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Validity of Small-Signal Analysis of Photoelectromagnetic and Photoconductive Effects in p-Type InSb

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Previous small-signal analyses of the photoelectromagnetic and photoconductive effect data on p-type InSb were based on the assumption of a linear electron-hole recombination rate. It is shown in this note that, for the recombination rate to be linear, the restriction on the excess minority carrier concentration Δn depends on the type of recombination centers involved, and can be much less severe than the condition suggested by Beattie and Cunningham, namely, $\Delta n \ll n_0$, where n_0 is the equilibrium electron concentration. The latter condition would require impracticably small values of Δn for a sample with an equilibrium hole concentration of about 10^{14} cm^{-3} at liquid-N_2 temperatures. In contrast, for the type of recombination models which have been applied to InSb, the less restrictive condition required values of Δn which are realizable in practice.

In a study of the large-signal photoelectromagnetic (PEM) effect in p-type InSb at 80 °K, Beattie and Cunningham[1] pointed out that earlier treatments of the PEM effect were based on the assumption that the thermal-equilibrium concentrations of carriers p_0, n_0 are much greater than their corresponding excess concentrations Δp, Δn. To show the limitations arising from this assumption, they used an example of p-type InSb with $p_0 = 10^{14}$ cm^{-3} at 80 °K; since the intrinsic carrier concentration $n_i \simeq 5\times 10^9$ cm^{-3}, $n_0 \sim 10^5$ cm^{-3}. With such a small value of n_0, it would obviously be very difficult to satisfy the condition $\Delta n \ll n_0$, because for a reasonably low light intensity of, say, 10^{15} photons cm^{-2} sec^{-1}, Δn would be of the order of 10^9 cm^{-3} when previously reported[2,3] values of lifetime and mobility are assumed. Beattie and Cunningham concluded that, since $\Delta n \gg n_0$, the recombination rate R may not be linear, and by implication, the small-signal PEM theory may no longer be applicable. If this is indeed the case, then the validity of previous low-temperature lifetime data[2,3] must be open to question, since these were analyzed on the basis of the small-signal theory.

The purpose of this note is to point out that while it is true that R is linear for $\Delta n \ll n_0$, it does not follow that R must be nonlinear for $\Delta n \gg n_0$. As we shall show below, the limitations which must be imposed on Δn for the small-signal theory to apply are far less stringent and depend on the characteristics of the recombination centers involved. Although we shall examine the small-signal assumption mainly in the context of the PEM effect, the same assumptions are involved in the small-signal theory of photoconductive (PC) effect, so that what follows will apply to the PC effect as well.

Our treatment is based on an earlier study of the surface photovoltage.[4] The problem there required a solution of ambipolar carrier diffusive transport in the direction of illumination, and is basically the same as in the case of the PEM effect. In that study, a detailed examination was carried out of the conditions required for linearizing the continuity equations for electrons and holes, in terms of both their net recombination rate and the divergence of the current. It was shown that for strong minority carrier trapping (as occurs in p-type InSb below 200 °K), the most severe restrictions on the excess carrier concentrations arise from the linearity constraints of the recombination-rate term rather than the divergence term. In the following discussion, therefore, we shall only be concerned with the recombination rate.

Compared to other semiconductors, the recombination behavior in InSb is relatively simple, since the same recombination levels have been found to occur in nearly all the materials studied thus far, what-in nearly all the materials studied thus far, whatever the source of these materials.[2,3,5] The recombination levels are donorlike, and are located at $E_1 = 0.11$ eV and $E_2 = 0.071$ eV[6] above the valence band, respectively. The question has arisen, however, whether these levels are interacting and thus belong to a single set of flaws,[3] or whether they are due to two independent sets of flaws.[4] In this note, we shall, therefore, consider both possibilities, and refer to them as the interacting-level (ITL) model and the independent-level (IDL) model.

