PHILOSOPHICAL MAGAZINE B, 1995, VOL. 72, NO. 6, 589–599

Effect of the recombination function on the collection in a p–i–n solar cell

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[*Received 15 October 1993*† *and accepted 11 April 1995*]

ABSTRACT

A closed-form expression for the recombination function associated with a single type of recombination centre that can exist in three charge states is applied to the problem of bulk collection in a p–i–n solar cell of hydrogenated amorphous silicon. It is shown that a linear approximation of the corresponding recombination function can be applied to determine bulk collection, if the p–i–n diode is under reverse bias voltage, a condition that allows the assumption of a constant electric field. The effects of two kinds of recombination function on the bulk collection are compared: first, the function found for a recombination centre that can exist in two charge states (i.e. the classical Shockley–Read–Hall expression) and second, the function found for a recombination centre that can exist in three charge states (as proposed by the present authors for dangling-bond recombination). The comparison demonstrates a significant difference between the two approaches with respect to the parameters that limit collection. In the first case the *longer* of the carrier drift lengths is the limiting factor; in the second case it is the *shorter* of the two drift lengths.

§ 1. INTRODUCTION

The collection mechanism in hydrogenated amorphous silicon (a-Si : H) solar cells with a p–i–n structure has been studied theoretically by a number of workers. Semi-analytical and numerical treatments have been published by Hack and Shur (1985), Okamoto, Kida, Nonomura and Hamakawa (1983), Rubinelli, Fonash and Arch (1992), and others. All these developments are to a large extent numerical and have the disadvantage of not being really illustrative in showing up the dominant factors that influence collection mechanisms and collection lengths in a-Si : H solar cells. This is due to the large number of material and cell parameters involved; numerical simulation results can only be computed each time for a given set of parameters, and parameter variations often have to be done in such a way that the actual dependences are masked by other factors. There have been very few attempts to obtain fully analytical descriptions of the collection mechanism. The pioneering work and, so far, the main fully analytical description of collection in amorphous p–i–n solar cells was published by Crandall (1983).

Crandall used the well known Shockley–Read–Hall (SRH) expression for recombination as derived for a two-state recombination centre (i.e. one that can exist in two charge states), as commonly used to describe recombination in all crystalline silicon devices; he, furthermore, employs the so-called 'regional approximation' to treat

† Received in final form 15 February 1995.

0141–8637/95 $10·00 © 1995 Taylor & Francis Ltd.

the SRH expression and assumes a constant electric field (plus negligible diffusion). His main result (Crandall 1983) was to give a closed-form expression for collection as a function of the sum of the two carrier drift lengths l_n and l_p for electrons and holes respectively. According to Crandall's result, it is the longer of the two drift lengths that determines collection, that is in all probability it is the electron drift length and not the hole drift length. This result has subsequently been heavily contested on the basis of numerical simulations, such as by Hack and Shur (1985). The latter workers also use an approach involving two-state recombination centres but obtain a conclusion drastically different from that found by Crandall, that is according to them it is the 'limiting carrier' (as they call it) and not the sum of the two carrier drift lengths that determines collection. Hack and Shur have criticized the result of Crandall by arguing that the assumptions of Crandall's calculation are not valid for a realistic case of a p–i–n solar cell; more exactly, Hack and Shur have stated that the concept of constant drift lengths is invalid for a p–i–n a-Si : H diode, that is they show that both the lifetimes and the electric field (involved in the drift lengths) are strongly varying within the i region. Note that Crandall, because of the regional approximation, does preserve more or less correctly the variation in lifetimes, since he only assumes individually for each region (i.e. n or p) that the lifetimes are constant, that is the lifetimes do vary in his case qualitatively in accordance with the SRH expression from one region to the other. On the other hand, by considering a strong distortion of the electric field, the calculation of Hack and Shur is certainly more realistic than that given by Crandall, but conceptually less relevant. It is difficult to decide whether the distortion of the electric field itself has any effect on determining which of the two drift lengths (either the shortest or the longest) dominates the collection. We contend that there is a far more basic reason that explains the difference between the result of Crandall and that of Hack and Shur. There is a fundamental difference between the recombination models; Crandall assumes only a *single* type of two-state recombination centre (i.e. the 'classical' SRH recombination), whereas Hack and Shur assume *two* different types of recombination centre which act in parallel (one type of recombination centre being 'donor like' and the other type being 'acceptor like'). With a single type of two-state recombination centre, recombination occurs via a single recombination path only; thus the successive capture of one free hole and one free electron is a *serial* process. Now, for such a serial process, it is evidently the slower of the two successive capture processes that will control the recombination and thus the carrier with the longer drift length will determine the collection (the carrier which possesses the longer drift length is also the carrier which is associated with the slower capture). This is precisely the result obtained by Crandall. On the other hand, with a combination of two types of two-state recombination centre (donor like and acceptor like), recombination occurs via two parallel recombination paths. Now, for such a parallel recombination process, as detailed in § 3 of the present paper, it is the carrier with the shorter drift length that will determine the collection. This is the result obtained by Hack and Shur.

