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Current–voltage analysis of a-Si:H Schottky diodes

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Abstract

Direct current (dc)–voltage (*I–V*) characteristics of the hydrogenated amorphous silicon (a-Si:H) Schottky diode have been measured at different temperatures under dark and light. From the fourth quadrant of illuminated characteristics, fill factor (FF) values were obtained for each temperature measured (173–297 K). We have found that FF increases very little as the temperature is decreased. The measured data from *I–V* characteristics has been analyzed in detail. In particular, from dark *I–V* characteristics obtained, the density of state (DOS) near the Fermi level was determined using a simple model based on the space-charge limited current (SCLC). On the other hand, from the illuminated *I–V* characteristics, the density of carriers was calculated for each temperature using the analysis of diode equation as known. A comparison of the carrier density and the measured photocurrent as a function of the reverse temperature was also made and a good correspondence was obtained.

Keywords: A-Si:H Schottky diode; Fill factor; Space-charge limited current; DOS; Carrier density

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1. Introduction

Amorphous (a-) materials are a powerful alternative for technological developing and applications based on semiconductors because of their lower cost and processing. Nowadays, many semiconductor devices are made using a-semiconductors such as solar cells, low-dimensional structures, etc. [1–3]. Hence, the determination of basic physical characters of these materials is very important. For this purpose, a lot of measurement techniques have been developed for defining their basic physical properties such as current–voltage (*I–V*) or current density–voltage (*J–V*) measurements, capacitance–voltage (*C–V*) measurements, frequency resolved photocurrent measurements, etc. [4–8]. Any technique has some intrinsic own advantages or disadvantages. The most simple and at the same time the most used technique is *I–V* measurements. *I–V* measurements performed

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under different physical conditions, such as the temperature, the excitation wavelength and the intensity give very important informations about the physical properties of semiconductors and their applications.

The density of states (DOS) in the forbidden gap of a-Si:H plays an important role in optical and electrical properties of this material. Hence, it is very important to know the DOS distribution in the gap. Although many techniques [9] were used to determine the DOS, one of the easiest and best known technique is the space-charge limited current (SCLC), and thus many workers employ this method [10–12] in the frame of den Boer approximation [13]. According to this approximation, the DOS can be determined from dark *I–V* characteristics measured. Even though the den Boer analysis gives the defect density distribution in a limited part of the band gap, the information about the DOS determined by this analysis is quite correct.

The photocurrent and thus the photoconductivity (PC) is an important property of a-semiconductors, with particular relevance for the operation of solar cells and other photonic devices [14]. PC is the change of the electrical conductivity of a material when illuminated. When the 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, generation of excess carriers, and transport and recombination mechanisms [15]. Experimental data on both undoped and doped a-Si:H have shown that a decrease of PC is measured for high temperatures (above about room temperature). This effect is known as the thermal quenching [16]. Several models have been proposed to explain this decrease, but its interpretation is still controversial [16,17].

The illuminated *I–V* characteristics of a solar cell diode permit us to determine some parameters for the cell performance, such as the fill factor, the conversion efficiency, the short-circuit current and the open-circuit voltage. Further, by using diode equations, one can easily derivative the carrier concentration created by the light.

In our previous work, we have already presented the intensity- and temperature-dependence of photocurrent of a-Si:H Schottky diode used [18]. Here, we calculate the DOS and density of carrier concentrations for the same diode using some simple models developed. We also compare the measured photocurrent and the calculated carrier density as a function of inverse temperature.

2. Experimental details

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 the transparent conducting oxide (TCO) of SnO_2. All details concerning the deposition properties were given elsewhere [19]. 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 the 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.

For temperature-dependent measurements, 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 an HeNe laser (632.8 nm, 15 mW o/p max) through the n^+ layer. The electrical measurements were carried out with an electrometer either in forward or reverse-bias conditions.

