Photoconductivity and recombination in amorphous silicon alloys

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We have developed a new model to describe realistically the steady-state photoconductivity in amorphous silicon alloys. In agreement with experimental data, we find photoconductivity to be very dependent on the position of the dark Fermi level. This sensitization is a consequence of both a change in the recombination path together with the effects of dopant-created gap states. We also demonstrate the relationship between the power dependence of the photoconductivity and the dark-Fermi-level position and show that, as a result of space-charge neutrality, this dependence can be related to a characteristic energy slope of the density of states only in the absence of injected charge or dopants. Moreover, in agreement with recent experimental data, we find a power dependence of less than 0.5 for high-intensity illumination on n-type amorphous silicon.

I. INTRODUCTION

One of the important properties of amorphous silicon alloys is the high ratio of photoconductivity to dark conductivity when illuminated with global air mass 1.5 radiation. This, together with other good transport properties, has led to these alloys being ideally suited for photovoltaic devices as well as for electrophotography and other image sensing applications.[1–4]

There is now much experimental data[5–9] in the literature showing the relationship between the photoconductivity and dark conductivity in amorphous silicon alloys. In particular, experimental results show that the photoconductivity increases as the Fermi level is moved closer to the conduction-band edge. This was first reported on by Anderson and Spear[5] and more recently by Beyer and Hoheisel[7] who have shown the dependence of photoconductivity on Fermi-level position for both undoped and lightly doped samples from different laboratories. Simultaneously, there is a reduction in γ, the power dependence of the photoconductivity with intensity.[5,8,10] It is interesting to note that there appears to be a general trend relating these properties for films grown under different deposition conditions.

It seems therefore that a generalized theoretical model for the photoconductivity of amorphous silicon-based materials should predict both its dependence as well as the change in its power dependence on the position of the dark Fermi level.

Rose[11] proposed a model for photoconductivity based on the assumption of an exponential distribution of traps, and directly related the power dependence to the characteristic energy slope of this distribution. This model is appropriate for undoped samples but a more detailed approach is required in the analysis of doped samples, or films into which charge has been injected. We propose a new model based on two exponential distributions of both acceptorlike and donorlike traps that adequately explains both the change in photoconductivity and its power dependence with dark-Fermi-level position, E_{F0}. The sensitization of the photoconductivity is interpreted in terms of a change in the occupation of these traps, which is also responsible for the variation of the power dependence.

In the case of Fermi-level shifts caused by the addition of dopants we also investigate the effects of dopant-created gap states and show that in some cases they can actually increase the sensitization with respect to the dark-Fermi-level position.

In Sec. II A of this paper we describe, in detail, our complete photoconductivity model and in Sec. II B a simplified analytic approach which clearly illustrates the change in recombination path with movement of the dark Fermi level. In Sec. III we show the results of our computer simulation and a detailed discussion follows in Sec. IV.

II. THEORY

A. Complete photoconductivity model

We propose a simplified representation of the density of localized states within the mobility gap of amorphous semiconductors. It is based on the assumption that there are both acceptorlike states and donorlike states with the former predominantly in the upper-half of the gap and the latter dominating below midgap. Various experimental measurements[12–14] made on undoped amorphous silicon alloys suggest that the acceptorlike states consist of two different distributions both exponential in energy. First, there are tail states near the conduction-band edge, whose characteristic energy slope E_1 is comparable with the thermal voltage at room temperature, and deep localized states whose characteristic energy E_2 is approximately 86 meV. For the lower-half of the gap the tail states[14] have a characteristic energy E_3 of 43 meV and we have assumed that the deep donorlike states have an exponential distribution with a characteristic energy E_4 equal to 129 meV. Figure 1 shows our representation of the density of states in amorphous silicon alloys. We should point out that in reality, the density-of-states spectrum may be much more complicated than that shown in Fig. 1. In particular, it may depend critically on deposition conditions. However, the good agreement between experimental data and the computed results based on this model

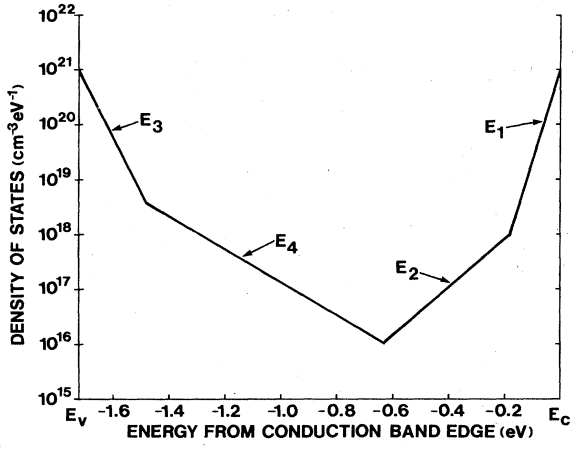

FIG. 1. Density-of-states spectrum for amorphous silicon. E_1, E_2, E_3, and E_4 are the characteristic energies of the four exponential distributions (see text).

suggest that the simplified representation is indeed useful.