As stated in our discussion above, the main characteristic of the collection process will be strongly dependent on the particular recombination model chosen. Another effect that influences the collection is the distortion of the electric field (this distortion, in the case of a-Si : H, is mainly due to the effect of the charge captured in the localized states). If it is clear that a distortion of the electric field enhances the recombination rate and decreases the value of the collection; nevertheless, as already stated above, it is difficult to obtain a simple intuitive physical comprehension of the effect of such a distortion on which the two drift lengths (either the shortest or the longest) is dominating

the collection. For didactic and conceptual reasons, one may legitimately study the collection by choosing a particular condition, such as a constant electric field, in order to separate the various effects. As our aim here is precisely to study the 'direct' effect of the specific chosen recombination model, we will consider only situations where a constant electric field is assumed. To this end, the work of Crandall (1983) and his result can be considered as representative of collection obtained by a single type of two-state recombination centre approach (SRH expression). We shall compare the result of Crandall with the result we obtain hereunder by using a specific model for a single type of three-state recombination centre. The so-called 'dangling bonds' present in amorphous materials are generally considered to process *three* distinct conditions of occupation and hence charge and are thus amphoteric in nature (see below).

As Crandall has done, we shall also present a fully analytical description, under the very same restrictive assumptions as Crandall, that is constant electric field and negligible diffusion in the i layer. These assumptions can indeed be considered to be applicable for thin p–i–n diodes under reverse-bias conditions. As discussed previously, the assumption of a constant electric field made both by Crandall and also in our present work allows a comparison of the 'direct' effect of these two different recombination functions on collection, *without* further complication due to the distortion of the electric field. There is yet another more practical reason to assume a constant electric field. In a recent paper, Fischer and Shah (1994) have shown that the distortion of the electric field due to the dangling-bond charge may be technologically minimized by compensation throughout the i layer, using a low-level doping profile, thereby obtaining a nearly constant electric field. On the other hand, nothing comparable can be done with respect to the 'direct' effect of recombination itself.

In the last few years, it has become increasingly clear that dangling bonds are the main recombination centres in a-Si : H at room temperature and for 'usual' illumination conditions as applicable to solar cells, that is 10–100 mW cm^{-2} of white light absorbed by an i layer 0·3–1 μm thick. It is also well known that dangling bonds are amphoteric in nature and have three distinct charge states. We shall therefore use the same methodology as SRH in treating recombination, but applied to three-state recombination centres in order to describe recombination in the i layer. A closed-form expression obtained by Hubin, Shah and Sauvain (1992) will be used for the recombination function R_{DB} of dangling bonds. It will be shown that R_{DB} can be further simplified to a linearized form that is valid for the whole of the i layer except for two narrow zones bordering the interfaces. This linearized form of R_{DB} will be used to calculate the collection. The main result is a closed-form expression for collection as a function of the two carrier drift lengths, l_n and l_p, with the shorter of these governing the collection, in contrast with the result of Crandall (1983).

We may add another secondary difference between Crandall's work and ours. Because the SRH recombination function R_{SRH} is nonlinear, Crandall was forced to employ the so-called 'regional approximation' method for the i layer, that is to use a first approximation for the region of the i layer where electrons are in the majority and another approximation for the region of the i layer where holes are in the majority (R_{SRH} has a linear form when a distinction between majority and minority carriers is possible). Crandall had to estimate analytically the position of the boundary between these two regions. However, in the context of amorphous p–i–n solar cells, the main part of bulk recombination, in all probability, occurs in the middle of the i layer, that is precisely in the zone where holes and electrons are approximately equal in density (as shown in the present paper) and thus where the 'regional approximation' method

is a relatively poor description. Owing to the possibility of linearizing R_{DB}, especially in the middle and even in most of the bulk of the i layer, here we do not need the 'regional approximation' and subsequent calculations are streamlined with respect to Crandall's treatment.

