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Consistency between experimental data for ambipolar diffusion length and for photoconductivity when incorporated into the "standard" defect model for *a*-Si:H

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Reasonable consistency between experimental data for the ambipolar diffusion length and experimental data for the photoconductivity is demonstrated for steady-state measurements performed on *a*-Si:H layers. This consistency is obtained based on the "standard" defect model for *a*-Si:H. In this model the dangling bonds are taken into account, considering their amphoteric behavior and treating then as recombination centers, whereas the band tails are taken into account as simple two-valued defects acting as traps. Consistency is obtained based on (1) a particular form of the recombination function such as is considered appropriate for the dangling bonds, as well as, additionally, (2) the local charge neutrality condition. The experimental data analyzed are power laws of the ambipolar diffusion length and of the photoconductivity (versus light intensity); they are obtained for a series of slightly *p* and *n*-doped samples including the undoped case.

I. INTRODUCTION

The steady-state photoconductivity (σ_{ph}) and its variation vs light intensity has already been extensively studied in undoped as well as in doped *a*-Si:H films.[1-10] Various models have been successfully used for predicting the behavior of the dependence on light intensity as observed in this measurement. In the early pioneering works, one generally finds models based on two-valued recombination centers [as associated with the well-known Shockley–Read–Hall (SRH) function] for the description of the recombination process (see, for example, Refs. 2, 3, and 7). In more recent work the models were completed, taking into account the amphoteric nature of the dangling bonds, for the description of the recombination process (these then become recombination models based on three-valued, correlated recombination centers) (see, for example, Refs. 5, 6, 8, 10): in both cases one sometimes additionally considers exponential band tails; recently, one has further introduced a new concept by employing the "defect pool" model (see, for example, Ref. 9). We have to remark that practically all these models have been used with reasonable success to predict the light intensity dependence of the photoconductivity for doped and undoped samples. The analysis carried out by Balberg[11] of all these different models summarizes clearly that even simple models predict relatively well the power-law dependence of photoconductivity for doped and undoped materials. Balberg distinguishes between "standard" defect models for recombination centers which are based on a single level (or a single occupation-correlated set of levels) and more complicated defect models for recombination centers which are constituted by several different uncorrelated recombination levels (see, for example, Ref. 9). As discussed by Balberg[11] (see also Ref. 12), steady-state photoconductivity as a simple experiment does not yield enough information for one to conclude which of the different models is the most appropriate.

Balberg suggests that, with a supplementary measurement, i.e., with the measurement of the ambipolar diffusion length L_{amb} [as measured by the steady-state photocarrier grating technique (SSPG)[13,14]], one may hope to gain complementary information that would allow one to distinguish between the different models. The ambipolar diffusion length yields the mobility lifetime of the minority free carrier $(\mu\tau)_{amb}$ (here μ and τ denote the band mobility and the recombination time of the minority free carrier), and the photoconductivity yields the mobility lifetime of the majority free carrier $(\mu\tau)_{ph}$ (here, μ and τ denote the band mobility and the recombination time of the majority free carrier). By combining the data on the effect of the dark Fermi level E_f on $(\mu\tau)_{amb}$ and $(\mu\tau)_{ph}$ and on their light intensity dependencies, Balberg claims to deduce a clue for the more likely model. He concludes that to explain a certain dependence of $(\mu\tau)_{amb}$ with the light intensity (as really experimentally observed in Refs. 15, 16, and 17) it is necessary to consider at least two different uncorrelated recombination levels. In fact, Balberg claims that if one considers only a single level (or a single occupation-correlated set of levels) for the recombination model, then $(\mu\tau)_{amb}$ will be independent of the light intensity. Thus, according to Balberg's conclusion, the experimentally observed variation of $(\mu\tau)_{amb}$ versus light intensity (i.e., with a power-law exponent λ different from zero) excludes the "standard" model (i.e., a model based on a single recombination level or a single occupation-correlated set of levels) and favors models based on several uncorrelated recombination levels, as obtained in the defect pool model.

The aim of our present article is to demonstrate that a simple "standard" defect model, if correctly used, can indeed explain quantitatively the dependencies versus light intensity of both ambipolar diffusion length and photoconductivity [i.e., for both $(\mu\tau)_{amb}$ and $(\mu\tau)_{ph}$]. Thereby, we show the consistency between the data for the ambipolar diffusion length and for the photoconductivity when incorporated into a simple standard defect model. Contrary to Balberg's conclusion, we contend here that a more complicated model

such as the defect pool model is not at all necessary to simultaneously understand the behavior of steady-state photoconductivity and ambipolar diffusion length versus light intensity. To obtain such a conclusion we have used in our study a model where the localized states are composed of exponentially distributed band tails and dangling bonds. In our model the dangling bonds are the main recombination centers: They are considered being three-valued recombination centers (positively ionized D^+, negatively ionized D^-, and neutral D^0 dangling bonds) and constitute a single correlated set of levels; our model must, thus, be considered a standard type of defect model for the recombination. In a previous work by our group,[18] a closed-form expression was derived for this type of recombination via three-valued correlated dangling bonds; it is the same closed-form expression that is used in the present article. In our present considerations the band tails act only as traps for holes and electrons (we neglect the contribution of the band tails to recombination). Our predictions are obtained by considering, in addition to the recombination traffic via dangling bonds, also the condition of local charge neutrality (including in the local charge neutrality equation both the charge due to the band tails and the charge due to the dangling bonds).

We have to remark that Balberg,[11] in his study, took into account, when looking at the standard model, the recombination mechanism in an oversimplified form by asserting that the density of the capture centers for minority carriers cannot be significantly affected by a variation in light intensity [all the recombination centers are, according to his considerations, occupied by trapped majority carriers and, thus, all these centers can only capture free minority carriers; thereby $(\mu\tau)_{\mathrm{amb}}$ becomes independent of the light intensity]. Balberg has thereby implicitly reduced the process of recombination via dangling bonds to a SRH-like recombination process for which the minority carriers control the recombination and for which, in effect, no dependence on light intensity is predictable for L_{amb}. However, in reality there does exist a particular case specific to the recombination process via three-valued, correlated recombination centers, for which this process is not reduceable to a SRH-like recombination process, for which, surprisingly, the majority-carrier density governs the recombination; now, indeed, a dependence of L_{amb} on light intensity is predictable. Such a situation is intuitively and physically explained in Sec. III and is treated in detail in Sec. II as the third "specific" case studied in the present article [case c]. This situation is assimilated to that of "undoped" material where free electrons (holes) are in majority (minority), and where a light-intensity dependence of $(\mu\tau)_{\mathrm{amb}}$ is experimentally observed (see Sec. IV).

In addition to the recombination mechanism, we also consider in the present article the local charge neutrality equation: thus, both free-carrier densities become mathematically related to each other and their relative variations versus light intensity can be quantitatively predicted; the measured variations of both σ_{ph} and L_{amb} versus light intensity can be related in a rather straightforward way to the variation of the free photogenerated carrier densities.[19,20]

The extensive literature that deals so far with photoconductivity is mainly based on Rose's concepts.[21] The key concept of Rose's model is the distinction between two different roles assigned to the localized states in the recombination mechanism. Assuming a continuous density of states (DOS) in the gap, Rose introduced, on an intuitive basis, the concept of "demarcation levels," a concept that allows one to distinguish between those localized states in the gap that act as "recombination centers" and those that act simply as "traps." In the framework of Rose's concepts, two distinct effects are to be distinguished when considering the recombination mechanism: first, the fact that an increase in light intensity leads to an increase in the density of localized states playing the role of recombination centers by the displacement of the demarcation levels and, second, the change in the occupation functions of the recombination centers produced by the change in the light intensity. For example, Refs. 3, 6, and 22 consider only the second effect (assuming a constant density of recombination centers when changing the light intensity), whereas in Refs. 7 and 8 the two effects are simultaneously taken into account. In the present work we deliberately consider only the second effect, assuming—as an approximation—that the density of recombination centers remains constant (here all the dangling bonds are considered to act as recombination centers and all band-tail states as traps).