It has been shown that for an IDL model[7] or an ITL model[8] having recombination levels at E_1 and E_2, the steady-state electron lifetime τ_n and hole lifetime τ_p are given by

$$\tau_n^{-1} = [(p_0 + \Delta p)(1+\gamma_p) + n_0(1+\gamma_n)] \sum_j \frac{c_{nj} c_{pj} N_j / H_j}{1+\gamma_p}, \quad (1)$$

$$\tau_p^{-1} = [(p_0 + \Delta p)(1+\gamma_p) + n_0(1+\gamma_n)] \sum_j \frac{c_{nj} c_{pj} N_j / H_j}{1+\gamma_n}, \quad (2)$$

where c_{nj} and c_{pj} are the electron and the hole capture coefficients of the flaws at E_j, n_j and p_j are the equilibrium carrier concentrations when the Fermi level lies at E_j,

$$H_j = c_{nj}(n_0 + \Delta n + n_j) + c_{pj}(p_0 + \Delta p + p_j), \quad (3)$$

$$\gamma_n = (1+\beta_2)\mu_{n1} + (1+\beta_1)\mu_{n2} - \beta_1\beta_2, \quad (4)$$

$$\gamma_p = (1+\beta_2)\mu_{p1} + (1+\beta_1)\mu_{p2} - \beta_1\beta_2, \quad (5)$$

and the remaining symbols are defined separately below for the IDL and ITL model.

For the IDL model, with $j = 1, 2$,

$$\beta_j = 0, \quad \mu_{nj} = c_{nj} N_{j0}^{+} / H_j, \quad \mu_{pj} = c_{pj} N_{j0}^{-} / H_j, \quad (6)$$

and N_j, N_{j0}^{+}, and N_{j0}^{-} are, respectively, the total concentration of flaws and the equilibrium concentrations of empty and filled flaws at E_j.

For the ITL model, where the flaws are divalent donors, there are three possible charge states associated with -2, -1, and 0 units of electronic charge. Using N_{-2}, N_{-1}, and N_0 to denote the flaw concentrations in the three charge states, with the superscript 0 designating their equilibrium values, we have

$$\beta_j = N_{2j-4}/N_j, \quad \mu_{nj} = c_{nj} N_{j-3}^{0} / H_j, \quad \mu_{pj} = c_{pj} N_{j-2}^{0} / H_j, \quad (7)$$

$$N_{j-3}/N_{j-2} = [c_{nj} n_j + c_{pj}(p_0 + \Delta p)] / [c_{nj}(n_0 + \Delta n) + c_{pj} p_j], \quad (8)$$

$$N_j = N_{j-3} + N_{j-2} \quad (j = 1, 2), \quad (9)$$

$$N = N_{-2} + N_{-1} + N_0. \quad (10)$$

From the expressions for the carrier lifetimes, it is obvious that R is linear or, equivalently, that τ_n and τ_p are constant or independent of Δn and Δp if $p_0 \gg \Delta p$ and $n_0 \gg \Delta n$. However, closer examination of the lifetime expressions for the IDL model reveals that the latter condition on Δn can be relaxed since, even though $\Delta n \gg n_0$, it suffices to have

$$p_0 \gg \Delta p, \quad (11)$$

$$c_{p1}(p_0 + p_1) \gg c_{n1}\Delta n, \quad (12)$$

$$c_{p2}(p_0 + p_2) \gg c_{n2}\Delta n, \quad (13)$$

to ensure that H_1 and H_2 are constant. Reference to Eqs. (4)–(6) then shows that this leads to constant γ_n and γ_p, and hence constant τ_n and τ_p.

For the ITL model, the linearization conditions (12) and (13) are replaced by

$$c_{p1}p_0, \; c_{p1}p_1 \gg c_{n1}\Delta n, \quad (14)$$

$$c_{p2}p_0, \; c_{p2}p_2 \gg c_{n2}\Delta n. \quad (15)$$

These more stringent conditions are required to ensure that β_1, β_2 and N_1, N_2 are independent of Δn.

It is important to emphasize that conditions (11)–(15) are for a two-level model. If, however, conditions are such that only one of the levels – say, level 1 – is operative, the linearization conditions for both the IDL and the ITL models would reduce to (11) and (12).

Let us now apply the above models to p-type InSb with $p_0 = 10^{14}$ cm^{-3} at 80 °K, the example considered by Beattie and Cunningham.[1,9] As an initial estimate, let us use values of the recombination parameters deduced from previous lifetime measurements done at low but unspecified light intensities.[2,3,5] These are $c_{n1} = 3 \times 10^{-5}$, $c_{p1} = 6 \times 10^{-10}$, $c_{n2} = 2 \times 10^{-6}$, and $c_{p2} = 2.2 \times 10^{-8}$ cm^{-3} sec^{-1}; $p_1 = 3 \times 10^{13}$, $n_1 = 1 \times 10^{6}$, $p_2 = 1 \times 10^{11}$, and $n_2 = 3 \times 10^{8}$ cm^{-3}.

