-1}\sinh\lambda y+\cosh\lambda y)-(k+s_1/D_T)\\
&\times[s_2\lambda^{-1}D_T{}^{-1}\sinh\lambda(t-y)+\cosh\lambda(t-y)]\},
\end{aligned}\tag{B.10}$$

in which

$$C=\frac{kQ}{D_T(\lambda^2-k^2)},$$

and

$$\Lambda^{-1}=(s_1s_2+\lambda^2D_T{}^2)\sinh\lambda t+(s_1+s_2)\lambda D_T\cosh\lambda t;$$

the other quantities of interest are:

$$\begin{aligned}
J_y{}^+=&eD_TCke^{-ky}-eD_T{}^3C\Lambda\lambda\{e^{-kt}(k-s_2/D_T)\\
&\times(s_1D_T{}^{-1}\cosh\lambda y+\lambda\sinh\lambda y)+(k+s_1/D_T)\\
&\times[s_2D_T{}^{-1}\cosh\lambda(t-y)+\lambda\sinh\lambda(t-y)]\},
\end{aligned}\tag{B.11}$$

$$\begin{aligned}
I^{sc}=&\int_0^t J_xdy=(\theta_p-\theta_n)\int_0^t J_y{}^+dy\equiv\theta\int_0^t J_y{}^+dy\\
=&eD_T\theta C(1-e^{-kt})+eD_T{}^3\theta C\Lambda\lambda[e^{-kt}(k-s_2/D_T)\\
&\times(1-\cosh\lambda t-s_1\lambda^{-1}D_T{}^{-1}\sinh\lambda t)\\
&+(k+s_1/D_T)(1-\cosh\lambda t\\
&-s_2\lambda^{-1}D_T{}^{-1}\sinh\lambda t)],
\end{aligned}\tag{B.12}$$

$$\begin{aligned}
\Delta G=&e\mu\int_0^t(n_f+b^{-1}p_f)dy=e\mu(b^{-1}+\Gamma)\int_0^t p_fdy\\
=&e\mu(b^{-1}+\Gamma)Ck^{-1}(1-e^{-kt})\\
&+e\mu(b^{-1}+\Gamma)C\Lambda D_T{}^2\{e^{-kt}(k-s_2/D_T)\\
&\times[s_1\lambda^{-1}D_T{}^{-1}(\cosh\lambda t-1)+\sinh\lambda t]+(k+s_1/D_T)\\
&\times[s_2\lambda^{-1}D_T{}^{-1}(1-\cosh\lambda t)-\sinh\lambda t]\}.
\end{aligned}\tag{B.13}$$

We shall now focus our attention on the case when

all carriers are generated right near the illuminated surface. The solutions for this case are the limiting forms of the expressions just derived, in which $k\to\infty$. Alternatively, the problem may be defined in terms of the differential equation (B.8) in which $\mathcal{G}=0$, and the new boundary conditions:

$$\begin{aligned} &\text{at}\quad y=0,\quad D_T dp_f/dy=s_1 p_{f1}-Q;\\ &\text{at}\quad y=t,\quad D_T dp_f/dy=-s_2 p_{f2}. \end{aligned} \tag{B.14}$$

The results are

$$p_f=Q\Lambda[s_2\sinh\lambda(t-y)+\lambda D_T\cosh\lambda(t-y)], \tag{B.15}$$

$$J_y^+=eD_TQ\Lambda\lambda[s_2\cosh\lambda(t-y)+\lambda D_T\sinh\lambda(t-y)], \tag{B.16}$$

$$I^{sc}=eD_TQ\theta\Lambda[s_2\sinh\lambda t+\lambda D_T(\cosh\lambda t-1)], \tag{B.17}$$

$$\Delta G=e\mu(b^{-1}+\Gamma)Q\Lambda\lambda^{-1}[s_2(\cosh\lambda t-1)+\lambda D_T\sinh\lambda t]. \tag{B.18}$$

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# Radiation Effects in Silica at Low Temperatures

GEORGE W. ARNOLD AND W. DALE COMPTON
*United States Naval Research Laboratory, Washington, D. C.*

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Optical absorption bands induced in fused silica and crystalline $\alpha$ quartz of low impurity content at 77°K by fast electrons or x-rays bleach slowly at room temperature. The presence of $OH^-$ ions in fused silica inhibits the formation of such radiation-induced absorption. Comparison of the number of centers produced at 215 m$\mu$ ($C$ band) in Corning 7943 fused silica ($OH^-$ free) for equal absorbed dose when irradiated with electrons and x-rays indicates that displacements are not involved in the initial formation of the color centers. A defect model requiring simple ionization seems adequate to explain most of the observed phenomena in this pure fused silica. No simple model can be proposed which adequately describes the data in the case of the Corning 7940 fused silica ($OH^-$ bearing).

## INTRODUCTION

IRRADIATION of fused silica or crystalline quartz with x-rays, gamma rays, fast electrons, or fast neutrons creates defect centers. These defect centers alter the properties of the original material in many ways. For example: (1) absorption of electromagnetic energy occurs at optical frequencies where the material was formerly transparent; (2) an appreciable number of paramagnetic centers is produced; (3) the thermal conductivity at low temperatures is altered; (4) the density is changed; (5) the crystalline structure is altered or even destroyed; and (6) the average separation among atoms is changed. Many of the property changes are related, for a given defect type may contribute to several of them. It is thus of considerable interest to determine, if possible, the nature of the defect centers that are responsible for the macroscopic property changes.

Information concerning specific models can often times be gained by studying the damage produced by x-rays and by fast electrons of various energies. For example, if a threshold energy for the production of the defect can be established, then the defect model requires the direct displacement of atoms to form vacancies and interstitials. This can be determined by measuring the optical absorption arising from the defect as a function of the incident energy of a fast electron. Furthermore, x-rays would not be expected to produce this type of damage. On the other hand, defects which can be formed by simple ionization of the lattice atoms would be expected to be produced by both x-rays and by fast electrons. The number of centers formed by fast electrons should be directly proportional to the stopping power of the material for electrons. A comparison of the optical absorption in fused silica for equal absorbed doses of electron and x-irradiation can also establish which of these two models more nearly describes the observed effects. This paper presents data on the damage induced in fused silica and crystalline $\alpha$ quartz by x-rays and by fast electrons of energies between 0.5 and 2.0 Mev. These data are then used to examine the models of the radiation-induced defects that give rise to the color centers in this material.

Some very definite models for the defects giving rise to optical absorption maxima have been proposed. These models and the experimental factors which bear on them are discussed in the following section.

## PRESENT MODELS OF THE DEFECTS

### *A*, *C*, and *E* Centers

The model of the center giving rise to the $A_1$ (620 m$\mu$) and $A_2$ (450–477 m$\mu$) bands in crystalline quartz has been firmly established as a result of combined optical[1]

[1] Ditchburn, Mitchell, Paige, Custers, Dyer, and Clark, *Report of Bristol Conference on Defects in Crystalline Solids July, 1954* (The Physical Society, London, 1955), p. 92.