We have also to add that the recombination model we use is based on the assumption that the capture cross sections σ of the dangling bonds vary strongly with their charge state (capture by neutral dangling bonds is assumed to be much weaker than charge-assisted capture, i.e., $\sigma^0 \ll \sigma^{\pm}$); this assumption is in agreement with Ref. 23 and, for the capture of free electrons only, with Ref. 24. This latter point is a controversial one in the literature: see the discussion and the presentation of the different results found in the literature in Sec. V of the present article.

The proposed theoretical approach predicts a sublinear behavior of both σ_{ph} and L^2_{amb} versus generation rate G_0, the latter being proportional to the illumination intensity. The values of the power-law exponent γ for σ_{ph} vs G_0 and of λ for L^2_{amb} vs G_0 are predicted to be $\gamma=0.65$ and 0.55 and $\lambda=0$, respectively, in the two cases where the ratio of free-electron density n_f to free-hole density p_f is "extreme," such that $n_f/p_f \ll 1$ and $n_f/p_f \gg 1$ (lightly p doped and lightly n doped). For the undoped case, the predictions are $\gamma=1$ and $\lambda=-0.33$.

These theoretical predictions are confirmed by experimental results from a series of lightly doped a-Si:H samples: While we go from the lightly p-doped case $(n_f/p_f \ll 1)$ via the intrinsic case to the lightly n-doped case $(n_f p_f \gg 1)$, the experimentally observed value of γ goes from around 0.5 to near 1 and then again to around 0.4, whereas the experimentally observed value of λ goes from around 0 to -0.4 and then again to around 0 (see Fig. 4).

It is the contention of the present article that a standard defect model can certainly give satisfactory predictions for the power-law exponents of both photoconductivity and ambipolar diffusion length, provided the band tails are included as exponentially distributed densities of states. This is developed in the following section, in a simple and analytical (rather than numerical) manner.

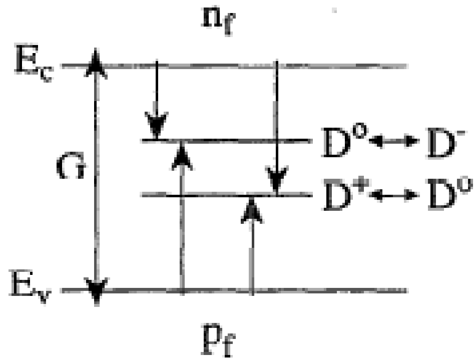

FIG. 1. Schematic diagram showing the recombination model used. Recombination can proceed through two parallel paths: $D^0+e\rightarrow D^-+h\rightarrow D^0$ or $D^0+h\rightarrow D^++e\rightarrow D^0$. Depending on whether most dangling bonds are positively or negatively charged, one path or the other will dominate in the recombination traffic. When most dangling bonds are neutral, both paths have to be taken into account.

II. THEORY

Assume that recombination traffic is routed from extended states (bands) to dangling bonds, and that an illumination level prevails such that all dangling bonds act as recombination centers. In this case, thermal emission from the dangling bonds towards the bands can be neglected.[18,25] Furthermore, let the recombination traffic be as sketched in Fig. 1. Generation of carriers is assumed to be from band to band. Then, as derived in Ref. 18, the expression for the recombination function becomes

$$R_{\mathrm{db}}=\left(\frac{n_f}{\tau_n^0}+\frac{p_f}{\tau_p^0}\right)\left(\frac{p_f}{n_f}\frac{\tau_n^+}{\tau_p^0}+1+\frac{n_f}{p_f}\frac{\tau_p^-}{\tau_n^0}\right)^{-1}, \tag{1}$$

where n_f and p_f are the densities of free photogenerated electrons and holes, respectively, and $\tau_i^j=(v_{\mathrm{th}}\sigma_i^j N_{\mathrm{db}})^{-1}$ are the "capture times:" N_{db} is the total density of dangling bonds, σ_i^j is the capture cross section for the capture of the carrier i (n_f or p_f) on a dangling bond in the charge state j (+, −, or 0) and v_{th} is the thermal velocity (assumed equal for electrons and holes). Equation (1) does not explicitly take into account the distributed nature of the dangling bonds states; this is due to the assumptions on the illumination level (implying that all dangling bonds act as recombination centers[18]).

The occupation functions of the dangling bonds obtained by using the same approximations as those used for the derivation of Eq. (1) are given by[18]

$$f^+=\frac{p_f}{n_f}\frac{\tau_n^+}{\tau_p^0}\left(\frac{p_f}{n_f}\frac{\tau_n^+}{\tau_p^0}+1+\frac{n_f}{p_f}\frac{\tau_p^-}{\tau_n^0}\right)^{-1}, \tag{2a}$$

$$f^-=\frac{n_f}{p_f}\frac{\tau_p^-}{\tau_n^0}\left(\frac{p_f}{n_f}\frac{\tau_n^+}{\tau_p^0}+1+\frac{n_f}{p_f}\frac{\tau_p^-}{\tau_n^0}\right)^{-1}, \tag{2b}$$

$$f^0=\left(\frac{p_f}{n_f}\frac{\tau_n^+}{\tau_p^0}+1+\frac{n_f}{p_f}\frac{\tau_p^-}{\tau_n^0}\right)^{-1}. \tag{2c}$$

The algebraic terms contained in Eqs. (1) and (2) suggest four specific cases of simplification:

case (a):

$$\frac{\tau_n^0}{\tau_p^0}\ll\frac{\tau_n^0}{\tau_p^-}\ll\frac{n_f}{p_f}\Rightarrow\left\{\begin{matrix}R_{\mathrm{db}}\approx p_f/\tau_p^-\\ f^-\approx 1\gg f^0\gg f^+\end{matrix}\right\};$$

case (b):

$$\frac{n_f}{p_f}\ll\frac{\tau_n^+}{\tau_p^-}\ll\frac{\tau_n^0}{\tau_p^0}\Rightarrow\left\{\begin{matrix}R_{\mathrm{db}}\approx n_f/\tau_n^+\\ f^+\approx 1\gg f^0\gg f^-\end{matrix}\right\};$$

case (c):

$$\frac{\tau_n^0}{\tau_p^0}\ll\frac{n_f}{p_f}\ll\frac{\tau_n^0}{\tau_p^-}\Rightarrow\left\{\begin{matrix}R_{\mathrm{db}}\approx n_f/\tau_n^0\\ f^0\approx 1\gg f^-\gg f^+\end{matrix}\right\};$$

case (d):

$$\frac{\tau_n^+}{\tau_p^0}\ll\frac{n_f}{p_f}\ll\frac{\tau_n^0}{\tau_p^0}\Rightarrow\left\{\begin{matrix}R_{\mathrm{db}}\approx p_f/\tau_p^0\\ f^0\approx 1\gg f^+\gg f^-\end{matrix}\right\}.$$