There have now been various approaches used to model the photoconductivity in amorphous materials, based on a continuous distribution of localized states in the mobility gap.[15–17] For uniform absorption of light in the absence of electric fields, the material must be neutral and the generation rate G equal to the recombination rate R. Hence:

$$\rho=0\ , \tag{1}$$

$$G=R\ , \tag{2}$$

where ρ is the space-charge density.

ρ is given by

$$\rho=q(p_t-n_t+N_D^+-N_A^-+p-n)\ , \tag{3}$$

where p_t,n_t are the densities of trapped charge; N_D^+,N_A^- are the densities of ionized dopants and n,p the free-carrier densities. To determine the densities of trapped charge we have used the approach first proposed by Taylor and Simmons.[15] For each trap level we apply the Shockley-Read-Hall (SRH) recombination model to determine the probability that it is occupied by an electron. The total density of trapped negative charge will then be given by integrating this probability function with the density of acceptorlike states throughout the gap, and conversely p_t can be found by integrating the donorlike state spectrum with the probability of their being empty.

In previous publications, where we have used a photoconductivity model to provide a trial solution for the numerical solution of the complete set of transport equations for a p-i-n diode we used zero-temperature statistics in calculating n_t and p_t.[17,18] This approach is valid provided that the trap quasi-Fermi levels do not significantly enter the tail states. This is because, as has been shown previously in an analysis of the characteristics of amorphous silicon field-effect transistors,[13] when the Fermi level (or quasi-Fermi levels in the case of optical excitation) enter the tail states the product of the density of states and the Fermi-Dirac distribution function may increase with increasing energy. Consequently, when the Fermi level is in the tail states, most of the trapped charge is actually located above the Fermi level if the characteristic energy of the tail states, E_1, is comparable with the thermal energy. In this analysis we want to investigate the change in the power dependence of photoconductivity as the trap quasi-Fermi levels do indeed enter the tail states, and so we have evaluated n_t and p_t with use of a full numerical integration.

For acceptorlike states, the probability of occupation $f_A(E)$ as given by the SRH analysis for a trap at an energy level E_t is

$$f_A(E)=\frac{n+CN_v\exp\left[\dfrac{E_v-E_t}{kT}\right]}{n+Cp+CN_v\exp\left[\dfrac{E_v-E_t}{kT}\right]+N_c\exp(E_t-E_c/kT)}\ , \tag{4}$$

where N_c and N_v are the effective densities of states in the conduction and valence bands, respectively, and

$$C=\sigma_c/\sigma_N\ , \tag{5}$$

where σ_c is the capture cross section of a charged trap and σ_N is the capture cross section of a neutral trap.

For donorlike states, the occupation probability $f_D(E)$ is given by

$$f_D(E)=\frac{nC+N_v\exp\left[\dfrac{E_v-E_t}{kT}\right]}{nC+p+N_v\exp\left[\dfrac{E_v-E_t}{kT}\right]+CN_c\exp\left[\dfrac{E_t-E_c}{kT}\right]}\ . \tag{6}$$

Hence n_t and p_t are given by

$$n_t=\int_{E_v}^{E_c} f_A(E)g_A(E)dE \tag{7}$$

and

$$p_t=\int_{E_v}^{E_c}[1-f_D(E)]g_D(E)dE\ , \tag{8}$$

where $g_A(E)$ and $g_D(E)$ are the distributions of acceptorlike and donorlike localized states, as shown in Fig. 1.

From the SRH model we find that carriers recombine via states whose energies lie between the electron and hole trap quasi-Fermi levels. In effect, these represent the demarcation levels between traps and recombination centers.

For acceptorlike states these are given by

$$E_{tn}^{a}=E_c+kT\ln\left[\frac{n+pC}{N_c}\right], \tag{9}$$

$$E_{tp}^{a}=E_v-kT\ln\left[\frac{p+n/C}{N_v}\right], \tag{10}$$

$$E_{tn}^{d}=E_c+kT\ln\left[\frac{n+p/C}{N_c}\right], \tag{11}$$

$$E_{tp}^{d}=E_v-kT\ln\left[\frac{nC+p}{N_v}\right]. \tag{12}$$

The recombination rate R is given by

$$R(x)=(pn-n_i^2)Cv\sigma_N\left[\frac{1}{(n+Cp)}\int_{E_{tp}^{a}}^{E_{tn}^{a}}g_A(E)dE+\frac{1}{(nC+p)}\int_{E_{tp}^{d}}^{E_{tn}^{d}}g_D(E)dE\right], \tag{13}$$

where n_i is the intrinsic carrier concentration and v the thermal velocity.

