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To cite this version:

H. Okamoto, T. Yamaguchi, S. Nonomura, Y. Hamakawa. DRIFT TYPE PHOTOVOLTAIC EFFECT IN a-Si p-i-n JUNCTION. Journal de Physique Colloques, 1981, 42 (C4), pp.C4-507-C4-510. <10.1051/jphyscol:19814108>. <jpa-00220723>
DRIFT TYPE PHOTOVOLTAIC EFFECT IN \textit{a-Si} p-i-n JUNCTION

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Abstract.- Photovoltaic property and related processes in an \textit{a-Si:H} \textit{p-i-n} junction have been examined by taking account the internal electric field distribution. Through the theoretical considerations combined with experimental data on the collection efficiency spectra, quantum efficiency and effective hole diffusion length have been evaluated to be at least 0.85 for $\mu_0 > 2.1$ eV and 1000 Å, respectively. An analysis has been also made on the photovoltaic performance of an inverted \textit{p-i-n} junction cell, and which confirms an efficient photovoltaic operation not so much different from a \textit{p-i-n} junction.

Introduction.- A great deal of extensive efforts paid on the fabrication technology of amorphous silicon solar cells has already realized a conversion efficiency on the practically feasible level\cite{1}. Despite, as regards the underlying physics of the photovoltaic effect, any sufficient understandings have not been given yet. The photocurrent generation generally involves three basic processes; light absorption, photo-carrier generation and collection processes\cite{2}. Owing to a considerably small carrier mobility inherent to amorphous materials, the latter two processes are quite different from those familiar in conventional crystalline semiconductors\cite{3}. That is, it has been believed that not only geminate recombination has a significant influence on the photo-carrier generation process\cite{4,5} but also non-geminate recombination becomes a strong obstacle to the carrier collection\cite{6}. Moreover, because of an existence of continuously distributed gap states, the junction profile and corresponding internal electric field distribution would be far more complicated compared with the case in crystalline junctions\cite{7,8}.

In this paper, under the recognition of these peculiarities, a careful examination is made on the photovoltaic property of amorphous hydrogenated silicon (\textit{a-Si:H}) in a \textit{p-i-n} junction structure through the theoretical considerations combined with various experimental data. In the course of these analyses, physical parameters relating to photo-carrier generation and collection processes are determined. The photovoltaic property in an inverted \textit{p-i-n} junction cell will also be discussed in comparison with a \textit{p-i-n} junction cell.

Photovoltaic effect in \textit{a-Si:H} \textit{p-i-n} junction cells.- The photocurrent $J_L$ can be expressed as a function of the photon energy $\hbar \omega$ and applied voltage $V_a$\cite{2,3},

$$J_L(\hbar \omega; V_a) = \int_0^{d_i} P_G(x, \hbar \omega; V_a) P_C(x; V_a) \left[-\frac{\partial \phi(x, \hbar \omega)}{\partial x}\right] \, dx,$$

where the integration with respect to the position $x$ is proceeded within the range of an active layer (i-layer) from $x=0$ to $d_i$. $\phi(x, \hbar \omega)$ is a photon flux distribution and is obtained for a set of geometrical and optical parameters of layers composing the cell. $P_C(x, \hbar \omega; V_a)$ is a photo-carrier generation probability, that is, quantum efficiency for photo-carrier generation. According to the Onsager's theory, this factor can be represented in terms of the internal electric field $E(x; V_a)$, Onsager radius $r_\circ$ (46 Å for \textit{a-Si:H}) and a thermalization distance $r_\theta(\hbar \omega)$ of photoexcited electron-hole pairs\cite{9}. While, a photo-carrier collection probability $P_C(x; V_a)$ is given as an extended formula of our previous one\cite{3} by assuming a complete sink for

Article published online by EDP Sciences and available at http://dx.doi.org/10.1051/jphyscol:19814108
holes at \( x=0 \) which corresponds to the interface between the p- and i-layer;

\[
P_c(x; V_a) = \left[ 1 + \frac{1}{L_p} \left( (g^+(0) + g^-(0))^2 \right) \right]^{1/2} \frac{1}{E(0)} \int_0^X (f^-(\xi) - f^+(\xi)) d\xi,
\]

where, \( f^\pm(x) = \exp \left[ \pm \frac{1}{E(0)} \int_0^x g^\pm(\xi) d\xi \right], \)
\( g^-(x) = \sqrt{1 + \gamma(x)}^2 \gamma(x) \), \( \gamma(x) = \frac{qL_p}{2k_B T} E(x; V_a) \).

\( L_p \) denotes an effective hole diffusion length which takes into account the ambipolar transport with a probable influence of traps.