Note that for the four cases to be distinguishable we have to assume that the capture times for capture by neutral dangling bonds are much larger than the capture times for capture by ionized dangling bonds (i.e., τ_n^0, $\tau_p^0\gg\tau_n^+$, τ_p^-).[23,24] For cases (a) and (b), R_{db} reduces to SRH-like expressions, where the minority carrier governs the recombination, whereas for cases (c) and (d) it is surprisingly the majority carrier that governs the recombination. The four cases correspond to different doping situations of the material. In the present study, case (a) is assimilated to that of n-doped material, case (b) to that of p-doped material. Case (c) is assimilated to that of intrinsic material; we assume that in intrinsic a-Si:H the electrons are in majority but they are not sufficiently in majority for the function R_{db} to be reduced to a SRH-like expression. Case (d) is an intermediate case between the p-doped case and the compensated case ("compensated" case refers to the situation where n_f is of the same order as p_f); this case is studied in the present section. In the following section, an intuitive and physical explanation will be shown for the description of the four cases. This description is made in terms of the two parallel recombination paths that are specific to a recombination via three-valued recombination centers as sketched in Fig. 1; one can thereby expect the transition from one recombination path to the other to have important effects on the steady-state transport properties.[19,20]

The occupation functions f^+, f^0, and f^- evidently control the intensity of the recombination process and also yield, when multiplied by the value of N_{db}, the corresponding density of dangling bonds in the states D^+, D^0, and D^-. These expressions [Eqs. (2a),(2b)] are used later for the formulation of the electric local charge neutrality condition.

In the case of the measurement of σ_{ph} and L_{amb}, local charge neutrality (or, in the case of L_{amb}, to be more precise, local "quasineutrality" of electrical charge[13,14]) prevails. In order to use the condition of local charge neutrality in our formalism, various contributions to charge in a-Si:H layers under illumination have to be taken into account and expressed as a function of the free-carrier densities. Therefore we hereunder study the following three cases separately: first, n-type layers [case (a)]; second, p-type layers [case (b)]; and third, intrinsic layers [i.e., layers that are not intentionally doped, case (c)]. We use a model for the DOS consisting of dangling bond states (as already mentioned their particular energy distribution is not relevant in our model, as long as the light intensity is high enough[18]) as well as of two

band tails falling off exponentially from the valence- and conduction-band edges, respectively. The densities of charged dangling bonds are given by $f^{+}N_{db}$ for positively charged dangling bonds and by $f^{-}N_{db}$ for negatively charged dangling bonds. In the case of doped layers, charged doping atoms will be considered. The states above the quasi-Fermi level for trapped electrons are considered, when they are occupied by one electron, as electrically charged by one negative unit (the corresponding charge density is thus proportional to the density of trapped electrons n_t). States below the quasi-Fermi level for trapped holes are considered, when they are occupied by zero electrons, as electrically charged by one positive unit (the corresponding charge density is thus proportional to the density of trapped holes p_t).[25] The free carriers with densities n_f and p_f also contribute to the total electrical charge, but their contribution can always be neglected with respect to that of the corresponding trapped carriers in band-tail states. The density of trapped electrons (or trapped holes) depends only on capture and reemission of electrons (or of holes, respectively).[25] As for the carriers in the band-tails below (for the conduction-band tail) and above (for the valence-band tail) the quasi-Fermi levels for trapped carriers, they act as recombination centers as well as electrical charge,[25] but we neglect both these contributions in our calculations. In fact, our approach distinguishes itself from the one in Ref. 21 precisely because we neglect the effect of the carriers at the bottom of the band tails on recombination and concentrate instead on dangling bonds as the main recombination centers. The most convincing evidence for the appropriateness of this approach comes from light-induced degradation experiments.[26]

Look now first at n-type a-Si:H layers [corresponding to the case (a): $n_f/p_f \gg \tau_n^0/\tau_p^- \gg \tau_n^0/\tau_p^0$; considering that due to the effect of positively charged donors (Q^+), $f^- \approx 1$, $f^0 \ll 1$]. Here, p_f is indeed very small, and we may also neglect the role of p_t and f^+N_{db} in the local charge neutrality. The local charge neutrality is expressed by the equality between $e(n_t + f^- N_{db})$ (for the negative charge) and Q^+ (for the positive charge: here, Q^+ is equal to the ionized doping impurities), i.e., we have: $e(n_t + f^- N_{db}) = Q^+$ (where e is the unit charge). We assume that in the dark, almost all dangling bonds are ionized: $f^- \approx 1$, $f^0 \ll 1$, and we assume, as proposed by Street,[27] that in thermal equilibrium there is approximate equality between negatively charged dangling bonds and ionized doping impurities: $eN_{db} \approx Q^+$ (valid for the "dark" condition).

As the light intensity and generation rate G_0 is increased, n_f and thus n_t increase, whereas Q^+ remains constant. Local charge neutrality will be preserved if, as we assume, the increase in n_t as G_0 increases is matched by a corresponding decrease in $f^- N_{db}$ (since Q^+ remains constant). This is achieved by an increase of the density of neutral dangling bonds ($f^0 N_{db}$), and so is the density of recombination centers for free electrons: n_f and consequently σ_{ph} only increase sublinearly.

In order to predict analytically the dependence of $n_f(G_0)$ we now need to express the above-described neutrality condition. Equations (2b) and (2c) describe $f^- N_{db}$ and $f^0 N_{db}$ with the ratio n_f/p_f. What we now need is a formal expression for n_t. Such an expression has already been given by Zeldov and Weiser,[28] but without much detail. Here we obtain such an expression by applying the approach of Ref. 25 to describe the occupation function of the traps. The latter can be approximated by a Boltzmann distribution falling off from the position of the quasi-Fermi level toward the band edge. The total density of trapped carriers is then obtained by integrating the Boltzmann distribution times the density of states within suitable limits (i.e., quasi-Fermi level and band edge). Considering an exponential distribution of band-tail states with a characteristic energy E_c^0, we obtain

$$n_t = \frac{N_{cbt} kT}{1-\alpha_n} \left(\frac{n_f}{N_c} \right)^{\alpha_n}, \tag{3}$$

where N_{cbt} is the DOS at the edge of the band, k is the Boltzmann constant, T is the absolute temperature, $\alpha_n = kT/E_c^0$, and N_c is an "effective DOS" at the edge of the band.[29] The expression of Eq. (3) is similar to that found in Ref. 28 for the relationship between n_t and n_f: They found a power law with the same exponent $\alpha_n = kT/E_c^0$ but with a different multiplicative constant than in our Eq. (3). However, a different value for the constant appearing in front of the power law has no bearing on what follows.

For $n_f/p_f \gg \tau_n^0/\tau_p^- \gg \tau_n^0/\tau_p^0$, a small deviation of f^- from unity, when illuminating the material, can be approximated by [according to Eq. (2b)]

$$f^- = 1 + \Delta f^- = 1 - \frac{\tau_n^0}{\tau_p^-} \frac{p_f}{n_f}. \tag{4a}$$

Thus, according to our arguments, the local charge neutrality condition, when illuminating the material, can be formulated as

$$(1 + \Delta f^-) N_{db} + n_t = Q^+/e. \tag{4b}$$

With the previously mentioned fact that, in the dark, we have $eN_{db} = Q^+$ (and remembering that Q^+ is independent of the illumination level), the local charge neutrality condition [Eq. (4b)] becomes

$$-\Delta f^- N_{db} = n_t. \tag{4c}$$

Using the expressions given by Eqs. (3) and (4a), the Eq. (4c) can be transformated into the condition

$$\frac{\tau_n^0}{\tau_p^-} \frac{p_f}{n_f} N_{db} = \frac{N_{cbt} kT}{1-\alpha_n} \left(\frac{n_f}{N_c} \right) \alpha_n. \tag{5}$$

From this last expression we obtain

$$n_f^{1+\alpha_n} = p_f \text{ const.} \tag{6}$$

At this stage, one has to use the continuity equation that relates the steady-state values of the free-carrier densities n_f and p_f by the following condition (continuity equation for spatially uniform generation: such uniform generation is given by the bias light for the case of the SSPG measurement):

$$R_{db} = G_0, \tag{7}$$

where G_0 is the generation rate. Thereby, by equating Eq. (1) to G_0, one sees that n_f and p_f become related together by a function of the capture cross sections of the dangling bonds in their different charge states.

