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Intensity and temperature dependence of photocurrent of a-Si:H Schottky diodes

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Abstract

The photocurrent of hydrogenated amorphous silicon (a-Si:H) Schottky diode has been studied as a function of light intensity from a HeNe laser, applied electric bias, and temperature, by using a constant photocurrent method. The *I*–*V* characteristics and thus fill factor (FF) values were also obtained over the temperature range 173–297 K. The FF increases very little as the temperature is decreased. The exponent γ in the power relationship $I_{ph} \sim G^{\gamma}$ between photocurrent and light intensity was found to be temperature and electric field dependent, and peaked around 260 K measured. The activation energy obtained from thermally activated photocurrent was also found to be electric field dependent. These experimental results are discussed by means of the influence of the trapping of charge carriers on the electric field profile.

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Keywords: a-Si:H Schottky diode; Intensity- and temperature-dependence; Recombination; Electric field profile

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1. Introduction

The photoconductivity (PC) is an important property of amorphous (a-)semiconductors, with particular relevance for the operation of solar cells and other photonic devices [1]. The PC is the change of the electrical conductivity of a material when illuminated. When a material is under constant illumination, a stationary regime is attained in which the electron–hole generation rate is balanced by recombination processes through which the charge carriers relax to their steady state distribution. The process is complex and involves the absorption of light, the generation of excess carriers, and the transport and recombination mechanisms [2]. Experimental data on both undoped and doped a-Si:H have shown that a decrease of the PC is measured for temperatures above 100 K. This effect is known as thermal quenching [3]. Several models have been proposed to explain this decrease, but its interpretation is still controversial [3,4].

In a-semiconductors, the photocurrent depends on the photogeneration rate G (which is proportional to the photon flux) as $I_{ph} \sim G^{\gamma}$. It is common practice to attribute γ between 0.5 and 1.0 to a mixture of two limiting recombination mechanisms [5]: a monomolecular recombination type occurring through recombination centers (dangling bonds, such as), which would correspond to $\gamma \sim 1.0$, and a bimolecular recombination process, in which the excess charge carriers recombine directly from the band tails ($\gamma \sim 0.5$). An alternative model proposed by Rose [6] considers an exponential distribution of density of states (DOS) whose states are increasingly

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converted from trapping to recombination states as the light intensity increased. Different γ values between 0.5 and 1.0 are obtained from this model, which depend upon the slope of the DOS being swept by the steady state Fermi level, and on temperature.

Recent numerical and analytical work on PC in a-Si:H by Bube [7] has demonstrated that a relatively simple model for recombination via dangling bonds can produce superlinear PC (exponent $\gamma > 1$) in undoped material. Furthermore, a sublinear characteristics with exponent γ as low as 0.4 has been observed by numerous group [8–11].

In spite of the many studies devoted to PC in undoped and doped a-Si:H based materials, a complete model for its temperature and light intensity dependences has not yet emerged. Many aspects of trapping and recombination are still poorly understood. Therefore the field is the main interest to work. In this work, we present PC results obtained on Schottky diodes by varying the applied electrical bias, the temperature and the light flux.

2. Experimental

The a-Si:H, n^+ and 2.2 μm thick intrinsic (i-)layers of n^+-i-Pt Schottky diode were deposited by radio-frequency powered plasma-enhanced chemical vapour deposition (rf-PECVD) on 7059 glass substrate coated with transparent conducting oxide. All details concerning the deposition properties were given elsewhere [12]. The density of deep states of diode was found to be lower than $10^{16}\,\mathrm{cm^{-3}\,eV^{-1}}$ from the modulated photoconductivity measurements. The platinum Schottky contact was formed from electron beam evaporated dots, 3 mm in diameter and about 200 Å thick. The diode was further annealed for 1 h at 150 °C. The rectification ratio, defined as the ratio of the currents measured in dark at +1 and −1 V, was about 10^9 at room temperature (297 K) while experimental determinations of the barrier height and diode quality factor yielded 1.1 eV and around 1.1, respectively.

The diode was placed in an isotherm glass type cryostat, which allowed us to set the temperature between 173 and 297 K. The diode was excited by a HeNe laser light (632.8 nm, 15 mW max) through the n^+ layer. The intensity of laser light (beam) was varied by neutral density filters. The electrical measurements were carried out with an electrometer either in forward or reverse bias conditions.

3. Results and discussion

Fig. 1 shows the I–V characteristics of a-Si:H Schottky diode at various temperatures for an intensity of 15 mW of HeNe laser (632.8 nm). Here, 1 mW corresponds to an intensity of about $10^{19}\,\mathrm{phs\,s^{-1}\,cm^{-2}}$. Fig. 2 shows the same characteristics at various levels of illuminations for a fixed temperature (297 K).