3. Results and discussion

3.1. SCLC analysis

The density of states at the Fermi level was determined from the dark *I–V* characteristic by using simple den Boer method [13], namely,

$$N(E_F) \cong \frac{2\varepsilon_r\varepsilon_0(V_2 - V_1)}{eL^2\Delta E_F}, \qquad (1)$$

where ε_r is the dielectric constant of the i-layer, and for a-Si, its value is 11.8 [20]. ε_0 is the dielectric

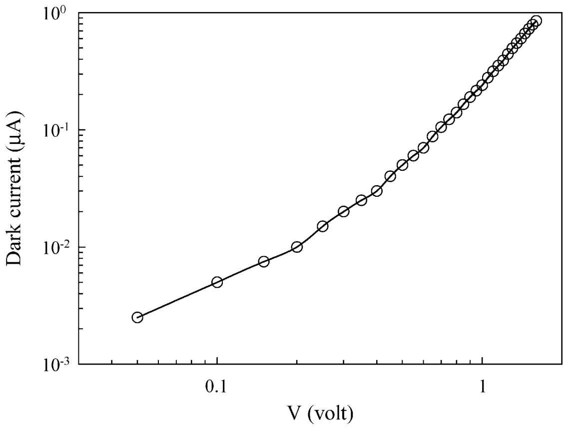

Fig. 1. Dark *I–V* characteristics of a-Si:H Schottky diode.

permittivity of the vacuum, e is the electronic charge, L is the thickness of i-layer of diode used, and ΔE_F is the shift in the quasi-Fermi level, V_1 and V_2 are two different voltages applied to the diode. When the applied potential is increased from V_1 to V_2, the quasi-Fermi level shifts to the conduction band edge by

$$\Delta E_F = kT \ln\left(\frac{I_2 V_1}{I_1 V_2}\right) \tag{2}$$

here, k is the Boltzmann constant, T is the temperature, I_1 and I_2 are the current values measured at the applied voltages V_1 and V_2, respectively.

Fig. 1 shows the dark *I–V* characteristic of our Schottky diode on the log–log scale at room temperature. As seen from the figure, an ohmic behaviour is observed at lower voltages. Beyond a critical voltage (~0.3 V), the current increases superlinearly. This region is known as the SCLC region, and thus ΔE_F and the DOS are determined from this region.

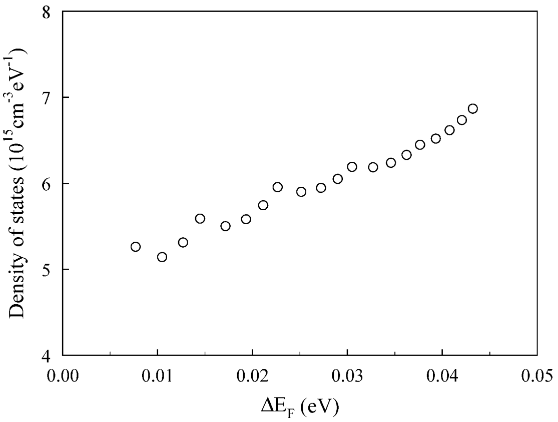

Fig. 2. Density of states (DOS) of a-Si:H Schottky diode, determined from the SCLC analysis.

We determined the DOS in the forbidden energy gap from the simple den Boer relations given above (Eqs. (1) and (2)). It is shown in Fig. 2. Obviously, the values of DOS are in the order of $10^{15}\ \text{cm}^{-3}\ \text{eV}^{-1}$. This result is in good agreement with the other studies performed for a-Si:H [21–23].

3.2. Illuminated I–V analysis

Fig. 3 shows the illuminated *I–V* characteristics of a-Si:H Schottky diode at various temperatures for a constant intensity of 15 mW from HeNe laser (632.8 nm). Here, 1 mW corresponds to an intensity of about 10^{19} phs $\text{s}^{-1}\ \text{cm}^{-2}$.