When $n_f/p_f \gg \tau_n^0/\tau_p^- \gg \tau_n^0/\tau_p^0$, then Eq. (1) is reduced to $R_{db}=p_f/\tau_p^-$. Thus, Eq. (7) becomes $G_0=p_f/\tau_p^-$. Then, we can immediately write

$$p_f \propto G_0, \tag{8a}$$

and according to Eq. (6)

$$n_f \propto G_0^{1/(1+\alpha_n)} \tag{8b}$$

Consider that when $n_f/p_f \gg 1$, σ_{ph} can (by neglecting the contribution of the holes) be written as

$$\sigma_{ph}=e\mu_n^0 n_f \tag{9}$$

and L_{amb} becomes[19]

$$L_{amb}^2=\frac{kT}{e}\mu_p^0\frac{p_f}{G_0}C, \tag{10}$$

where $\mu_n^0\mu_p^0$ are the band mobility, e is the unit charge, and C is a correction factor arising because of the small-signal conditions of the SSPG measurement,[20] whose value is between 1 and 2. From Eqs. (9) and (8b), σ_{ph} follows a power-law dependence on G_0 with an exponent γ_n,

$$\gamma_n=1/(1+\alpha_n), \tag{11a}$$

and from Eqs. (10) and (8a) L_{amb}^2 follows a power-law dependence on G_0 with an exponent λ_n,

$$\lambda_n=0. \tag{11b}$$

Second, we can in a similar manner look at sufficiently p-type a-Si:H layers [corresponding to the case (b): $n_f/p_f \ll \tau_n^+/\tau_p^0 \ll \tau_n^0/\tau_p^0$, considering that due to the effect of negatively charged acceptors (Q^-), $f^+\approx 1$, $f^0 \ll 1$]. Then, n_t and $f^- N_{db}$ become negligible charge contributions in comparison with p_t and f^+N_{db}. The local charge neutrality condition is maintained by a balance between $e(p_t+f^+N_{db})$ and Q^-, i.e., we have: $e(p_t+f^+N_{db})=Q^-$. Assuming analogous assumptions as for the n-type case (now, in the dark, we have $ef^+N_{db}=Q^-$, with $f^+=1$ and, furthermore, we have Q^- constant with respect to the illumination level), again the ionization degree of dangling bonds slightly decreases as p_f increases and thereby the density of trapped holes P_t increases with increasing G_0. By a calculation similar to the one employed for n_t [Eq. (3)], and considering a exponential distribution for the valence-band tail with a characteristic energy E_v^0, one obtains an expression for p_t:

$$p_t=\frac{N_{vbt}kT}{1-\alpha_p}\left(\frac{p_f}{N_v}\right)^{\alpha_p},$$

where N_{vbt} is the DOS at the edge of the band, N_v the effective DOS at the edge of the band, and $\alpha_p=kT/E_v^0$. For p-type layers, we have $\sigma_{ph}\approx e\mu_p^0 p_f$ and $L_{amb}^2=(kT/e)\times\mu_n^0(n_f/G_0)C$, and the continuity equation is $G_0=R_{db}\approx n_f/\tau_n^+$. With similar reasoning as for the n-type case, we obtain again a power-law dependence for σ_{ph} and L_{amb}^2 with G_0 but with exponents given by (γ_p for σ_{ph} and λ_p for L_{amb}^2)

$$\gamma_p=1/(1+\alpha_p), \tag{12a}$$

$$\lambda_p=0. \tag{12b}$$

Third, we look at the case when the ratio of the free-carrier densities is in the range $\tau_n^0/\tau_p^0 \ll n_f/p_f \ll \tau_n^0/\tau_p^-$ [case (c)], thereby assuming that p_t remains larger than n_t ($p_t \gg n_t$). Thanks to the fact that the valence-band tail is much broader than the conduction-band tail, this condition ($p_t \gg n_t$) is indeed compatible with the assumed range for the ratio n_f/p_f: These two assumptions are confirmed by the successful comparison between predictions and measured values of the power-law exponents (see Sec. IV). This case is identified as a first approximation to nonintentionally doped layers, generally called "intrinsic" a-Si:H layers. The small difference observed between the theoretical prediction and the measured power laws for "intrinsic" a-Si:H layers is explained (see the end of the present section and Sec. IV). Details for the calculation of this case can also be found in Ref. 16. When the relation $\tau_n^0/\tau_p^0 \ll n_f/p_f \ll \tau_n^0/\tau_p^-$ holds, most dangling bonds are neutral ($f^0\approx 1 \gg f^- \gg f^+$), and Eq. (1) is reduced to $R_{db}\approx n_f/\tau_n^0$. The continuity equation and the equation for f^- [Eq. (2b)] become

$$G_0 \approx n_f/\tau_n^0, \tag{13}$$

$$f^- \approx \frac{\tau_p^-}{\tau_n^0}\frac{n_f}{p_f}. \tag{14a}$$

With $p_t \gg n_t$ and $f^- \gg f^+$, the local charge neutrality condition is expressed by the balance between trapped holes and negatively charged dangling bonds,

$$p_t \approx f^- N_{db}. \tag{14b}$$

With Eq. (14a) and with the above expression for p_t (given in the development for the p-type case), Eq. (14b) leads to

$$p_t=\frac{N_{vbt}kT}{1-\alpha_p}\left(\frac{p_f}{N_v}\right)^{\alpha_p}=\frac{\tau_p^-}{\tau_n^0}\frac{n_f}{p_f}N_{db}. \tag{14c}$$

Equation (13) leads to $n_f \propto G_0$ and with Eq. (14c) to $p_f \propto G_0^{1/(1+\alpha_p)}$.

For $n_f > p_f$, $\sigma_{ph}=e\mu_n^0 n_f$ and $L_{amb}^2=(kT/e)\mu_p^0(p_f/G_0)C$; thus, the power laws of σ_{ph} (γ) and of L_{amb}^2 (λ) are predicted to be

$$\gamma=1, \tag{15a}$$

$$\lambda=-\alpha_p/(1+\alpha_p). \tag{15b}$$

Equation (15a) gives a fully linear behavior for σ_{ph}. In fact, the experimental result for the intrinsic case is (for our data) slightly sublinear (γ=0.8, see Sec. IV). This discrepancy is explained if we consider the effect of lower part of the band tails acting as recombination centers (this was neglected in our above calculations): As the light intensity increases the density of the recombination centers in the lower part of the band tails will also increase, and thus a slightly sublinear behavior of σ_{ph} occurs. The sublinear character is not very pronounced since the effect of the recombination centers in the band tails is almost negligible when compared to the effect of the dangling bonds (see Secs. IV and V).