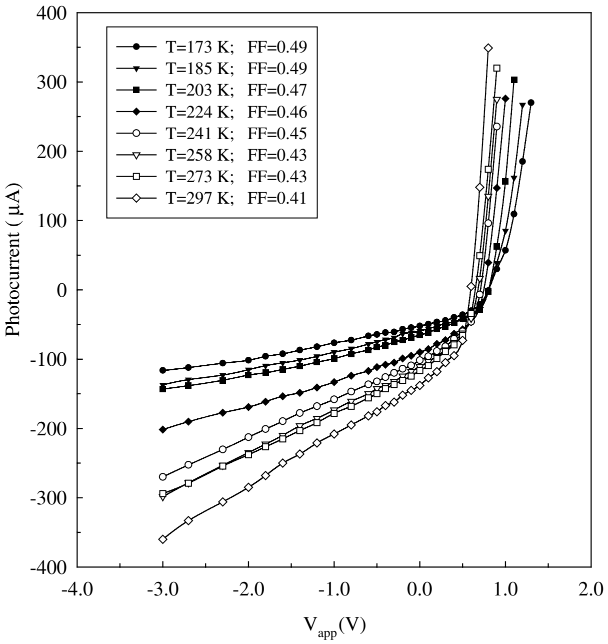

Fig. 1. The I_{ph}–V characteristics of a-Si:H Schottky diode at various temperatures. The calculated values of FF from the fourth region are also shown in each case. The average value of FF is 0.45 ± 0.04. The light intensity is 15 mW (632.8 nm).

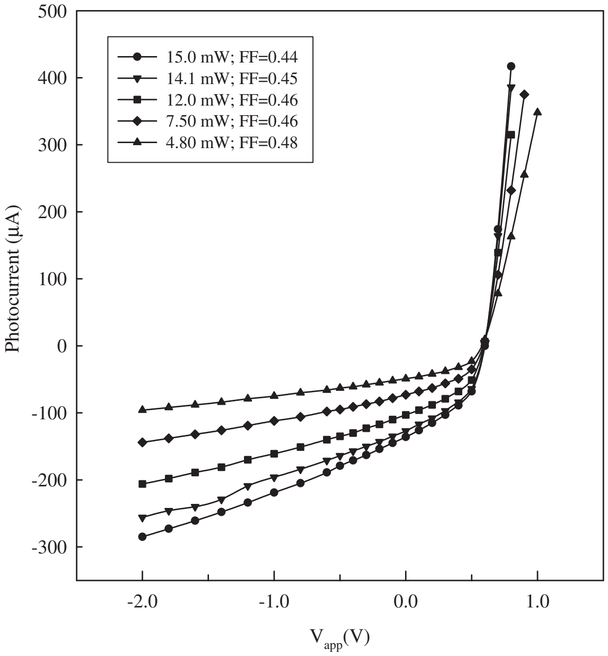

Fig. 2. The I_{ph}–V characteristics of a-Si:H Schottky diode at various levels of illuminations (632.8 nm) for a fixed temperature (297 K). The calculated values of FF from the fourth region are also shown in each case. The average value of FF is 0.46 ± 0.02.

Photodiodes or solar cells operate without an externally applied voltage and the collection of carriers results from the internal field at the junction. This is referred as the fourth quadrant in Figs. 1 and 2. Off all the parameters used to characterize photodiodes, the conversion efficiency η is the most important and defined as the percentage of the total power in light that is converted into electrical power. It may be expressed as [13],

$$\eta = \frac{I_\mathrm{m} V_\mathrm{m}}{P_\mathrm{i}} = (\mathrm{FF}) \frac{I_\mathrm{sc} V_\mathrm{oc}}{P_\mathrm{i}}, \tag{1}$$

where I_m and V_m are the output current and voltage of a photodiode operating under maximum power conditions, respectively, and P_i is the incident power density of the illumination. I_sc is the short-circuit current and V_oc is the open-circuit voltage. A "fill factor" FF, which shows how closely $V_\mathrm{m} I_\mathrm{m}$ approaches $V_\mathrm{oc} I_\mathrm{sc}$ and acts as a useful figure of merit for solar-cell or photodiode design, is often defined by

$$\mathrm{FF} = \frac{V_\mathrm{m} I_\mathrm{m}}{V_\mathrm{oc} I_\mathrm{sc}}. \tag{2}$$

From the fourth quadrant of Figs. 1 and 2, the determined values of FF of a-Si:H Schottky diode were presented on Figs. 1 and 2 for the indicated temperatures and illumination levels. The small value of FF may be due to high excitation intensity used (15 mW). As can be seen from Fig. 1, there is a minor decrease in FF with the increasing temperatures. When the temperature is increased, the lifetime and hence the diffusion lengths of charge carriers in a-Si:H based solar cells are expected to become larger. However, since the saturation current density exponentially depends on the temperature, the V_oc will drastically decrease. In Fig. 2, there is a minor increase in FF with decreasing illumination levels. According to a model proposed by Crandal [14], for the weakly absorbed light, the shape of I–V curve is completely specified by electron and hole drift lengths.