Photodiodes or solar cells operate without an externally applied voltage and the collection of carriers result from the internal field at the junction. This is referred as the fourth quadrant in Fig. 3. Of all

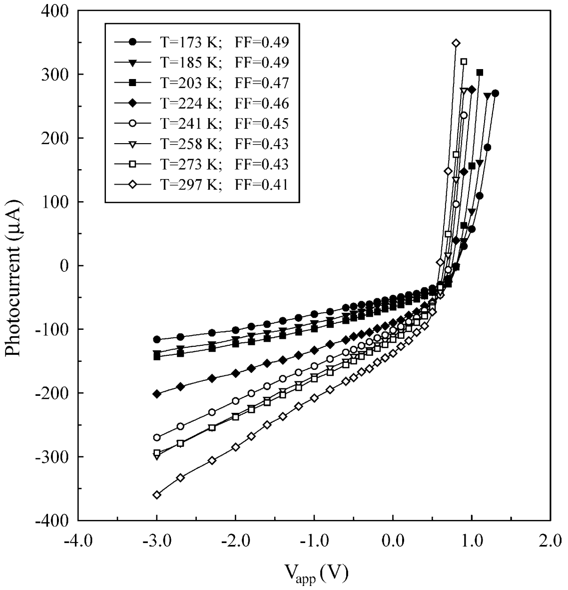

Fig. 3. I_{ph}–V characteristics of a-Si:H Schottky diode at various temperatures. The calculated values of FF from the fourth region were also shown for the each temperature. The average value of FF is 0.45 ± 0.04. The light intensity with the wavelength of 632.8 nm used is very high (15 mW).

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 can be expressed as [24]:

$$\eta = (I_m V_m)/P_i = (\mathrm{FF})(I_{sc} V_{oc})/P_i \tag{3}$$

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

$$\mathrm{FF} = (V_m I_m)/(V_{oc} I_{sc}). \tag{4}$$

From the fourth quadrant of Fig. 3, the determined values of FF of our a-Si:H Schottky diode were presented on the same figure for the indicated temperatures. The small value of FF may be due to high excitation intensity used (15 mW). As can be seen, there is a minor decrease in FF with 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 depends exponentially on the temperature, V_{oc} will decrease. According to a model proposed by Crandal [25], for the weakly absorbed light, the shape of *I–V* curve is completely specified by electron and hole drift lengths.

We have used the reverse-bias *I–V* characteristics for determining the carrier concentration created by light. The approximation for this calculation is based on the diode equations known under illumination. In reverse-bias, the dark current of Schottky diode is given by:

$$I_R = I_0 \exp\left(\frac{q\sqrt{qE/4\pi\varepsilon_r}}{kT}\right) \tag{5}$$

where E is the electric field and defined by:

$$E = \sqrt{\frac{2qN_D}{\varepsilon_r}}\left(V + V_{bi} - \frac{kT}{q}\right). \tag{6}$$

Here, N_D is the donor concentration, V is the applied bias, V_{bi} is the built-in potential [20], q is the fundamental electronic charge. Under illumination, the left side of Eq. (5) will be a sum of dark and light current together, that is:

$$I_R + I_{LR} = I_0 \exp\left(\frac{q\sqrt{qE/4\pi\varepsilon_r}}{kT}\right) \tag{7}$$

where I_{LR} represents the current under light. Since $I_{LR} \gg I_R$, in practice we can ignore I_R with respect to I_{LR}, i.e., $I_R + I_{LR} \sim I_{LR}$. This is exactly our approximation. In this approximation, the current mechanism is mostly controlled by the charge carriers created by light. Now we can use N_L, which represent the carrier density under light, instead of N_D in Eq. (6). Then, the illuminated reverse-bias photocurrent becomes:

$$I_{LR} = I_0 \exp(m(V + V_{bi})^{1/4}) \tag{8}$$

where m is defined by:

$$m = \left(\frac{q}{kT}\right)\left(\frac{N_L q^3}{8\pi^2\varepsilon_r^3}\right)^{1/4}. \tag{9}$$

Now, we can determine N_L from the last two equations. For this, we plot $\ln(I_{LR})$ versus $(V + V_{bi})^{1/4}$, as shown in Fig. 4. Clearly, it gives straight lines. From the slope of these lines, the values of m were calculated and indicated on the same figure for the each temperature measured. By using the calculated m values, we deter-