III. INTUITIVE AND PHYSICAL EXPLANATION OF THE THEORETICAL RESULTS

The aim of this section is to show how a dependence of L_{amb} and of $(\mu\tau)_{amb}$ on light intensity is conceivable in the framework of the standard defect model. Such a dependence is be established for the specific cases (c) and (d), as introduced in the previous section, whereas no dependence is shown for the specific cases (a) and (b). When considering a single set of correlated three-valued recombination centers (here, the dangling bonds), recombination occurs via two parallel paths as sketched in Fig. 1. r_n^+, r_n^0, r_p^0, and r_p^- denote the traffics of capture of free electrons and of free holes (+, −, 0, refer to the charge state of the dangling bond and n,p refer to either electron or hole). Their expressions are given, by Eqs. (16), in terms of occupation functions of dangling bonds and of capture times,

$$r_n^+ = \frac{n_f f^+}{\tau_n^+},$$

$$r_n^0 = \frac{n_f f^0}{\tau_n^0},$$

$$r_p^0 = \frac{p_f f^0}{\tau_p^0},$$

and

$$r_p^- = \frac{p_f f^-}{\tau_p^-}. \tag{16}$$

At steady-state conditions the two following equalities represent the two parallel recombination paths:

$r_n^+ = r_p^0$: first recombination path,

$r_p^- = r_n^0$: second recombination path.

The recombination function is given by

$$R_{db} = r_n^+ + r_n^0 = r_p^0 + r_p^- = G_0. \tag{17}$$

Now, using Eqs. (16 and 17), the recombination times of the free electrons and of the free holes can be written as

$$\frac{1}{\tau_n^R} = \frac{r_n^+ + r_n^0}{n_f} = \frac{f^+}{\tau_n^+} + \frac{f^0}{\tau_n^0} \quad \text{and}$$

$$\frac{1}{\tau_p^R} = \frac{r_p^- + r_p^0}{p_f} = \frac{f^-}{\tau_p^-} + \frac{f^0}{\tau_p^0}. \tag{18}$$

Now we examine the conditions of the specific cases (a) and (c) for the recombination traffic via dangling bonds, as expressed in terms of the ratio of free-carrier densities according to the previous section. We rewrite these conditions in terms of the ratio of the occupation functions of the dangling bonds.

Case (a): $\tau_n^0/\tau_p^0 \ll \tau_n^0/\tau_p^- \ll n_f/p_f$. The condition of case (a) leads to

$$\frac{f^-}{f^0} \gg 1 \quad \text{and} \quad \frac{f^0}{f^+} \gg \frac{\tau_n^0}{\tau_n^+},$$

$$r_n^0 \gg r_n^+ \quad \text{and} \quad r_p^- \gg r_p^0,$$

where the second recombination path is the dominant one, with $f^- \approx 1$. In this case, free electrons are clearly in majority with the occupation function of the negatively ionized dangling bonds being dominant over those of neutral and positively ionized dangling bonds. The second recombination path is dominant on the first one. Here, the recombination process is clearly reduced to a SRH-like recombination process, where the minority free carriers control the recombination function,

$$G_0 = R_{db} \approx r_n^0 = r_p^- = \frac{p_f f^-}{\tau_p^-} \approx \frac{p_f}{\tau_p^-} \quad (f^- \approx 1). \tag{19}$$

When using the condition pertaining to case (a) the recombination times of the free carriers, given by Eqs. (18), are reduced to

$$\frac{1}{\tau_n^R} = \frac{r_n^0}{n_f} = \frac{f^0}{\tau_n^0} \Rightarrow n_f = \frac{\tau_n^0}{f^0} G_0, \tag{20}$$

$$\frac{1}{\tau_p^R} = \frac{r_p^-}{p_f} = \frac{1}{\tau_p^-} \Rightarrow p_f = \tau_p^- G_0. \tag{21}$$

In this case, where $f^0 \ll f^- \approx 1$, the majority free-carrier density n_f is not simply proportional to G_0 since $f^0 \ll 1$ increases with increasing G_0. Thus, n_f and $\sigma_{ph} = e\mu_n^0 n_f$ will have a sublinear behavior for their dependencies with the light intensity. The minority free-carrier density p_f is itself simply proportional to G_0 since $f^- \approx 1$ does not vary significantively when increasing the light intensity. The recombination time of the minority free carriers is independent of G_0: This leads to a situation where L_{amb} and $(\mu\tau)_{amb}$ will be independent of light intensity. This case (a) is typical of a SRH-like recombination process and conforms to the analysis of the standard model as carried out by Balberg.[11]

Now, we look at case (c), $\tau_n^0/\tau_p^0 \ll n_f/p_f \ll \tau_n^0/\tau_p^-$. This condition of case (c) leads to

$$\frac{f^-}{f^0} \ll 1 \quad \text{and} \quad \frac{f^0}{f^+} \gg \frac{\tau_n^0}{\tau_n^+},$$

$$r_n^0 \gg r_n^+ \quad \text{and} \quad r_p^- \gg r_p^0,$$

where the second recombination path is the dominant one, with $f^0 \approx 1$. In this case, the free electrons are always in majority, the second recombination path is always the dominant one, but, this time, it is the occupation function of the neutral dangling bonds that is the dominant one (i.e., $f^0 \sim 1 \gg f^- \gg f^+$). This rather curious situation is specific to a recombination via three-valued and correlated recombination centers and does not exist in the classical scheme of two-valued recombination centers (i.e., in the classical SRH recombination scheme). This specific case [case (c)] is distinguishable from case (a) thanks to the hierarchy of the capture times that we assume here (i.e., τ_n^0, $\tau_p^0 \gg \tau_n^+$, τ_p^-). Now, the recombination process can not longer be reduced to a SRH-like recombination process, because f^0 is now the dominant occupation function (and not f^-) but at the same time the free electrons are still in the majority. For this case, it is the majority free carriers that control the recombination function (and not the minority carriers),

$$G_0 = R_{db} \sim r_p^- = r_n^0 \sim \frac{n_f}{\tau_n^0} \quad (f^0 \sim 1). \tag{22}$$

When using the condition pertaining to case (c), the recombination times of the free carriers, given by Eqs. (18), are reduced to

$$\frac{1}{\tau_n^R} = \frac{r_n^0}{n_f} = \frac{1}{\tau_n^0} \Rightarrow n_f = \tau_n^0 G_0, \tag{23}$$

$$\frac{1}{\tau_p^R} = \frac{r_p^-}{p_f} = \frac{f^-}{\tau_p^-} \Rightarrow p_f = \frac{\tau_p^-}{f^-} G_0. \tag{24}$$

For this case (c), where $f^0 \sim 1$, the majority free-carrier density n_f is simply proportional to G_0 since $f^0 \sim 1$, thus no sublinear behavior for n_f and for $\sigma_{ph} = e\mu_n^0 n_f$ will occur in their dependencies on the light intensity. On the over hand, the minority free-carrier density p_f is not proportional to G_0 since $f^- \ll 1$ will now vary when varying G_0. Thus, the recombination time of the minority free carriers will now vary when varying G_0: this leads to the situation where L_{amb} and $(\mu\tau)_{amb}$ are, for this case (c), dependent on light intensity.

We underline that such a case (c) exists in the framework of a standard defect model when considering three-valued correlated recombination centers: A more complicated defect model such as the defect pool model is not at all necessary to explain such a dependence of L_{amb} with the light intensity. Balberg,[11] in his analysis of the standard defect model, has ignored that a situation as given by case (c) could be a possible explanation for the observed behavior which remains within the framework of the standard defect model.