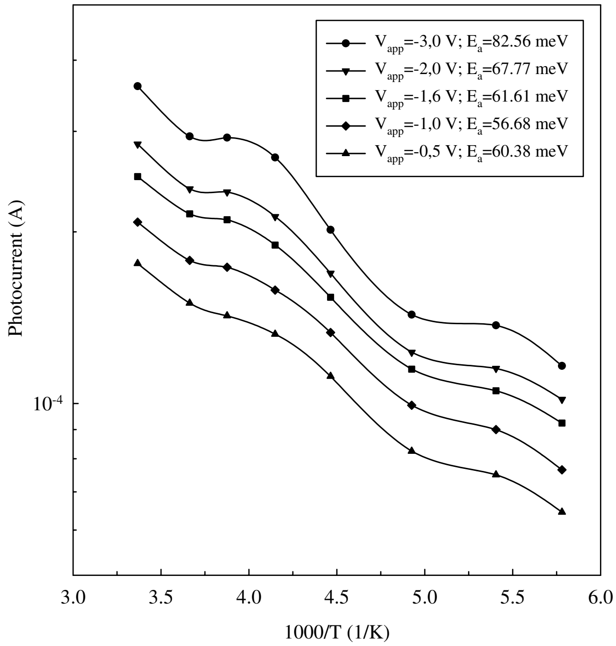

Fig. 3. Temperature dependence of photocurrent in a-Si:H Schottky diode for five different reverse biases. The calculated values of activation energy from third region are also shown in each case. The light intensity is 15 mW (632.8 nm).

Fig. 3 shows I_ph as a function of the inverse temperature T, for the reverse bias conditions. The excitation intensity is again fixed at 15 mW (632.8 nm). In general, the temperature dependence of I_ph shows three regions. At very low temperatures (lower than about 50 K), I_ph is approximately constant and does not show an activated behaviour. This can be explained by a theory [15] of energy loss hopping of photocarriers through a distribution of localized band tail states. With respect to this theory, at low temperatures, photoexcited carriers can only lose energy by tunneling to lower energy states, such as localized tail states or by recombination. For $T > 50$ K, there is an increase of I_ph with T until about room temperature ($T \sim 300$ K). In this region, the transport of carriers can be described by multiple trapping model [16], in which injected carriers thermalize in a broad distribution of localized, band tail states, moving to deeper energies as a result of thermal activation to transport states and subsequent retrapping. Above room temperatures, the change in kinetics from bimolecular to monomolecular classical kinetics occurs when the dark current exceeds the I_ph with increasing temperature. Analysis of the curves in Fig. 3 shows that there are two large shoulders or plateaus in which I_ph increases as the reverse bias increases. Similar results were also observed for forward bias conditions. These shoulders may be due to defects of Schottky diode under study. Further several interesting features were to be noted in literature, in particular in the thermal quenching range. It is known that the thermal quenching magnitude depends sensitively upon the position of the dark Fermi level: the deeper the Fermi level in the gap the larger is the thermal quenching [17].

In Fig. 3, at the temperatures between 200 and 230 K, the I_ph behaviour is approximately linear. It means that I_ph is an activated process, i.e.,

$$I_\mathrm{ph} = I_0 \exp\left(\frac{-E_\mathrm{a}}{kT}\right), \tag{3}$$

where I_0 is an initial constant, and k is Boltzmann constant as usual. The term E_a indicates the activation energy calculated from the slope of $\ln(I_\mathrm{ph})$ versus $10^3/T$ curve. Its determined values were shown on the Fig. 3 for the indicated reverse biases. Obviously, the E_a has a minimum at around -1.0 V, and then increases with increasing and decreasing reverse biases.