The term pn-n_i^2 is often referred to as the "driving force" of recombination. We added the n_i^2 term to take into account the thermal generation of carriers. We have found $v\sigma_c\sim 5\times 10^{-9}$ cm^3/sec to be an appropriate value and have assumed an electron band mobility of 20 cm^2/V sec. This value for $v\sigma_c$ leads to a fairly small effective trap size which may imply a small barrier for carrier capture. Equations (1)—(13) represent our photoconductivity model for amorphous silicon alloys. The solution of these equations requires iterative computer techniques and the results of these calculations will be presented in Sec. III.

Finally, we have also attempted to include the effects of dopant-created gap states into our model. As we shall see later, these states drastically alter the sensitization of the photoconductivity to dark-Fermi-level position. Recent experimental evidence[19,20] suggests that the created defect density is proportional to the square root of the dopant density, and so in our model for the density of states we have set

$$g_{\min}(N)=g_{\min}(N=0)+K[N/g_{\min}(N=0)]^{1/2}, \tag{14}$$

where

$$g_{\min}(N=0)=10^{16}\ \text{cm}^{-3}\ \text{eV}^{-1}$$

and N is the dopant concentration per cm^3. We also have assumed that the tail-state distributions are unaffected by dopants and hence an increase in $g_{\min}$ with dopants will consequently alter E_2 and E_4 accordingly.

B. Analytic photoconductivity model

It is also extremely useful to simplify the photoconductivity problem so that it can be solved analytically as this enables us to investigate the basic physics contained in the complete set of equations. This has enabled us to interpret more completely the results of the computer simulation.

Our analytical model is a simple SRH model involving two discreet trap levels, one acceptorlike and one donorlike, with equal densities n_T. The recombination rate for electrons, R_n, is simply given by

$$R_n=n\sigma_c n_T\left[1-f_D+\frac{1-f_A}{C}\right] \tag{15}$$

and for holes, R_p, where

$$R_p=p\sigma_c n_T\left[\frac{f_D}{C}+f_A\right]. \tag{16}$$

As $R_n=R_p$ we obtain

$$f_D=nC/(p+nC), \tag{17}$$

$$f_A=n/(n+pC). \tag{18}$$

Although this simple photoconductivity model can be solved analytically, its importance is in allowing us to calculate the ratio of free electrons to holes, as we can see from Eqs. (17) and (18), this determines the occupation of the traps and hence their "effectiveness" as recombination centers. As we shall see later it is the change in the recombination which takes place from donorlike states to acceptorlike states that causes the photoconductivity and its power dependence to vary with dark-Fermi-level position. If we write $N=N_D^{+}-N_A^{-}$ then for the two-level model we may approximate Eqs. (1) and (3) as

$$p_t=n_t-N. \tag{19}$$

This is based on the assumption that in amorphous silicon the densities of trapped carriers are very much greater than the density of free carriers. This is valid as long as the quasi-Fermi levels do not come within $3kT$ of the band edges.[21]

Equation (19) can be expanded such that

$$\frac{p}{p+nC}=\frac{n}{n+pC}-N/n_T \tag{20}$$

and hence

$$\frac{n}{p}=\frac{-DC-(D^2C^2-4D^2+4)^{1/2}}{2(D-1)} \quad \text{for } D=(N/n_T)<1 \text{ and } C\gg 1. \tag{21a}$$

For $DC\gg 1$ Eq. (21a) can be simplified to

$$\frac{n}{p}=\frac{DC}{1-D}. \tag{21b}$$

Figure 2(a) shows a plot of n/p versus D for various values of C. We can see that the addition of ionized donors increases the n/p ratio dramatically and that this increase is enhanced when C is large.

Using Eqs. (15)—(18), we can calculate the ratio of the recombination rate at the donorlike traps to acceptorlike traps as a function of D for various values of C. This is shown in Fig. 2(b). With the addition of ionized donors,

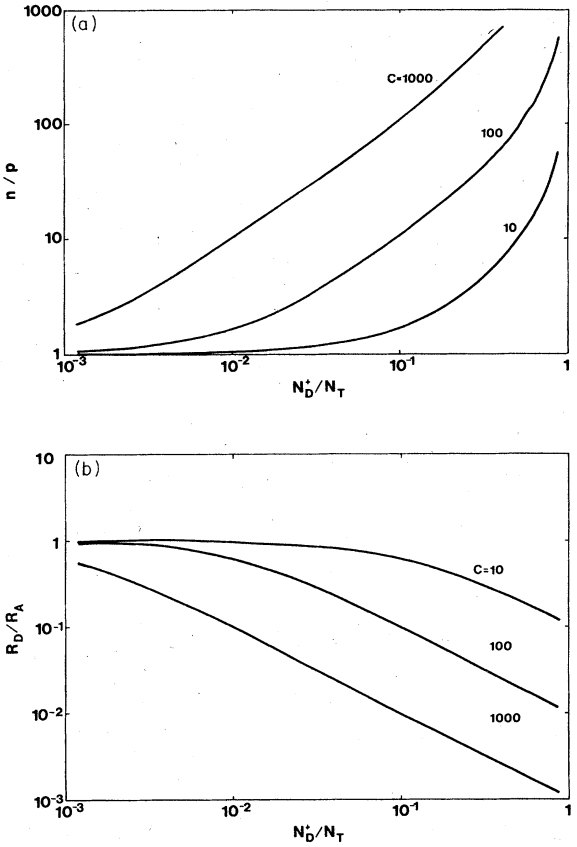

FIG. 2. (a) Ratio of free-electron to hole concentration. (b) Ratio of recombination taking place at donor traps to acceptor traps, as a function of doping for various ratios of C (the ratio of the charged to neutral capture cross section), as computed from the simplified two-level model. N_T is the trap density.