The other specific cases [(b) and (d)] are symmetric to the two cases previously studied, considering that cases (b) and (d) are for the side where holes are majority carriers whereas cases (a) and (c) are for the side where electrons are majority carriers. To obtain the results for cases (b) and (d) one must simply exchange the symbols n and p and exchange the symbols + and −, in the expressions obtained for cases (a) and (c). The main result is that a dependence for L_{amb} and $(\mu\tau)_{amb}$ on light intensity exists for case (d) [case (d) is the one corresponding to case (c)], whereas no such dependence exists for case (b) [case (b) is the one corresponding to case (a)].

IV. EXPERIMENT

Our samples were deposited on glass substrates (Corning 7059) at 220 °C with the VHF deposition technique (plasma frequency f=70 MHz) described elsewhere.[30] After deposition, all the films were annealed under vacuum at 200 °C for 1 h. These films have thicknesses ranging between 1.7 and 2.5 μm. Doping was achieved by first mixing the doping gases in hydrogen [500 ppm Diborane (B_2H_6) in H_2 for p-type samples and 1000 ppm phosphine (PH_3) in H_2 for n-type samples]. This mixture was then used with pure silane for the film deposition. The gas phase doping level of the boron-doped films was varied between 0.2 and 10 ppm_{vol} of B_2H_6 in silane gas; for the phosphorous-doped films it was varied from 0.1 to 1 ppm_{vol} of PH_3 in silane gas. L_{amb} was measured using the SSPG technique[13] and σ_{ph} was measured

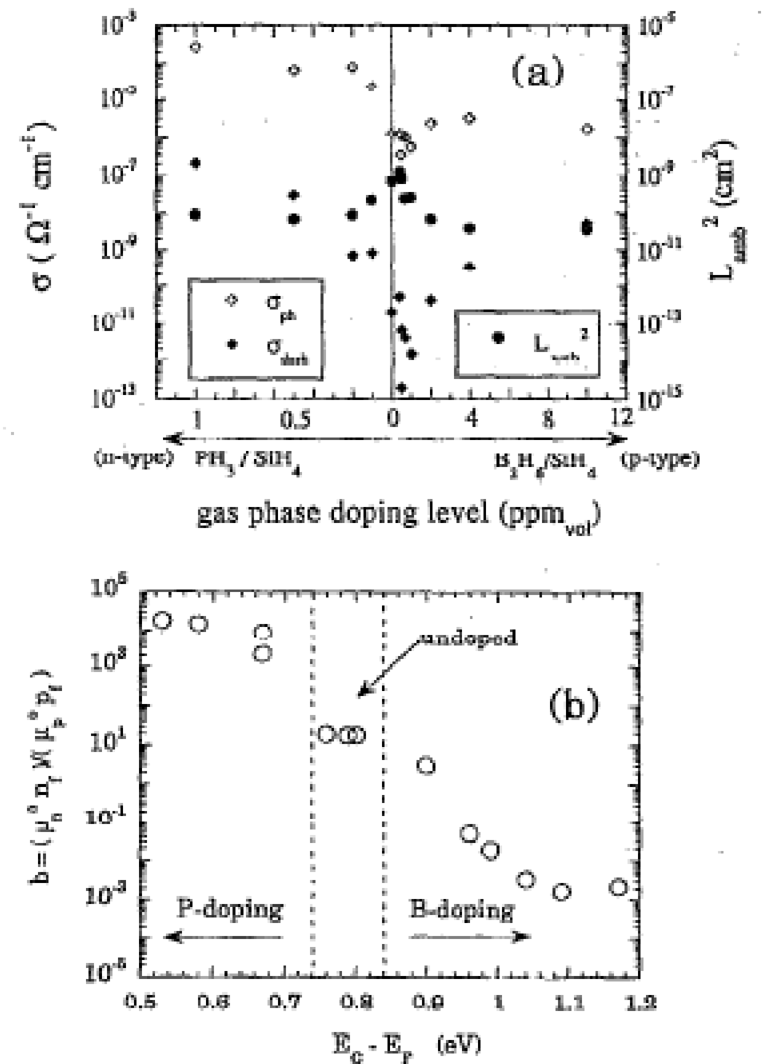

FIG. 2. (a) Effect of ppm_{vol} gas phase doping level on the dark conductivity and on the steady-state transport properties of a-Si:H films. σ_{ph} and L_{amb} were measured with an illumination intensity of I_0=2 mW cm^{-2} of monochromatic light (λ=647 nm, generation rate $G_0 \sim 10^{20}$ cm^{-3}). Note the different scales for n- and p-type doping. (b) Effect of light doping on the parameter $b = (\mu_n^0 n_f)/(\mu_p^0 p_f)$ and on the position of the Fermi level E_F; the parameter b is evaluated evaluated from the values of σ_{ph} and L_{amb} given in (a); the position of the Fermi level E_F has been computed from the activation energy of the dark conductivity.

simultaneously: It is the dc photoconductivity due to the bias light present in the SSPG measurement. The effect of the gas phase doping on the value of L_{amb} and σ_{ph} is shown in Fig. 2(a). The simultaneous evaluation of L_{amb} and σ_{ph} allows to determine $b = (\mu_n^0 n_f)/(\mu_p^0 p_f)$.[20] The variation of b as a function of the fermi level is shown on Fig. 2(b); such a variation is obtained by varying the gas phase doping as in Fig. 2(a). Assuming that the band mobilities remained constant in the whole series of sample, Fig. 2(b) shows that the ratio of free photogenerated carrier densities n_f/p_f has varied by seven orders of magnitude.

Photothermal deflection spectroscopy (PDS) as well as constant photocurrent method (CPM) measurements have been performed on the annealed films. The effect of doping on the CPM measurement is such that the deep defect density N_{db} cannot be properly evaluated.[31] The value of the absorption coefficient at a photon energy of 1.2 eV ($\alpha_{1.2}$) measured by PDS showed no significant variation with the gas phase doping level used here.[31,32] The value for N_{db} derived from the measurement of $\alpha_{1.2}$ as measured by PDS is between 2.4×10^{16} and 5×10^{16} cm^{-3} [this value depends on the calibration factor used: according to Ref. 33, $N_{db} = \alpha_{1.2}(1.2-2.5)\times10^{16}$ cm^{-3}]. Under the experimental

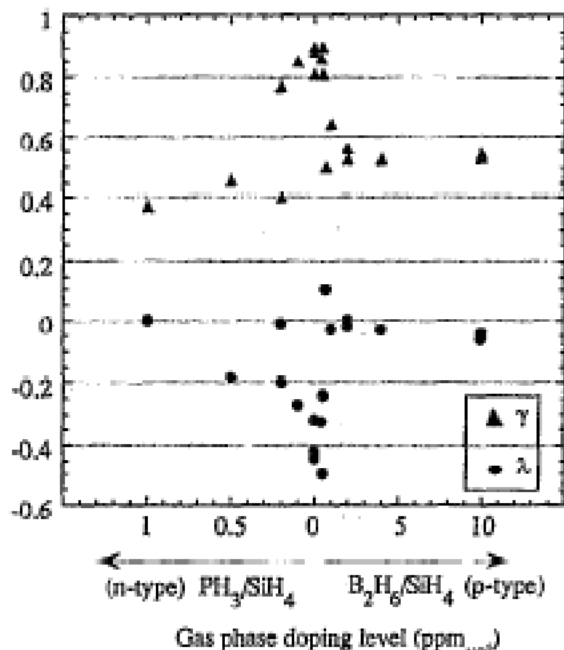

FIG. 3. Variation of the power-law exponents γ and λ for $\sigma_{ph}(G_0)$ and $L^2_{amb}(G_0)$, respectively, as a function of the gas phase doping level.