On the assumption of a constant electric field, the effect of the electric charge of the localized states (dangling bonds and band tails) is not considered.

§ 2. Development

With reference to fig. 1, the bulk collection χ is given by

$$\chi = \left(\int_0^L (G_0 - R)\,\mathrm{d}x \right) \Big/ G_0 L, \tag{1}$$

where G_0 is the uniform generation rate due to uniformly absorbed light and R is the recombination function in the i layer. We thereby do not consider excess recombination at the i–n and p–i interfaces. The recombination function R_{DB} for dangling bonds, as previously published by Hubin *et al.* (1992), is

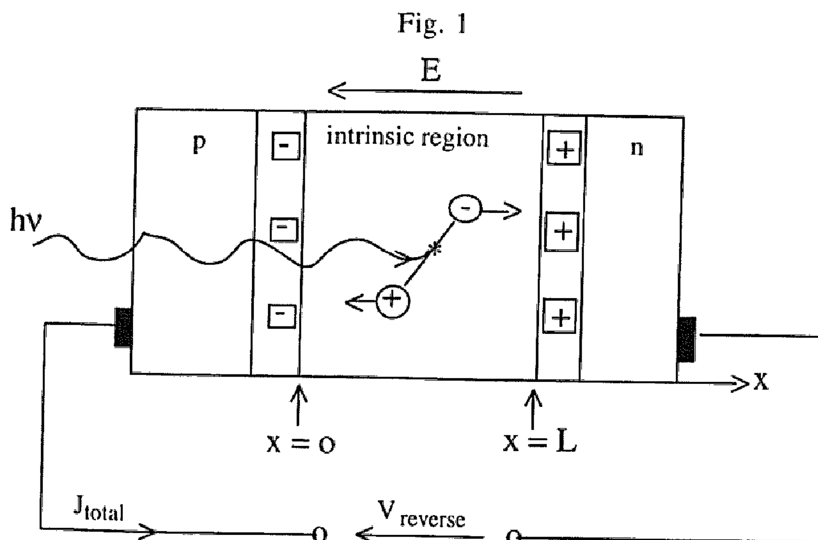
$$R_{DB} = \left(\frac{n_f}{\tau_n^0} + \frac{p_f}{\tau_p^0} \right) \Big/ \left(\frac{p_f}{n_f} \frac{\tau_n^+}{\tau_p^0} + 1 + \frac{n_f}{p_f} \frac{\tau_p^-}{\tau_n^0} \right), \tag{2}$$

where n_f and p_f are the densities of free carriers (electrons and holes), τ_n^0 and τ_p^0 are the capture times of free electrons and free holes respectively by neutral dangling bonds, τ_n^+ is the capture time of free electrons by positively ionized dangling bonds and τ_p^- is the capture time of free holes by negatively ionized dangling bonds. The capture times are defined by

$$\begin{aligned} \tau_n^0 &= (v_{th}\sigma_n^0 N_{DB})^{-1}, & \tau_p^0 &= (v_{th}\sigma_p^0 N_{DB})^{-1}, \\ \tau_n^+ &= (v_{th}\sigma_n^+ N_{DB})^{-1}, & \tau_p^- &= (v_{th}\sigma_p^- N_{DB})^{-1}, \end{aligned} \tag{3}$$

where σ_n^0, σ_p^0, σ_n^+ and σ_p^- are the capture cross-sections of the free carriers by the dangling bonds, N_{DB} is the total density of dangling bonds and v_{th} is the thermal velocity.

Fig. 1



p–i–n solar cell under reverse voltage. x is the position in the i layer. At $x = 0$ is the p–i interface and $x = L$ is the i–n interface. $V_{reverse}$ is the external applied voltage. E is the electric field in the i layer due to $V_{reverse}$ and due to the depletion region at the p–i and at the i–n interfaces.

Equation (2) was obtained by considering the steady-state equilibrium for the capture rates of free carriers by dangling bonds and neglecting the rates of thermal re-emission of carriers from dangling bonds, assuming that the material is under sufficiently high illumination intensity (Hubin *et al.* 1992).