the recombination takes place more and more at the acceptorlike states and this process is once again increased by large values of C. This is a consequence of the donorlike states becoming more neutral as n/p increases. These observations are needed to explain the results of the full photoconductivity model which are presented in the next section.

III. RESULTS

Figure 3 shows the variation in photoconductivity as a function of dark-Fermi-level position for various values of C (the ratio of charged to neutral capture cross section) and an absorbed photon density (flux multiplied by absorption coefficient) of 10^{19} photons/cm^3 sec^{-1}. These curves were computed using the complete photoconductivity model, i.e., Eqs. (1)—(14). The photoconductivity does indeed increase with decreasing $E_c - E_{F0}$ and it can be seen that for $E_c - E_{F0} \sim 900$ meV, σ_{ph} is independent of C; for "intrinsic" samples (i.e., $E_c - E_{F0} \sim 600$ meV) it is weakly dependent on C, and for $E_c - E_{F0} \sim 400$ meV the photoconductivity becomes linearly dependent on the value of C. Finally, we may note that in agreement with experimental data, the photoconductivity peaks at

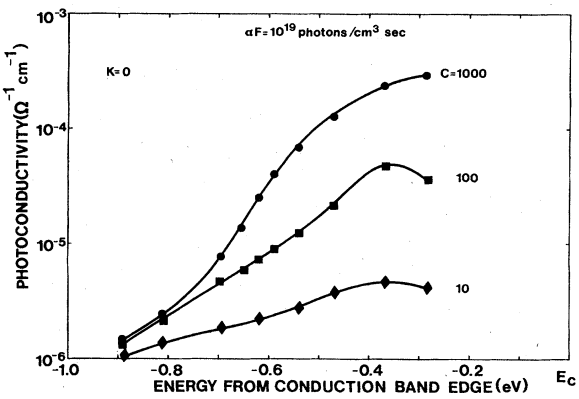

FIG. 3. Computed photoconductivity as a function of dark-Fermi-level position for varying values of C.

$E_c - E_F$ between 200 and 400 meV depending on the value of C. In calculating the results of Fig. 3, we have not introduced dopant-created defect states and so this corresponds to the case of the dark Fermi level shifted by injected charge such as in a field-effect structure.

In Fig. 4 we show the sensitization of the photoconductivity as a function of $E_c - E_{F0}$ for varying values of the parameter K as defined by Eq. (14), i.e., varying dependence of defect creation on the dopant concentration. In this case also, calculations have been carried out for an absorbed photon density of 10^{19} photons/cm^3 sec^{-1}, roughly corresponding to an incident flux of 5×10^{14} photons/cm^2 sec^{-1} for "uniform" absorption of light of energy 2 eV. Also plotted in Fig. 4 are experimental results from Anderson *et al.*[5] showing the sensitization of photoconductivity in gap-cell samples where $E_c - E_{F0}$ was shifted by the introduction of dopants.

As expected, we can see that the addition of dopant-created gap states ($K > 0$) does indeed reduce the photoconductivity of samples with $E_c - E_{F0} > 650$ meV. However, for $E_c - E_{FO} \sim 600$ meV we can see that the photoconductivity actually increases with increasing value of K and this will be fully discussed in the next section. Final-

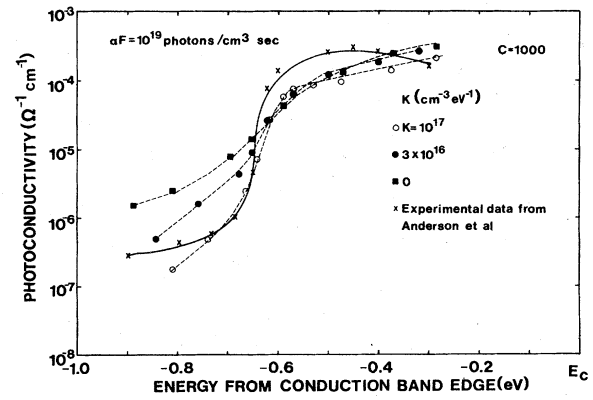

FIG. 4. Computed photoconductivity as a function of dark-Fermi-level position for various values of K, i.e., dependence of dopant-created gap states on dopant density, together with experimental data from Anderson *et al.*