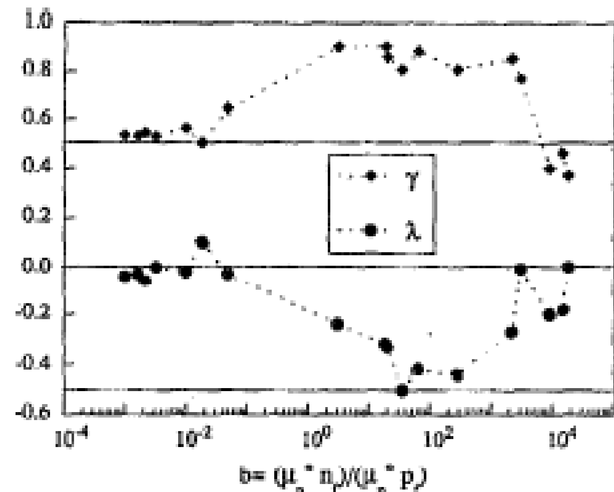

FIG. 4. Variation of the power-law exponents γ and λ for $\sigma_{ph}(G_0)$ and $L^2_{amb}(G_0)$, respectively, as a function of the parameter $b=(\mu^0_n n_f)/(\mu^0_p p_f)$.

conditions used to perform the PDS measurement on the different samples (thickness around 2 μm), variations of bulk deep defect density within a factor of 2 are difficult to detect because of the contribution of surface defects in the measurement. In the worst case, our experimental observation of an almost constant value of $\alpha_{1,2}$ with doping level could correspond to a variation of N_{db} within an order of magnitude.[31] Thus, we have to attribute the variation of n_f/p_f (seven orders of magnitude) to another effect than that of the variation of N_{db}. In fact, we attribute it to the variation of the average charge condition of the dangling bonds,[19,20,32] the latter being clearly dependent on the dopant concentration in the sample: the charged state of dangling bonds under illumination changes over from being predominantly empty (D^+ state) (on the p-type side of the series) to being predominantly doubly occupied (D^- state) (on the n-type side of the series).

We have observed that L^2_{amb} and σ_{ph} vary with light intensity according to power laws, whose exponents are λ and γ, respectively. In the range of intensities used here (1–100 mW cm^{-2}) we observed that for each sample $\sigma_{ph}(I_0)$ [and $L^2_{amb}(I_0)$] could be fitted by an unique power law. The evaluated power-law exponents γ and λ depend of the doping level and thus on b, as plotted in Figs. 3 and 4. Note that, in general, we did not observe an increase of L^2_{amb} with I_0 in our samples ($\lambda>0$), contrary to some observations made in Ref. 15. On the other hand, this behavior of L^2_{amb}, σ_{ph} and of their light-intensity power-law exponents is by and large consistent with data reported in Ref. 12.

As suggested in Sec. II the appropriate parameter for the interpretation of the observations is the ratio n_f/p_f. This ratio can be estimated from the value of the parameter $b=(\mu^0_n n_f)/(\mu^0_p p_f)$, assuming a value for μ^0_n/μ^0_p. The ratio n_f/p_f is as meaningful a parameter for the illuminated case as is the Fermi level for the case of thermal equilibrium: Indeed, the free-carrier densities n_f and p_f can be related in the usual manner (via Boltzmann statistics) to the quasi-Fermi levels E_{F_n} and E_{F_p}, respectively. Thus, the parameter b can be related to the mean value of E_{F_n} and E_{F_p} through the relationship

$$b=\frac{\mu^0_n}{\mu^0_p}\frac{N_c}{N_v}\exp\left(\frac{(E_{F_n}+E_{F_p})-(E_c+E_v)}{kT}\right), \tag{25}$$

where E_c and E_v are the conduction- and valence-band edges, respectively.

The measured values of b versus the Fermi level E_F are shown for the present doping series in Fig. 2(b).

In Fig. 4 one can distinguish roughly three regions of b in which γ and λ take particular sets of values:

$b>10^3$ n-type samples: $\gamma\approx0.4$, $\lambda\approx-0.1$;

$1<b\leq10^3$: undoped samples: $\gamma\approx0.8$, $\lambda\approx-0.4$;

$b<10^{-1}$: p-type samples: $\gamma\approx0.5$, $\lambda\approx0$.

V. DISCUSSION

We shall not consider the measured values of λ and γ as being adequate to characterize the DOS because of the large uncertainties that would thereby arise in the values for E^0_v and E^0_c. Rather, we test our model against the experimental observations by using measured/estimated values for E^0_v and E^0_c from which we derive theoretically the expected values of α_p and α_n. From, e.g., time-of-flight experiments,[34] an estimate for the value of $E^0_c\approx30$ meV is generally found for a-Si:H layers. On the other hand, an estimate of E^0_v can be obtained from the Urbach slope value measured on optical-absorption spectra, yielding $E^0_v\approx50$ meV for our samples.[31] The value of α_n and α_p at room temperature are thus $\alpha_n=kT/E^0_c\approx0.8$ and $\alpha_p=kT/E^0_v\approx0.5$. If we replace these values for α_n and α_p in the predictions of our model [Eqs. (11a),(11b) and Eqs. (12a),(12b)], we obtain for n-type samples $\gamma_n=0.55$, $\lambda_n=0$, for p-type samples $\gamma_p\approx0.65$, $\lambda_p=0$, and for undoped ones [Eqs. (15a),(15b)]: $\gamma=1$ and $\lambda\approx-0.33$. The agreement between experimentally observed power-law exponent (Fig. 4) and predicted ones can be considered very good if one takes into account the simplicity of the present model.

Besides noting this good agreement between the predicted and measured values for γ and λ, we can further con-

vince ourselves of the fulfilment of the conditions used for our recombination model by performing certain numerical evaluations, as follows.

(1) The basic assumption for our recombination model is that all dangling bonds act as recombination centers, i.e., that the quasi-Fermi levels for trapped carriers lie in the band tails. For the purpose of our discussion, we can approximate the quasi-Fermi levels for trapped carriers with the quasi-Fermi levels for free carriers.[25] The latter are related to the free-carrier densities by their definitions,[25]

$$n_f = N_c \exp[(E_{F_n} - E_c)/kT], \tag{26a}$$

$$p_f = N_v \exp[(E_v - E_{F_p})/kT]. \tag{26b}$$

The values of n_f and p_f can in turn be evaluated thanks to the measured values of $\sigma_{\rm ph}$ and $L_{\rm amb}$. In particular, in undoped and n-type samples, we can use the following relationships [Eqs. (9)–(10)]:

$$\sigma_{\rm ph} = e\mu_n^0 n_f,$$

$$L_{\rm amb}^2 = \frac{kT}{e}\,\mu_p^0\,\frac{p_f}{G_0}\,C,$$

In our series of samples $\sigma_{\rm ph}$ varies from 10^{-7} to 10^{-3} $\Omega^{-1}\,{\rm cm}^{-1}$ whereas $L_{\rm amb}$ decreases from 10^{-9} to 10^{-11} cm^2 (at a generation rate $G_0 = 10^{19}$ cm^{-3} s^{-1}) with increasing n-type doping [c.f., Fig. 2(a)]. Assuming band mobilities of $\mu_n^0 = 10$ and $\mu_p^0 = 1$ cm^2 V^{-1} s^{-1} yields $n_f = 10^{11} - 10^{15}$ cm^{-3} and $p_f = 4\times10^{11} - 4\times10^9$ cm^{-3}. Assuming that $N_c \approx N_v \approx 10^{19}$ cm^{-3} finally yields [by Eqs. (26a),(26b)] $E_c - E_{F_n} = 0.47 - 0.24$ eV and $E_{F_p} - E_v = 0.44 - 0.6$ eV. In a model for the DOS where dangling bond states lie around midgap ($E_c - E_{\rm db} \approx 0.8$ eV, $E_c - E_v \approx 1.8$ eV) and are spread over a range of 0.2 eV, all the dangling bonds are encompassed between the quasi-Fermi levels. This conclusion will hold—based on the above numerical values for any a-Si:H sample for which $\sigma_{\rm ph}$ takes a value between 10^{-3} and 10^{-7} $\Omega^{-1}\,{\rm cm}^{-1}$ and $L_{\rm amb}^2$ takes a value between 10^{-9} and 10^{-11} cm^2. This range includes undoped and degraded a-Si:H under a broad range of illumination intensities, showing that the fulfilment of this assumption is in practice not at all critical.