We consider that dangling bonds have a non-negligible positive correlation energy and are amphoteric and that charge-assisted capture is much more probable that neutral capture. Thus

$$(\sigma_n^+ \gg \sigma_n^0 \quad \text{and} \quad \sigma_p^- \gg \sigma_p^0) \rightarrow \frac{\tau_n^+}{\tau_p^0} \ll \frac{\tau_n^0}{\tau_p^0} \ll \frac{\tau_n^0}{\tau_p^-}. \tag{4}$$

Condition (4) is in agreement with the work of Wyrsch and Shah (1991) and, for the capture of free electrons only, with the work of Spear, Steemers, Le Comber and Gibson (1984). When the condition

$$\frac{\tau_n^+}{\tau_p^0} \ll \frac{n_f}{p_f} \ll \frac{\tau_n^0}{\tau_p^-}, \tag{5}$$

occurs, R_{DB} (eqn. (2)) reduces to the simple linear form

$$R_{DB} \approx \frac{n_f}{\tau_n^0} + \frac{p_f}{\tau_p^0}. \tag{6}$$

In order to solve for the collection (eqn. (1)), we need to express R_{DB} as a function of the position x within the i layer: $R_{DB}(n_f, p_f(x)) = R_{DB}(x)$. The quantities $n_f(x)$ and $p_f(x)$ are obtained by solving the steady-state continuity equations and the transport equations. Under the reverse-bias condition, the electric field E can be assumed to be a constant E_0 (the charge of the localized states in the i layer creates only a small distortion of the total magnitude of E) and assuming the diffusion currents are negligible compared with the drift currents. Thus we have

$$\text{steady-state continuity equations} \quad \begin{cases} 0 = G_0 - R_{DB}(x) + \dfrac{1}{e}\dfrac{d}{dx} j_n(x), \\ \\ 0 = G_0 - R_{DB}(x) - \dfrac{1}{e}\dfrac{d}{dx} j_p(x), \end{cases} \tag{7}$$

$$\text{transport equations} \quad \begin{cases} j_n(x) = e\mu_n^0 n_f(x) E_0, \\ j_p(x) = e\mu_p^0 p_f(x) E_0, \end{cases} \tag{8}$$

where μ_n^0 and μ_p^0 are the band mobilities for the free carriers, j_n and j_p are the current densities of the free carriers, and e is the elementary charge.

2.1. *First step*

We shall first show that the linear form of R_{DB} is appropriate for describing the recombination in the i layer when the p–i–n diode is under reverse voltage. We have to compare the complete form (eqn. (2)) with the linear form (eqn. (6)), when expression R_{DB} as a function of the position x in the i layer. To arrive at this verification, a very crude approximation of $n_f(x)$ and $p_f(x)$ will be sufficient, that is we solve, for this first step, eqn. (7) and eqn. (8) with the additional hypothesis that recombination is negligible in eqn. (7) (i.e. that collection is almost complete for reverse voltage). (Note that we shall do a more precise calculation for n_f and p_f, without neglecting R_{DB} in eqn. (7), in

the second step where we calculate the collection.) With the boundary conditions $n_f(x=0)=0$ and $p_f(x=L)=0$, we obtain

$$n_f(x)=\frac{G_0 x}{\mu_n^0|E_0|} \quad \text{and} \quad p_f(x)=\frac{G_0(L-x)}{\mu_p^0|E_0|}, \tag{9}$$

$$\frac{n_f}{p_f}(x)=\frac{\mu_p^0}{\mu_n^0}\frac{x}{L-x}. \tag{10}$$

The ratio given by eqn. (10) depends now only on the ratio μ_n^0/μ_p^0 and on the position x within the layer, that is it does not depend on the parameters of the dangling bonds; this is due to the simplifications mentioned above.

Introducing eqn. (9) into the complete form (eqn. (2)) and into the linear form (eqn. (6)) with the additional simplification $\tau_n^0=\tau_p^0=\tau^0$, $\tau_n^+=\tau_p^-=\tau^{\pm}$, we obtain, first, for the complete form of R_{DB},