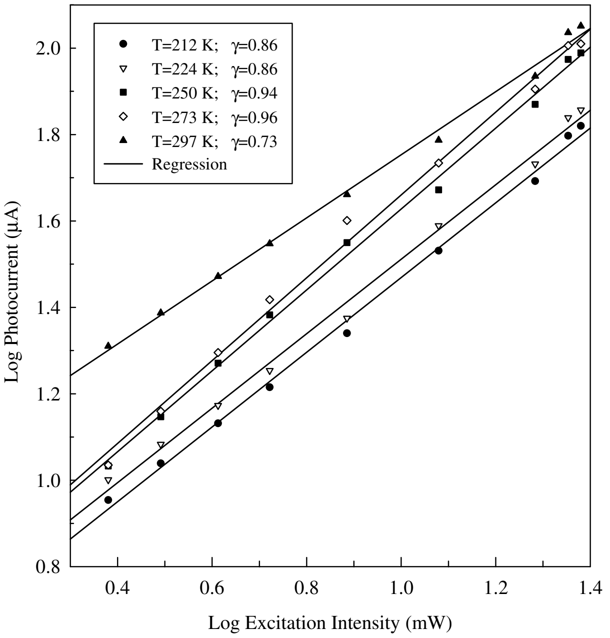

Fig. 4. Intensity dependence of photocurrent of a-Si:H Schottky diode at different temperatures. The applied forward bias is 0.2 V. The exponent γ in the relationship $I_{ph} \sim G$, is indicated in each case.

As mentioned at the beginning, the intensity of photocurrent is proportional to the generation rate: $I_{ph} \sim G^{\gamma}$, where the exponent γ is determined to be temperature dependent. This dependence can be seen in Fig. 4 for five different temperatures, where the exponent calculated from $\gamma = d[\ln(I_{ph})]/d[\ln(G)]$. This data was taken under the forward bias condition of 0.2 V. For the whole data taken under either reverse or forward bias conditions used, the temperature dependence of γ was plotted in Fig. 5 for comparison. As seen, the γ has a peak or maximum at around 250 K for −1.0 V, and then it shifts towards higher temperatures with the bias condition in which the applied voltage was changed from reverse to forward. At around 265 K, the γ is close to unity for the biases of 0.2, 0.0, and −0.2 V. This also leads to high values of photocurrent (plateau) in Fig. 3. Above and below about this temperature (265 K), $\gamma < 1$, which is to be associated with the particular photocurrent losses.

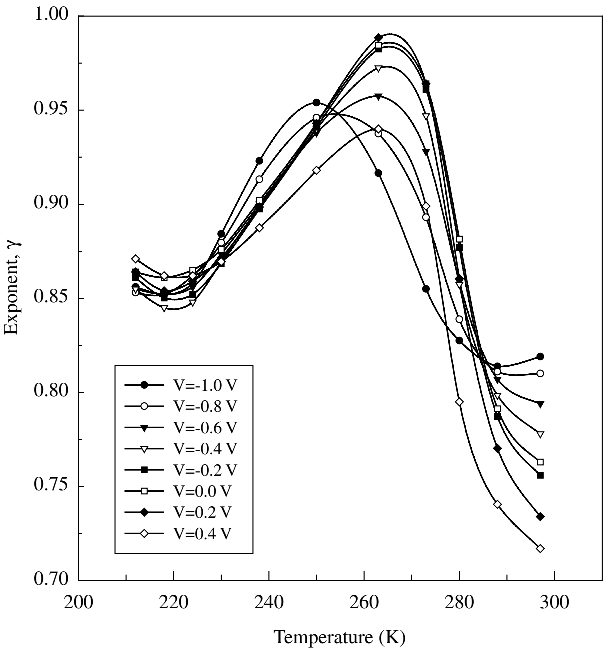

Fig. 5. Temperature dependence of the exponent γ in a-Si:H Schottky diode for different forward and reverse biases. Solid lines to guide the eye.

The temperature dependence of γ has a complex sample- and temperature-dependent behaviour as frequently reported in the literature [18–23]. This is also valid for our results, which are in agreement with others [19,22–24].

4. Conclusion

The I–V characteristics, and thus the fill factor FF were investigated in detail at various temperatures between 173 and 297 K. A small decrease in FF has been found with increasing temperatures. We reported that it is due to the carrier with the longer drift length, which determines the I–V curve and hence fill factor.

The dependence of γ ($I_{ph} \sim G^{\gamma}$) on temperature and on the bias level (forward and reverse) has been studied. A $\gamma_{max} = 0.95$ has been found at around 250 K for −1.0 V. This maximum shifts towards higher temperatures with the bias conditions in which the applied voltage was changed from reverse to forward. At around 265 K, the γ is close to unity for most biases. Above and below about 265 K, $\gamma < 1$, which is to be associated with the particular photocurrent losses at different temperatures. We expect that this complex temperature dependence of γ is sample characteristics. The large decrease of I_{ph} with light exposure results from an increase in γ.

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