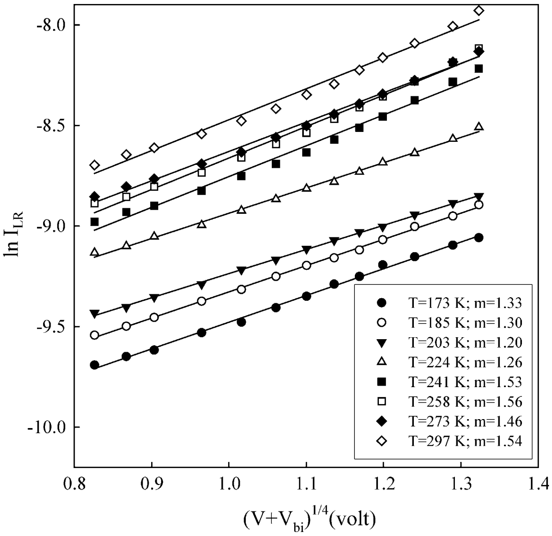

Fig. 4. The $\ln(I_{LR})$ vs. $(V + V_{bi})^{1/4}$ (in Eq. (8)).

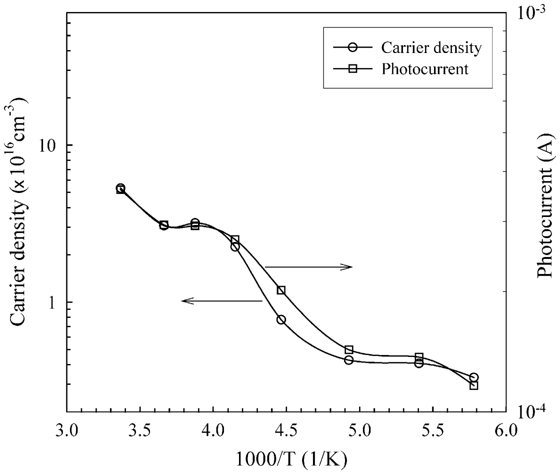

Fig. 5. A comparison of the carrier density (calculated) and photocurrent (measured) as a function of the reverse temperature.

mined N_L in Eq. (9). N_L values and their corresponding values for photocurrent were comparatively plotted as a function of inverse temperature in Fig. 5. The data for photocurrent were taken under the reverse-bias of −3 V. As seen from the figure, there is a good agreement between both curves. This shows that the determined N_L values are rather accurate and our approximation is very good. Obviously, both the carrier density and photocurrent is thermally activated in the temperature range covered. This is in agreement with the results of multiple trapping model [26] proposed for the photoconductivity at high temperatures ($\sim$120 K $< T <$ 300 K). According to this model, the transport of carriers in a variety of a-semiconductors can be described by the such model, in which injected carriers thermalize in a broad distribution of localized band tail states [26,27], moving to deeper energies as a result of thermal activation to transport states and subsequent retrapping. Under these circumstances, the time dependence of transient photocurrent provides a spectroscopy of DOS in the tail [28].

The shoulders or plateaus seen in Fig. 5 may be due to the defect levels of our Schottky diode used [18].

4. Conclusion

I–V characteristic in the dark, and from this the density of states (DOS) of a-Si:H Schottky diode was determined in space charge limited current regime. The DOS in the gap was found to be in the order of 10^{15} cm^{-3} eV^{-1}. It is in good agreement with the results of other researchers. The illuminated *I–V* characteristics were also analyzed in detail. The fill factor (FF), which is a parameter for the cell performance as known, was determined at various temperatures between 173 and 297 K. We found that FF increases as the temperature decreases. This is due to the carrier with the longer drift length, which determines the *I–V* curve and hence the fill factor. We also compared the theoretically calculated carrier concentration and the measured photocurrent in the whole temperature range covered. It is observed that there is a good correlation between them. Therefore, the approximation used here is rather good.

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