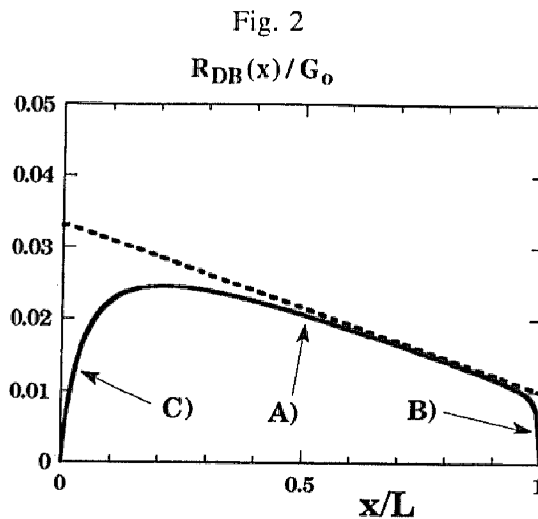
$$R_{DB}(x)=\frac{[(1-x/L)^2+(\mu_p^0/\mu_n^0)(x/L)(1-x/L)]x/L}{(\tau^{\pm}/\tau^0)(1-x/L)^2+(\mu_p^0/\mu_n^0)(x/L)(1-x/L)+(\tau^{\pm}/\tau^0)(\mu_p^0/\mu_n^0)^2(x/L)^2}\frac{LG_0}{\tau^0\mu_n^0|E_0|}, \tag{11}$$

and, second, for the linear form of R_{DB},

$$R_{DB}(x)\approx\left[\frac{x}{L}+\frac{\mu_n^0}{\mu_p^0}\left(1-\frac{x}{L}\right)\right]\frac{LG_0}{\tau^0\mu_n^0|E_0|}. \tag{12}$$

The shape of $R_{DB}(x)$, for both eqn. (11)) and eqn. (12), depends here only on the ratio $\tau^{\pm}/\tau^0$ and μ_p^0/μ_n^0 and not on the absolute values of $\tau^{\pm}$, τ^0 μ_p^0, μ_n^0, $|E_0|$ and G_0. Thus comparison of the complete and the linear forms of R_{DB} does not depend on these absolute values. We have plotted eqn. (11) and eqn. (12) in fig. 2, so that we can easily compare them. We can distinguish three regions A, B and C. A is the zone where the linear and the complete forms give almost the same result; B and C are zones in the neighbourhood of the i–n and p–i interfaces respectively, where the complete form approaches zero (and becomes very different from the linear form). From fig. 2, the

Fig. 2



Computed recombination function (eqn. (2)) as a function of the position x in the i layer of a p–i–n solar cell for reverse voltage and uniformly absorbed light: (- - -), linear form of $R_{DB}(x)$ (eqn. (12)); (——), complete form of $R_{DB}(x)$ (eqn. (11)). Numerical values for the plot are $\tau^0/\tau^{\pm}=80$, $\mu_n^0/\mu_p^0=3$, $\tau^0=10^{-7}$ s, $\mu_n^0=10\,\text{cm}^2\,\text{V}\text{s}^{-1}$, $L=1\,\mu\text{m}$ and $E_0=10^4\,\text{V}\,\text{cm}^{-1}$.

linear form can be seen to be a 'worst case' as it always gives a higher value of R_{DB} than the complete expression does. The higher the ratio $\tau^0/\tau^{\pm}$, the narrower the zones B and C become and the more the use of the linear form, in place of the complete form, is justified for describing recombination in the whole of the i layer of the p–i–n diode. The value $\tau^0/\tau^{\pm} = 80$, used for the plot, is in accordance with condition (4) and references cited there.

The linear form of R_{DB} corresponds to the case for which most of the dangling bonds are neutral (Hubin *et al.* 1992). Thus we have shown that the major part of the bulk recombination occurs in those zones of the i layer where most of the dangling bonds are in the neutral state, if we assume a high ratio $\tau^0/\tau^{\pm} = \sigma^{\pm}/\sigma^0 \gg 1$.

Rather than use this 'crude' approximation to calculate directly $n_f(x)$ and $p_f(x)$ and also the collection function, as was done previously by Hubin *et al.* (1992) we shall introduce here a further refinement in the next step ('second step').

2.2. *Second step*

Calculating the bulk collection by solving eqn. (7) and eqn. (8), *without* neglecting R_{DB} in eqn. (7) but using the linear form for R_{DB}, we obtain more precise solutions for $n_f(x)$ and $p_f(x)$ than the 'crude approximations' given previously by eqn. (9):

$$n_f(x) = G_0\tau_n^0 \frac{l_p}{l_n \exp(L/L_c) - l_p \exp(-L/L_c)} \left[\exp\left(\frac{2x-L}{L_c}\right) - \exp\left(-\frac{L}{L_c}\right)\right],$$

$$p_f(x) = G_0\tau_p^0 \frac{l_n}{l_n \exp(L/L_c) - l_p \exp(-L/L_c)} \left[\exp\left(\frac{L}{L_c}\right) - \exp\left(\frac{2x-L}{L_c}\right)\right]. \quad (13)$$