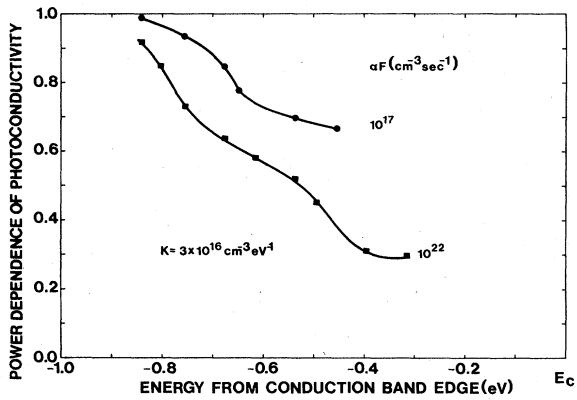

FIG. 5. Computed power dependence of photoconductivity as a function of dark-Fermi-level position for two different photon fluxes.

ly, we may note that a value of $K=3\times10^{16}$ cm^{-3}eV^{-1} yields a very good fit to the experimental data of Anderson *et al.*[5]

Assuming $K=3\times10^{16}$ cm^{-3}eV^{-1} to be useful representation of the relationship between $g_{\min}$ and the dopant density as related by Eq. (14), in Fig. 5 we show the power dependence of the photoconductivity, γ, as a function of E_c-E_{F0} for two different absorbed photon densities. At low-light levels γ changes from approximately unity for "boron"-doped samples to 0.6 for $E_c-E_{F0}=0.4$ eV. In the case of high-light levels, we see γ reduce from around unity to 0.3 as E_c-E_{F0} is reduced from 0.9 to 0.3 eV, having a value close to 0.5 for intrinsic films.

In Fig. 6 we compare the high-intensity γ dependence on E_c-E_{F0} for $K=0$ and $K=3\times10^{16}$ cm^{-3}eV^{-1} corresponding to Fermi-level shifts by injected charge and ionized dopants, respectively. It appears that dopant-created gap states are responsible for a steeper variation of γ with E_c-E_{F0}. Also shown in Fig. 6 is our own experimental result of a gap-cell PH_3-doped amorphous silicon sample

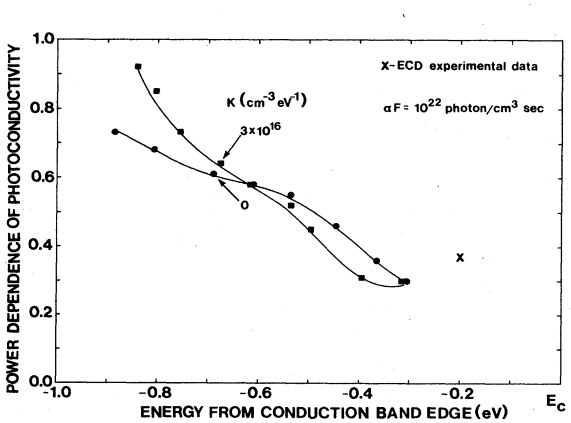

FIG. 6. Power dependence of photoconductivity as a function of dark-Fermi-level position for samples where this has been moved by doping ($K=3\times10^{16}$) and injected charge ($K=0$). Also shown is experimental data showing $\gamma=0.37$.

with an activation energy of 0.2 eV whose γ factor was 0.37. Further details of our sample preparation are given in Ref. 22. As will be discussed later, there is every reason for γ to be less than 0.5 in heavily doped samples at high illumination intensities as a result of space-charge considerations. This also agrees with published results by Kagawa *et al.*[8]

IV. DISCUSSION

A. Photoconductivity dependence on C

An increase in photoconductivity with movement of the Fermi-level position was first described by Rose.[11] He interpreted this sensitization as a change in the occupancy of the traps in the "band gap" of a material, resulting in a change in the recombination path.

This is indeed the basic mechanism causing the increase in photoconductivity with decreasing E_c-E_{F0} as shown in Fig. 3. It is worth stressing at this point that Fig. 3 shows photoconductivity results at low illumination intensities, i.e., where E_{tn}^a does not enter the tail states. In previous publications[17,18] where we have considered recombination in undoped amorphous films, we have noted that most of the recombination takes place around the hole trap quasi-Fermi level of the donorlike states. Hence, we may express the recombination rate R as

$$R=K_1 n p_t \ , \tag{22}$$

where K_1 is a constant of proportionality. For samples with E_c-E_{F0} greater than that of intrinsic films $p_t>n_t$ and hence we still expect the recombination to predominantly occur at donorlike states. From the results of our two-level simplified photoconductivity model, we can see that as E_c-E_{F0} decreases from its intrinsic value, the recombination occurs more increasingly at acceptorlike states. This is because, n-type doping increases the n/p ratio, see Fig. 2(a). From Eq. (17) we can see that this results in the donorlike states becoming "full" of electrons, i.e., $1-f_D\rightarrow0$ as $n/p\rightarrow\infty$. This means that electrons can no longer recombine at charged donorlike states, resulting in the main process now being that of holes to charged acceptorlike states.