As is easily accepted, one should examine firstly the internal electric field \( E(x; V) \) in the i-layer which is essentially correlated with the density of states in the gap because it would play an important role in determining the photovoltaic property through the photo-carrier generation and collection processes. Figure 1(a) and (b) display examples of space charge \( \rho(x) \) and internal electric field distribution \( E(x; 0) \), respectively obtained by solving Poisson's equation with realistic boundary conditions and physical parameters summarized in the figure. Here, an exponentially distributed gap states is assumed with a minimum gap states density \( g_p \) and characteristic energy \( E_g[10]. \) One of the noticeable features found in \( E(x; 0) \) is an existence of a high internal electric field in excess of \( 10^4 \text{V/cm} \) throughout the i-layer in an a-Si:H p-i-n junction cell of actual dimension[11]. Photo-carrier generation and collection probability corresponding to this \( E(x; 0) \) are demonstrated in Fig.2 (a) and (b), respectively. From Fig.2 (b), a "drift type" photovoltaic behavior of a-Si:H junctions[8] can be confirmed, where a high internal electric field effectively enhances a drift component of the photocurrent and restricts non-geminate recombination loss arisen from a very small carrier diffusion length.

Figure 3(a) and (b) show variations of the internal electric field \( E(x; V) \) in the i-layer corresponding to those of the i-layer thickness and forward bias voltage \( V \), respectively. These results put forward a new recognition that the concept of depletion region considered in crystalline junctions no longer holds good in the case of a-Si junctions, instead, an overall change in \( E(x; V) \) should be taken into account in response to the variation of cell dimension or bias voltage.
Fig. 3 Variations of internal electric field $E(x; V_a)$ corresponding to those of $i$-layer thickness $d_i$ (a) and forward bias voltage $V_a$ (b).

**Geminate and non-geminate recombination in a-Si:H.** In the following discussion, firstly, the photo-carrier generation probability is assumed to be constant throughout the $i$-layer in the extent of the cases encountered in the usual operation of an a-Si:H p-i-n junction cell of actual dimension [11]. Coupling the result in Fig. 3 with eqs. (1) and (2), an $i$-layer thickness dependence of the collection efficiency for monochromatic light is derived, which is illustrated in Fig. 4 with a parameter of effective hole diffusion length $L_p$. A comparison between experimental data [2,11] and this calculated one yields an evaluation for $L_p$ of about 1000A. A similar procedure is also applied with the result in Fig. 3(b) to get the photocurrent versus forward bias voltage $V_a$ curves. Figure 5 shows these dependencies for two different illumination wavelengths with corresponding experimental data obtained in several efficient p-i-n junction cells [12] under various bias light conditions. This examination also supports an $L_p$ of around 1000A. It is added here that an experimental $J_l-V$ curve for an illumination of further short wavelength light could not be fitted by $L_p$ of 1000A and this might imply an effective lowering of $L_p$ near the p/i interface.

On the other hand, through the same way described in our previous papers [2,3], the photo-carrier generation probability $P_g(\hbar \omega, E)$ can be estimated by attributing a discrepancy observed between experimental and calculated collection efficiency spectra to geminate recombination. The result is summarized in Fig. 6. That is, zero-field quantum efficiency $P_g(\hbar \omega, 0)$ defined by $\exp[-E_F/r_0]$ exhibits a sharp rise from the photon energy higher than the optical gap energy and exceeds about 0.85 for $\hbar \omega > 2.1eV$. Here, a slight decrease of $P_g$ in the photon energy region of higher than 2.2eV might indicate an extra non-geminate recombination loss in the vicinity of p/i interface which is not taken into consideration in the present analysis.

**Inverted p-i-n junction cell.** In this section, we will examine how a small hole diffusion length would affect on the photovoltaic performance of an inverted p-i-n junction cell where most of photo-holes are

Fig. 5 Photocurrent $J_l$ versus forward bias voltage $V_a$ curves for illumination wavelengths of 5500 and 6500A.
generated near the i/n interface and so obliged to pass through whole the i-layer. Figure 7 shows the calculated collection efficiency spectra for various p-i-n and inverted p-i-n junction cells. Here, $\Delta E_p$ and $\Delta E_n$ denote the Fermi level shifts by doping in n- and p-layer, respectively. These calculations are carried out with realistic cell construction parameters by taking account of the absorption losses in p- and n-layers[11]. As can be seen in the figure, an inverted p-i-n junction cell exhibits an inferior photocurrent to that of a p-i-n junction cell so far as a slightly doped i-layer is employed. However, a sufficiently doped p-layer would improve the photocurrent of an inverted cell, at least, up to the same degree as in a p-i-n junction cell. While, our preliminary analysis on J-V curves indicates that an inverted p-i-n junction cell essentially involves a lower fill factor as compared with p-i-n junction cells.

**Conclusion.** In the photovoltaic effect of a-Si:H p-i-n junction cells, both geminate and non-geminate recombination processes are considered to play a significant role. However, in the actual operation, non-geminate recombination loss might be almost saved by a high internal electric field in the active i-layer. Moreover, an influence of geminate recombination is also thought to be relatively small for higher photon energy region since in a well prepared a-Si:H film quantum efficiency for photo-carrier generation exceeds 0.85 and is enhanced up to 0.95-0.98 by the internal electric field for the excitation photon energy higher than 2.1eV. Instead, a probable existence of extra non-geminate recombination in the vicinity of the p/i interface would restrict the photovoltaic performance of the present a-Si:H p-i-n junction cells. While, an analysis on inverted p-i-n junction cells confirms a similarly efficient operation, if well designed, as compared with p-i-n junction cells.

**References.**