Introducing $n_f(x)$ and $p_f(x)$ given by eqn. (13) into R_{DB} we are now able to calculate the bulk collection (eqn. (1)); we obtain

$$\chi = \frac{1}{L} \frac{l_n l_p}{l_n \exp(L/L_c) - l_p \exp(-L/L_c)} \left[\exp\left(\frac{L}{L_c}\right) - \exp\left(-\frac{L}{L_c}\right)\right], \quad (14)$$

where l_n and l_p are the drift lengths (Schubwegs) for free electrons and free holes:

$$l_n = \mu_n^0\tau_n^0|E_0|, \quad l_p = \mu_p^0\tau_p^0|E_0|, \quad L_c = 2\frac{l_n l_p}{l_n - l_p}.$$

Note that, if $l_n = l_p = l$, then eqn. (14) becomes $\chi = l/(l + L)$. Figure 3 represents χ (eqn. (14)) as a function of the individual drift lengths l_n and l_p. From fig. 3, one sees that it is the carrier with the shorter drift length that limits here the bulk collection. From eqn. (14), one sees that the $\mu\tau$ products involved in the bulk collection for this particular regime for the p–i–n diode are $\mu_n^0\tau_n^0$ and $\mu_p^0\tau_p^0$ (the capture times τ_n^+ and τ_p^- are not involved; this is in accordance with the previous conclusion that the major part of the recombination essentially occurs in those zones of the i layer where most of dangling bonds are in the neutral state).

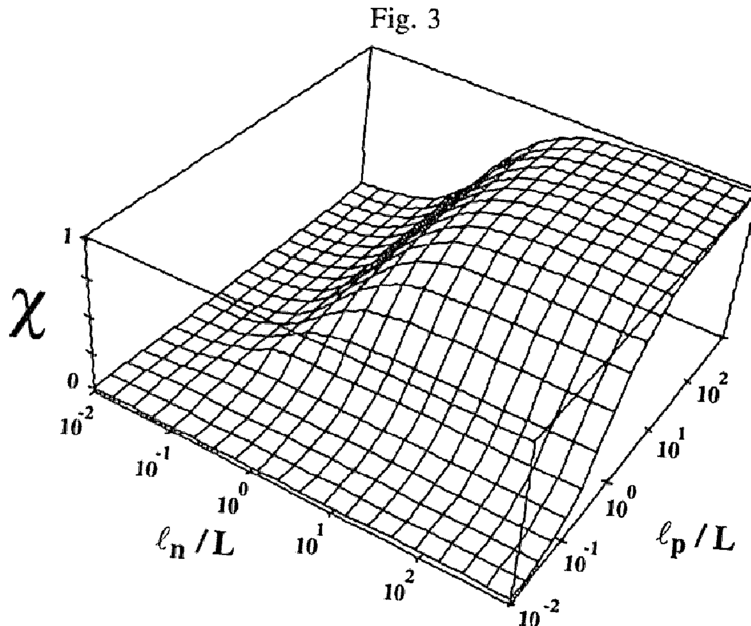
2.3. *Third step*

The classical version of the SRH recombination function is

$$R_{SRH} = \frac{n_f p_f}{n_f\tau_p + p_f\tau_n}. \quad (15)$$

Using this function (eqn. (15)) plus the so-called 'region approximation' for R_{SRH}

Fig. 3



Bulk collection (eqn. (14)) obtained with the linear form of the recombination function R_{DB} and represented as a function of the normalized drift lengths l_n/L and l_p/L of free carriers.

($R_{SRH} \approx p_f/\tau_p$ if $n_f > p_f$, and $R_{SRH} \approx n_f/\tau_n$ if $p_f > n_f$), Crandall (1983) obtained for the collection, in an otherwise similar manner as we did in our second step:

$$\chi = \frac{l_n + l_p}{L}\left[1 - \exp\left(-\frac{L}{l_n + l_p}\right)\right]. \tag{16}$$

From this equation, one would conclude that it is the longer drift length that limits collection for R_{SRH}. This is just the opposite conclusion to that obtained here by using R_{DB}. The fundamental difference between R_{SRH} and the linear form of R_{DB} is governed by the fact that the collection given in eqn. (16) forms *a serial system* for l_n and l_p (e.g. $l_n + l_p$) while, on the other hand, the collection given in eqn. (14) is similar to *a shunt system* (e.g. $l_n l_p/(l_n - l_p)$).