(2) The second assumption for the validity of our recombination model is that thermal emission from the dangling bonds can be neglected. If, for example, the temperature is raised or very low illumination intensities are used, this assumption may not be valid. Numerical calculations[32] have shown that in the series of samples studied here the thermal reemission rate from the dangling bonds at room temperature is of the order $G_{\rm th} \sim 10^{16} - 10^{18}$ cm^{-3}. The range of light intensities used for the measurement of γ and λ here corresponds to $G_0 = 10^{19} - 10^{21}$ cm^{-3}. Thus, $G_0 > G_{\rm th}$ and this second assumption is fulfilled for all the measurements presented here. Thus, both assumptions used in the derivation of the recombination model are fulfilled at room temperature in the whole series of samples.

We have fully neglected any contribution to the recombination process of the band-tail states lying between the quasi-Fermi level for trapped carriers and midgap. In fact, recombination through centers in the band tails could possibly account for a part of the discrepancy between the predicted value $\gamma = 1$ and observed value $\gamma \approx 0.8$ in undoped a-Si:H. As the discrepancy is slight, one may infer that the effect of band-tail states on recombination is quite small at the light intensities used here (less than 100 mW/cm^2). Another experimental evidence in favor of this approximation comes from measurement of the light-induced degradation effects on both $\sigma_{\rm ph}$ and $L_{\rm amb}$ in the same series of samples.[26] On the other hand, the contribution to recombination of the recombination centers at the bottom of the band tails may become preponderant in situations like in a-Si:H layers with much lower dangling bond densities, and for similar a-Si:H layers (as those used) at substantially higher light intensities. As for the range of validity of the equations used in order to describe the way local charge neutrality is maintained in the different doped samples, numerical simulations (such as given, for example, in Ref. 35) are needed for a complete discussion, and such a study does not pertain to the framework of this article.

Within the framework of our model, those experimental values of b for which a transition in the values of λ and γ from one set to the other are observed can be used to obtain an estimate of the ratio of the capture cross-sections $\sigma^{\pm}/\sigma^0$. We assume for this discussion that $\sigma_n^0 \approx \sigma_p^0$ and $\sigma_n^+ \approx \sigma_p^-$ (an assumption that is experimentally verified to be approximately correct in Ref. 19). The transition from the "undoped" behavior (i.e., when $1 \ll n_f/p_f \ll \sigma^{\pm}/\sigma^0$) to the "$n$-type" behavior (i.e. when $n_f/p_f \gg \sigma^{\pm}/\sigma^0$) occurs around $b \approx 10^3$. At this transition point, one has $n_f/p_f \approx \sigma^{\pm}/\sigma^0$ so that $b \approx \mu_n^0\sigma^{\pm}/\mu_p^0\sigma^0 \approx 10^3$, thus, one can estimate $\sigma^{\pm}/\sigma^0 \approx 10^3\mu_p^0/\mu_n^0 \approx 10^2$ (assuming[19] that the ratio of the band mobilities is about 10). This proposed value for the ratio of the capture cross section depends, of course, on the value chosen for the ratio of the band mobilities, and would, e.g., increase if we assume a lower ratio for the band mobilities). According to our evaluation, there is a hierarchy between the capture cross sections such that $\sigma_n^+ \gg \sigma_n^0$ and $\sigma_p^- \gg \sigma_p^0$. This can be understood if the effect of Coulombic attraction between a free carrier and an oppositely charged dangling bonds is considered to be important in the capture process. However, such a hierarchy between the capture cross sections is the object of controversy in the literature: Street[36] reported $\sigma^{\pm}/\sigma^0 = 2.5 - 3$, Henry and Lang[37] give $\sigma^{\pm}/\sigma^0 = 10 - 10^3$, Spear *et al.*[24] give $\sigma_n^+/\sigma_n^0 = 10 - 100$ and $\sigma_p^-/\sigma_p^0 < 1$, Vaillant and Jousse[38] use $\sigma^{\pm}/\sigma^0 = 5 - 50$, and finally Wyrsch and Shah[23] report $\sigma_n^+/\sigma_n^0 = 100$; see also Bube *et al.*[39] who report values such as $\sigma^{\pm}/\sigma^0 \approx 1$. The value of the ratio of capture cross section $\sigma^{\pm}/\sigma^0$ that one assumes is important for the present theory: If the latter ratio has a too low value the four specific cases (a),(b),(c),(d), cases presented in Sec. II of the present article, will be undistinguishable between them and consequently the present theory will have no relevance. However, the good accordance between the present theory and the measurements is in favor of our assumption of $\sigma^{\pm}/\sigma^0 \gg 1$.

VI. CONCLUSIONS

The power-law exponents that describe the light intensity dependence of ambipolar diffusion length and of photo-

conductivity have been predicted within the framework of a simple, fully analytical standard defect model. The agreement of these theoretical predictions with experimental values is reasonably good. The model used here for the localized states is constituted by the classical exponential band tails which are considered acting only as traps, and by the dangling bonds which are considered acting, all, as recombination centers. Thus, the recombination center density is assumed to be constant with varying light intensity. The model used for the dangling bonds can be termed a standard defect model, as it considers only a single, occupation-correlated set of levels.

The closed-form expression used in the present treatment to describe recombination via dangling bonds has been recently published by the authors.[18] It takes into account the existence of two parallel recombination paths, as related to the three possible charge states of the dangling bonds. Closed-form expressions for the densities of charged dangling bonds as well as for the densities of trapped carriers as a function of the free photogenerated carrier densities have been given and used together with the closed-form expression for the recombination function, while determining theoretically the values for the power-law exponents.

A satisfactory fit is obtained thereby, between experimental results and theoretical predictions, for the power-law exponents of both photoconductivity and ambipolar diffusion length, and that with a whole series of undoped and lightly doped samples: This shows that the standard defect model itself is quite sufficient to describe transport in uniform layers at room temperature, as long as the Fermi level is not shifted away from midgap by more than ±0.3 eV. Contrary to what is claimed in some recent publications,[11,12] the authors therefore conclude that it is not necessary to take concepts from the defect pool model into account for such a situation. This, however, is in no way an indication against the validity of the defect pool model. It may simply mean that for transport at room temperature and in uniform samples which are not too strongly doped, the defect pool model, if correctly applied, will not significantly modify the physical description, as compared to the standard model, whereas there well can be other experimental situations, such as strongly doped layers, where the defect pool model gives indeed significantly different results. This is, in fact, basically a question of the exact parameters one chooses for the defect pool model. The values of these parameters are at this moment not very well known and therefore further work is certainly called for—e.g., on strongly doped layers and/or with other types of experiments—to clarify the situation.

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