For the IDL model, we find that, since

$$c_{p2}/c_{n2} \gg c_{p1}/c_{n1} = 2 \times 10^{-5},$$

condition (12) is the most stringent of the three conditions (11)–(13). Numerically, condition (12) may be stated as $\Delta n \ll 3 \times 10^{9}$ cm^{-3}. Note that, had we applied the condition $\Delta n \ll n_0$, the restriction on Δn would have been $\Delta n \ll 10^5$ cm^{-3}.

For the ITL model with the value of p_0 and the recombination parameters as given, it turns out that, as long as (11) and (12) are satisfied, the effect of level 2 on the lifetimes is negligible anyway.[10] Now, conditions (11) and (12) also happen to be the linearization conditions when only level 1 is operative. We conclude, therefore, that whether we use the IDL or the ITL model, the restriction on Δn is the same, and is given by (12).

The above conclusions apply to more extrinsic p-type material as well, since the approximation of both the IDL and ITL models to a one-level model improves as the Fermi level moves closer to the valence band. In this connection, it is interesting to observe that according to (12), the restriction on Δn should be less severe the larger the value of p_0. This is contrary to what we would expect if the restriction on Δn is governed instead by $\Delta n \ll n_0$. Thus, if $p_0 = 2 \times 10^{15}$ and $n_0 = 10^4$ cm^{-3}, condition (12) would become $\Delta n \ll 4 \times 10^{10}$ cm^{-3}, whereas using $\Delta n \ll n_0$ would require $\Delta n \ll 10^4$ cm^{-3}, an impracticably low value.

As stated earlier, the value of c_{p1}/c_{n1} that we use in evaluating condition (12) is obtained from previous measurements done at unspecified values of Δn. However, if we take the values of τ_n and τ_p obtained by Beattie and Cunningham[9] at the smallest photon flux density they used (corresponding to a value of Δn less than 10^9 cm^{-3}) and analyze them in terms of level 1 with a typical value of N_1 ($\simeq 10^{14}$ cm^{-3}), we arrive at a ratio of $c_{p1}/c_{n1} \simeq 2 \times 10^{-5}$, in excellent agreement with our value.

In the light of the foregoing discussion, it would appear that previous low-temperature lifetime data, which are self-consistent over a wide range of carrier concentrations, are unlikely to be seriously in error, despite the fact that they were analyzed on the basis of the small-signal PEM and PC theory.

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[3]R. A. Laff and H. Y. Fan, Phys. Rev. 121, 53 (1961).
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[5]J. E. L. Hollis, S. C. Choo, and E. L. Heasell, J. Appl. Phys. 38, 1626 (1967).
[6]As pointed out in Ref. 5, the difference between the value of 0.071 eV used here and the value of 0.055 eV given by Laff and Fan is due simply to the different values of hole effective mass used.
[7]J. Okada, J. Phys. Soc. Japan 13, 793 (1958).
[8]S. C. Choo, Phys. Rev. B 1, 687 (1970).
[9]A. R. Beattie and R. W. Cunningham, J. Appl. Phys. 35, 353 (1964).
[10]For the IDL model with N_1 comparable to N_2, the same conditions would also make the effect of level 2 negligible.

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ERRATA

Quantum Dielectric Theory of Electronegativity in Covalent Systems. II. Ionization Potentials and Interband Transition Energies, J. A. Van Vechten [Phys. Rev. 187, 1007 (1969)]. There are six errors among the values of the spectroscopic or Phillips fraction of ionic character,

$$f_{i\,\text{Phillips}},$$

quoted in Table IV. The values of the energy gaps E_h, C, and E_g and of the other parameters are correct. These errors do not affect the results of this paper, but should be noted when applying the ionicity concept to the compounds involved. A table of the quoted and corrected values follows.

Crystal	f_i (quoted) Phillips	f_i (corrected) Phillips
BeSe	0.299	0.261
BeS	0.312	0.286
GaP	0.374	0.327
ZnTe	0.546	0.609
CdTe	0.675	0.717
ZnSe	0.676	0.630