2.4. *Numerical examples*

The above-mentioned collection theories are also applicable to p–i–n solar cells with red-light illumination and under short-circuit conditions, provided that the i layer is thin enough and/or of sufficient quality to guarantee approximate constancy of the electric field. Let us take two cases for the i-layer thickness: $L = 0{\cdot}3$ μm (thin cell) and $L = 1$ μm (thick cell). The built-in voltage V_{bi} can be considered to be approximately 1·2 V for a-Si:H, so that $E_0 = V_{bi}/L = 4 \times 10^4$ and $1{\cdot}2 \times 10^4$ V cm^{-1}, for thin and thick cells respectively. Measured $\mu\tau$-products are according to recent work (Shah *et al.* 1993, Beck, Wyrsch, Sauvain and Shah 1993), approximately equal for both holes and electrons are, for device quality material, are about $\mu_n^0\tau_n^0 \approx \mu_p^0\tau_p^0 \approx 3 \times 10^{-7}$ cm^2 V^{-1} for the annealed state and $\mu_n^0\tau_n^0 \approx \mu_p^0\tau_p^0 \approx 10^{-9}$ cm^2 V^{-1} for the degraded state. The following values that we obtain for the drift lengths and for the collection according to eqn. (14) are shown in the table.

Note that in the cases of degraded layers or thick cells, the collection values are coarse approximations only; the constancy of the electric field is not maintained any more. The results do, however, indicate that there is a serious collection problem for the degraded state (as observed experimentally), especially for cells 1 μm thick. The

Numerical values for the drift lengths and for the collection according to eqn. (14).

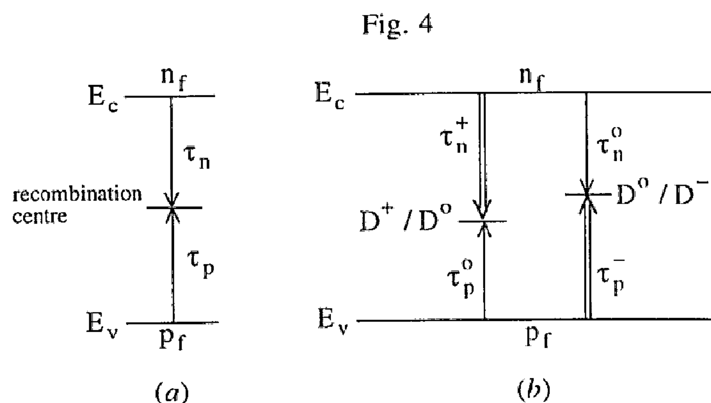
		$l_{n,p}$ (μm)	χ (%)
Thin cell ($L = 0{\cdot}3$ μm),	annealed layer	120	99·75
Thin cell ($L = 0{\cdot}3$ μm),	degraded layer	0·4	57
Thick cell ($L = 1$ μm),	annealed layer	36	97·3
Thick cell ($L = 1$ μm),	degraded layer	0·12	11

$\mu\tau$ values given above are 'band mobility × capture time' products and were derived in the publications cited while correcting for the dangling-bond occupation functions. If this correction is not done, and since the $\mu\tau$ value as measured for minority carriers by the grating method is 'band mobility × recombination time' product, the $\mu\tau$ value would be significantly lower, by a factor of about 10^2 (see Balberg (1992) for measured values). This hardly changes the collection value in the case of Crandall's approach, but it would very substantially reduce collection according to our present approach, to such low values for annealed layers as to be inconsistent with experimental evidence.

§ 3. Intuitive explanation of the obtained results

If we look at fig. 4 (*a*), it is easy to grasp why the SRH recombination function leads to a collection which is governed by the carrier with the longer drift length. The two arrows symbolizing the capture processes (in fig. 4 (*a*)) are connected 'in series'. Thus recombination will be determined by the arrow which is associated with the lower capture probability, that is collection will be governed by the carrier with the higher $\mu\tau$ product (it should be recalled that recombination is a pair process; the carrier which has the higher capture probability has always to wait for the carrier which has the lower capture probability so that the recombination can be completed). Figure 4 (*b*), on the