The solution of the two-level model does indeed show that this change in the recombination path causes an increase in photoconductivity. The solution of the full photoconductivity model shows that the main factor determining the magnitude of this increase in photoconductivity with decreasing E_c-E_{F0} is the value of C (see Fig. 3).

In analyzing the effect of the ratio C (charged to neutral capture cross-section area) we may derive analytic expressions to relate $\sigma_{\rm ph}$ and C in three different regions.

(a) "Boron"-doped samples, with $E_c-E_{F0}>650$ meV where recombination predominantly occurs at donorlike states.

(b) "Intrinsic" samples where $n_t=p_t$ and recombination occurs at donorlike states.

(c) "Phosphorous"-doped samples where recombination now occurs at acceptorlike states.

1. Case (a)

In this case, we may now rewrite Eq. (19) as

$$p_t = n_t + N_A^-$$

and in the extreme case $p_t \sim N_A^-$. Hence from Eq. (22),

$$G \doteq R = K_1 n N_A^- \ . \tag{23}$$

Hence

$$\sigma_{\rm ph} \propto \frac{G}{N_A^-} \ . \tag{24}$$

Thus the photoconductivity is independent of C (as seen in Fig. 3) or rather does not depend on the neutral capture cross section. It also decreases with increasing boron content, and is linearly dependent on incident flux (agreeing well with Figs. 5 and 6), i.e., $\gamma = 1$.

2. Case (b)

Case (b) has been interpreted using zero-temperature statistics which are valid as here we are only concerned with low-level illumination and E_{tn}^a does not enter the tail states. As $n_t = p_t$ we may rewrite Eq. (22) as

$$R = G = K_1 n n_t \ . \tag{25}$$

Now n_t is given by

$$n_t = \int_{E_v}^{E_{tn}^a} f_A(E) g_A(E) dE \approx \frac{n}{n+Cp} \int_{E_{tp}^a}^{E_{tn}^a} g_A(E) dE \ . \tag{26}$$

For the illumination levels used in Fig. 3 the contribution to n_t from states below E_{tp}^a is negligible. We may express

$$g_A(E) = g_{A\min} \exp[(E - E_{mc})/kT_2] \tag{27}$$

and similarly

$$g_D(E) = g_{D\min} \exp[(E_{mc} - E)/kT_4] \ , \tag{28}$$

where E_{mc} is the energy difference between the minimum in the density of states and the conduction-band edge. Once again we need only consider deep states as E_{tp}^d does not enter the valence-band tail-state region at low intensities.

From Eqs. (26) and (27)

$$n_t = \left[\frac{n}{n+Cp} \right] kT_2 g_{A\min} \exp \left[\frac{E_{tn}^a}{kT_2} \right] \ , \tag{29}$$

where E_{mc} is taken as a reference energy, i.e., $E_{mc} = 0$, and

$$g_A(E_{tn}^a) \gg g_A(-E_{tp}^a) \ . \tag{30}$$

Substituting for E_{tn}^a from Eq. (9),

$$n_t = \left[\frac{n}{n+Cp} \right] kT_2 g_{A\min} \exp \left[\frac{E_c}{kT_2} \right] \left[\frac{Cp+n}{N_c} \right]^{T/T_2} \ . \tag{31}$$

For $n > Cp$ this leads to

$$R = G \propto n^{(T_2+T)/T_2} \tag{32}$$

or

$$\sigma_{\rm ph} \propto G^{T_2/(T+T_2)} \ . \tag{33}$$

Hence γ, the power dependence of photoconductivity, is given by

$$\gamma = \frac{T_2}{T+T_2} \ . \tag{34}$$

For $Cp > n$, which is more realistic for large C,

$$R = G \propto \frac{n^2 (Cp)^{T/T_2 - 1}}{N_c^{T/T_2}} \tag{35}$$

To interrelate n and p we note that in this case $n_t = p_t$ and p_t is given by

$$p_t = \frac{p}{nC} \int_{E_c}^{E_{tp}^d} g_D(E) dE \ , \tag{36}$$

whence

$$p_t = \frac{p}{nC} kT_4 g_{D\min} \exp \left[\frac{-E_v}{kT_4} \right] \left[\frac{nC}{N_V} \right]^{T/T_4} \tag{37}$$

as $nC \gg p$. Once again for the results shown in Fig. 3, p_t is determined by states in the vicinity of E_{tp}^d. By equating Eqs. (31) and (37) and noting $Cp > n$,

$$n^{2-T/T_4} \propto p^{2-T/T_2} \left[\frac{C}{N_v} \right]^{T/T_4 - T/T_2} \tag{38}$$