Fig. 4



Symbolic representation of recombination traffic for two recombination models: (*a*) SRH recombination model; (*b*) three-state recombination centre model as used for the dangling-bond recombination in the present paper. D^+, D^0 and D^- are the positively charged, neutral and negatively charged dangling bonds respectively. E_c and E_v are the energy levels at the edges of the conduction band and of the valence band respectively. The intensity of recombination traffic is inversely proportional to the corresponding capture time τ_i, that is directly proportional to the corresponding capture cross-section σ_i. In the case of the linear approximation (used in the present paper, eqn. (6)), recombination traffic is governed by the two 'single arrows', that is by τ_n^0 and τ_p^0, because one assumes that τ_n^+, $\tau_p^- \ll \tau_n^0$, τ_p^0 and n_f is not too different from p_f.

other hand, symbolizes the situation for recombination via a three-state recombination centre, such as dangling bonds. The capture times associated with the 'double arrows' in fig. 4 (*b*) (τ_n^+ and τ_p^-) are assumed to have very low values when compared with the values of the capture times associated with the 'single arrows' (τ_n^0 and τ_p^0). Thus the 'double-arrow paths' are virtually 'short-circuits' and consequently, do not limit and hardly influence the recombination traffic. The recombination will be thus limited by the 'single-arrow paths' associated with τ_n^0 and τ_p^0. Thus one may consider the 'single-arrow paths' as governing recombination and this leads to the linear form of the recombination function used in the previous section (eqn. (6)). These single-arrow paths are connected 'in parallel'. Thus recombination will be governed by the arrow (within these two single arrows) which is associated with the higher capture probability, that is collection will be governed by the carrier with the lower $\mu\tau$ product; of course, recombination still remains a pair process, but we now have two parallel paths of recombination (one via the D^+–D^0 transition and the other via the D^0–D^- transition) so that it will be the more probable of these two paths that will dominate.

The result obtained for a three-state recombination centre is specific to a parallel situation. Hack and Shur (1985), by numerical simulations and by using a two-state recombination centre model, reached the same conclusion regarding the limiting carrier for the collection as the one we obtain with a three-state recombination centre. The result of Hack and Shur is, however, not surprising since the model they used consists of two types of two-state recombination centre which are acting in parallel (one type or recombination centre being 'donor like' and the other type being 'acceptor like'). Thus Hack and Shur also obtain the conclusion that is specific to a situation where there are two parallel recombination paths.

§ 4. Conclusions

Considering a p–i–n solar cell in a-Si : H under reverse bias voltage (i.e. a condition that allows one to assume a constant electric field), we have studied the recombination by dangling bonds (a single type of three-state recombination centre) in the i layer neglecting excess recombination at the p–i and i–n interfaces. We have shown that, assuming a high ratio of capture times (or capture cross-sections) for charged to neutral dangling bonds, that is $\tau^0/\tau^{\pm} = \sigma^{\pm}/\sigma^0 \gg 1$, the major part of the bulk recombination essentially occurs in those zones of the i layer where most of the dangling bonds are in the neutral state. This leads to the use of a simple *linear expression* (eqn. (6)) to describe recombination in the i layer. Furthermore, we have assumed a constant electric field within the i layer of the p–i–n diode. Assumption of a constant electric field allows separation of the 'direct' effect of the recombination from the effect of the distortion of the electric field. Thus we may correctly compare the effect of two different recombination functions on bulk collection: first, the function for a single type of three-state recombination centre (by using the closed-form expression proposed by the present authors) and, second, the function for a single type of two-state recombination centre (by using the SRH classical expression). The 3-state recombination approach leads to totally different conclusions from use of the two-state recombination approach. In the first case it is the carrier with the *shorter drift length* that limits collection and in the second case it is the carrier with the *longer drift length*. This result emphasizes the importance of taking into account a correct model for recombination, as appropriate to localized states with three charge conditions (dangling bonds) in place of the classical version of SRH theory.

We emphasize that the linear expression (eqn. (6)) is relatively simple to handle if

one desires a simplified analytical calculation for devices rather than a complete numerical treatment.

To discriminate decisively between the two approaches (use of the new dangling-bond recombination function R_{DB} or use of the classical SRH recombination function R_{SRH}), further experimental evidence is needed.

ACKNOWLEDGMENTS

The authors wish to thank Dr M. Hack for valuable suggestions. They also acknowledge financial support from the Swiss Federal Renewable Energy Programme under Contract No. EF-REN93(032) and from the Swiss National Science Foundation under Grant No. FN-39377.

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