Hence Eq. (35) becomes

$$R = G \propto \frac{n^{2+[(T-T_2)/T_4](2T_4-T)/(2T_2-T)} \left[\frac{C}{N_v} \right]^{[(T-T_2)/T_2](T/T_4)(T_4-T_2)/(2T_2-T)}}{(N_c)^{T/T_2}} \tag{39}$$

or

$$\sigma_{\rm ph} \propto (N_c^{T/T_2} G)^{1-(T/2)(1/T_2+1/T_4)} \left[\frac{C}{N_v} \right]^{T/T_4[(T_4-T_2)/(2T_2)](1-T/2T_4-T/T_2)} \tag{40}$$

In deriving these equations, we have assumed that $T_2 > T$ and $T_4 > T$. As can be seen, the power dependence in this situation no longer equals $T_2/(T+T_2) \approx 1 - T/T_2$. However, for T_4 comparable to T_2 the two power dependencies are close numerically. In addition σ_{ph} is virtually independent of C, as for the case of $n > Cp$, whereas examining the results shown in Fig. 3, we see that for undoped material, the photoconductivity is in fact weakly dependent on C. This weak dependence is a consequence of some recombination occurring at acceptorlike states which will be discussed below.

3. *Case (c)*

Here we are considering n-type samples at low illumination intensities and from space-charge neutrality $n_t \sim N_D^+$ and as the recombination occurs at acceptorlike states

$$G = R = K_2 p n_t \ , \tag{41}$$

where K_2 is a suitable constant of proportionality. For large C, $Cp > n$ and hence n_t from Eq. (31) is given by

$$n_t \propto \frac{n}{Cp} \left[\frac{Cp}{N_c} \right]^{T/T_2} . \tag{42}$$

As

$$G = R \sim K_2 p N_D^+ \ , \tag{43}$$

$$p \propto \frac{n^{T/T_2 - 1}}{C} . \tag{44}$$

Hence

$$n \propto (GC)^{1 - T/T_2} . \tag{45}$$

We may note that Eq. (45) is in good agreement with the results shown in Fig. 3, and also the power dependence of n-type samples at low levels of illumination—see Fig. 5. As $T/T_2 \sim 0.3$ we see that photoconductivity in this situation is strongly dependent on the value of C. This result is very important as we find that to adequately fit the experimental data of phosphorous-doped samples, we require a large value for C so that the photoconductivity increase with Fermi-level shift is large.

B. Defect-created gap states

As can be seen from Figs. 3 and 4, a value of C in the range 100—1000 appears to be appropriate to yield a realistic sensitization with decreasing $E_c - E_{F0}$ from ~ 650 meV. In Fig. 4 we investigate the effects of dopant-created gap states on this sensitization so that we can simulate movement of the Fermi level by both dopants as well as injected charge. It is at first surprising to see that for $E_c - E_{F0} \sim 600$ meV the photoconductivity increases as K increases, i.e., we introduce more defect-created states. This is a consequence of the relationship between the density-of-states spectrum, dark-Fermi-level position, and photoconductivity. Movement of the dark Fermi level is determined by states around itself whereas photoconductivity is controlled by the states around the trap quasi-Fermi levels. Now the sensitization of the photoconductivity is a result of the induced or ionized charge altering the occupation probability of the traps and hence changing the recombination mechanism. Thus, if we can somewhat pin the dark Fermi level but also introduce charge into the material, we will increase the sensitization with respect to Fermi-level shift. The photoconductivity will be increased by the addition of negative charge to the system. Defect-created midgap states will result in more charge being added to the system for any given shift of the dark Fermi level, increasing the photoconductivity with respect to E_{F0}.

Hence, defect-created gap states, in this case, will increase the ratio of the photoconductivity to dark conductivity as shown in Fig. 4. Obviously a large increase in the density of the states around the trap quasi-Fermi levels would also suppress the photoconductivity, reducing the sensitization dependence on E_{F0}. However, as the trap quasi-Fermi levels are in a much higher density-of-states region than the dark Fermi level, it is reasonable to expect that dopant-created states will suppress movement of the dark Fermi level more than increasing the recombination around the trap quasi-Fermi levels.

C. Power dependence of photoconductivity

From Eqs. (34) and (40) it can be seen that for intrinsic samples the power dependence of photoconductivity, γ, can be simply related to the energy slope of the acceptorlike states. However, in deriving these equations, we have assumed that $n_t = p_t$. If charge is introduced into a sample, this condition no longer holds and γ no longer equals $T_2/(T+T_2)$. Figure 5 shows γ versus $E_c - E_{F0}$ for two different absorbed photon densities. For both intensities γ is approximately unity for boron-doped samples, as predicted by Eq. (24).

For low-light levels where E_{tn}^a does not enter the tail states, addition of negative charge to the system reduces γ, even though for $E_c - E_{F0} < 650$ meV addition of more charge actually increases the value of T_2, due to an increase in g_{min}. Hence, from the simple formula $\gamma = T_2/(T+T_2)$ we would expect γ to increase. At high intensities we see γ reduce to less than 0.5, which cannot be explained by conventional models of monomolecular or bimolecular recombination. It is the change in the space-charge neutrality condition to

$$p_t = n_t - N \tag{19}$$

that invalidates simplified models for this γ dependence.

From Eqs. (19) and (22)

$$R = G = K_1 n (n_t - N) . \tag{46}$$

It may be noted that at high intensities, for heavily n-type samples, the main recombination path is electrons to charged donorlike states as opposed to low intensities where we have shown it to be holes to charged acceptorlike states. This is because as the illumination intensity is increased E_{tn}^a moves into a higher density of states. In the two-level model, this is equivalent to increasing the trap density and hence will decrease the n/p ratio, pushing recombination back to donorlike states. In this situation, E_{tn}^a will be in the tail states, and hence most of the nega-

tive space charge n_t lies in the tail states. Representing their distribution as $g_{ta}(E)$ where

$$g_{ta}(E)=g_{tc}\exp[(E_c-E)/kT_1] , \tag{47}$$

where g_{tc} is the density of states at an energy $E=E_c$. Hence

$$n_t=\int_{E_v}^{E_c} f_A(E)g_{ta}(E)dE . \tag{48}$$

Assuming $T_1\sim T$ or less than T, this integral lies at E_c and hence we may write n_t as

$$n_t\sim g_{tc}kT_1f_A(E_c) . \tag{49}$$

Substituting $E=E_c$ into Eq. (4) gives $f_A(E_c)=n/N_c$ and hence

$$n_t\sim g_{tc}kT_1\frac{n}{N_c} , \tag{50}$$

and thus n_t will be directly proportional to n (and independent of p). Thus we may write $n_t=K_3n$ and by substituting this into (46) we obtain

$$R=G=K_1n(K_3n-N) , \tag{51}$$

hence

$$n=\frac{K_1N+(K_1^2N^2+4GK_1K_3)^{1/2}}{2K_1K_3} . \tag{52}$$

Examining Eq. (52) we can see therefore that at high fluxes, in the absence of dopants, n is proportional to the square root of intensity, but that the addition of negative charge ($N>0$) will reduce the apparent power dependence to less than 0.5. This is clearly shown in Figs. 5 and 6 and confirmed by our own experimental result shown in Fig. 6. However, when $N>0$ we can also see that this power dependence is also a function of intensity, and so strictly we can see that doping leads to a breakdown of the conventional relationship of photoconductivity being proportional to flux to a specific power. Hence, in this case, it is more realistic to regard γ as an apparent power dependence at any particular flux.

We may mention that reports of a power dependence greater than unity[6] have been reported in the literature. This has been interpreted as a sensitization effect involving traps of different capture cross sections in the lower-half of the gap. Since this feature has not been universally observed,[5,7,8] we have not incorporated this mechanism into our model.

Finally, in another publication[23] we have also examined the temperature dependence of the photoconductivity of undoped samples as predicted by our model and find it to be in good agreement with experimental results. At low temperatures, the photoconductivity increases with increasing temperature with a power-law dependence which appears activated over specific temperature ranges. Around room temperature or above, the photoconductivity peaks, and this peak is associated with the dark conductivity becoming larger than the photoconductivity and the dominant role played by thermally generated carriers at high temperatures.

V. CONCLUSION

In conclusion, we have developed a new model to describe the steady-state photoconductivity in amorphous silicon alloys. In particular and in agreement with experimental data we show the following.

(1) Increase in photoconductivity as the dark Fermi level is moved from midgap towards the conduction-band edge. This sensitization is a consequence of both a change in the recombination path as well as the effects of dopant-created gap states. The magnitude of this sensitization has been shown to strongly depend on the ratio of the charged to neutral trap cross sections.

(2) The relationship between the power dependence of photoconductivity and dark-Fermi-level position. As a result of space-charge considerations γ cannot be directly related to the slope of the density of states in doped material. Moreover, in agreement with experimental data, γ is found to be less than 0.5 in n-type samples at high levels of illumination.

(3) Dopant-created defect states affect the sensitization with respect to Fermi-level position and can cause an increase in the photoconductivity to dark conductivity ratio for lightly n-type samples.

Note added in proof. There are some recent papers [H. Dersch, L. Schweitzer, and J. Stuke, Phys. Rev. B **28**, 4678 (1983) and R. A. Street, Philos. Mag. B **46**, 273 (1982)], which suggest that in amorphous silicon alloys dangling bonds are the predominant recombination centers. In this paper we have assumed that there is a continuous distribution of recombination centers (dangling bonds together with other defects) throughout the gap which in low defect density material controls carrier recombination. In another work [S. Guha and M. Hack, (unpublished)], we show that for high-quality samples recombination at dangling bonds alone is inconsistent with data from photoluminescence, photoconductivity, field-effect, and space-charge limited conduction experiments.

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