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Difference of Characteristics of a-Si: H Solar Cells between under Illumination and Dark

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The purpose of this paper is to show that the a-Si: H p-i-n type solar cells become more conductive as the incident light intensity increases. A new method for the determination of the series resistance R_s, the shunt resistance R_{sh} and the diode factor (n-value) is given from the measured dc current I-the dc voltage V curve under the illumination of a fixed light intensity. Consequently, as the light intensity increases from zero to 140 mW/cm^2, it is found that R_s decreases from 47.3 ohm to 0.1 ohm and that R_{sh} decreases from 2.2×10^5 ohm to 7×10^2 ohm in the case of #E7-1 sample as well as the other samples. The increase of the n-value with increasing light intensity suggests that the a-Si: H cells show a tendency toward the property due to the recombination current in the space charge region near the p-i junction.

§1. Introduction

The photovoltaic property of a solar cell is characterized by the conversion efficiency η, the open-circuit voltage V_{oc}, the short-circuit current I_{sc} and the fill factor FF, depends strongly on the series resistance R_s, the shunt resistance R_{sh} and the diode factor n which is also called n-value. In a crystalline Si junction-type solar cell, it is reported that R_s, R_{sh} and n-value hardly depend on the incident light intensity.[1] In a hydrogenated amorphous silicon (a-Si: H) p-i-n type cell, it is reported that FF decreases as the light intensity increases.[2] In Pt-gate Schottky-barrier type a-Si: H cell[3] and a-Si: F: H cell,[4] the light intensity dependence is reported. The purpose of this paper is to show the dependency of R_s, R_{sh} and n on the light intensity in the case of a-Si: H p-i-n type solar cell which is called "light conductive-type solar cell". A new method for the determination of R_s, R_{sh} and n on the a-Si: H cell at a fixed light intensity is given without searching the n-value. There have been a few methods for the determination. The value of R_s has been calculated from the relation[5] $R_s=(V_d-V_{oc})/I_L$, where I_L is the photocurrent, V_d is the voltage in the dark for the current equal to I_L. In Handy method,[6] two measured curves between dc current I and dc voltage V under two different light intensity have been necessary for the determination of R_s. A curve fitting method[7] to the experimental I-V curve has been used by searching the n-value. In the case of a-Si: H cells, these determination methods on the condition of the different light intensity can not be used, because a-Si: H cell is light conductive-type. By this new method, it is quantitatively shown how conductive the a-Si: H cell becomes as the light intensity increases. As a result, in the case of #E7-1 sample, it is found that R_s varies from 47.3 ohm to 0.1 ohm with increasing the light intensity from zero to 140 mW/cm^2. The shunt resistance varies from 2.2×10^5 ohm to 7×10^2 ohm. The diode factor varies from 1.1 to 1.9.

§2. Theory for the Determination of R_s, R_{sh} and n-value

The relation of dc current I versus dc voltage V under illumination is given as

$$I=I_L-I_s\exp[q(V+R_sI)/(nkT)]+I_s-(V+R_sI)/R_{sh}, \quad (1)$$

where I_L is the photocurrent, I_s is the saturation current and kT/q is the thermal voltage. Differentiating eq. (1) with respect to V yields the following relation

$$B=\frac{1+[I_L+I_s-I-(V+R_sI)/R_{sh}]qR_s/(nkT)+(R_s/R_{sh})}{[I_L+I_s-I-(V+R_sI)/R_{sh}]q/(nkT)+1/R_{sh}}, \quad (2)$$

where B is defined as $1/B=-\mathrm{d}I/\mathrm{d}V$. Using the application of both $I=I_{sc}$ at $V=0$ and $I=0$ at $V=V_{oc}$ to eq. (1), we obtain the following relations

$$I_s=[I_{sc}+R_{sh}^{-1}(R_sI_{sc}-V_{oc})]\exp[-qV_{oc}/(nkT)], \tag{3}$$

$$I_L+I_s=(1+R_s/R_{sh})I_{sc}, \tag{4}$$

where the assumption of $\exp[qR_sI_{sc}/(nkT)]<\exp[qV_{oc}/(nkT)]$ is used. By defining $B=A$ at $V=0$, eq. (2) can be reduced to

$$(A-B)/[A(I_{sc}-I)-V]=[q/(nkT)](B-R_s), \tag{5}$$

using eq. (4). From eqs. (2) and (4), we obtain the relation

$$A=R_s+R_{sh}. \tag{6}$$

If the value of B at each dc bias is known, R_s and n under illumination can be determined by using the property of the straight line between $(A-B)/[A(I_{sc}-I)-V]$ and B. From eq. (6), R_{sh} under illumination can be determined.

From the condition of $I_L=0$ in the dark, eq. (2) can be reduced to

$$(B-A)/(V+AI)=[q/(nkT)](B-R_s), \tag{7}$$

where A is defined as $1/A=-(dI/dV)_{V=0}$ and $I_sR_{sh}<[(R_s+R_{sh})I+V]$ is used. Equation (6) holds even in the case of no illumination on the assumption of $1/R_{sh}>qI_s/(nkT)$. Using the property of the straight line between $(B-A)/(V+AI)$ and B from eq. (7), the value of R_s, n and R_{sh} in the dark can be known.

§3. Experiment

The samples used in this experiment are the p-i-n type a-Si: H solar cells fabricated by a capacitive glow discharge method. The thickness of n-type a-Si: H layer deposited on a stainless steel is 1100 Å. The thickness of p-type layer is 70 Å. The thickness of i-type layer is 1000 Å, 3000 Å and 5500 Å which is named E7-1, E6-2 and E9-1 as a sample number, respectively. The ITO film of 750 Å thickness was deposited on the p-layer and a Ti–Ag film as a grid electrode was formed on the ITO film. All samples are sealed in a glass case. The active area of E7-1, E6-2 and E9-1 is 0.825 cm^2, 0.852 cm^2 and 0.845 cm^2, respectively. The *I-V* measurement at room temperature was carried out under the variable condition of light intensity using Xe solar simulator. Figures 1(a), (b) and (c) show the *I-V* curves of a-Si: H p-i-n solar cells at various light intensity with a good agreement between theory and experiment. The theoretical curves are calculated from eq. (1) using R_s, R_{sh} and n which will be seen later as shown in Figs. 3 and 4. Figure 2 shows the *I-V* curves in the dark. Figures 3(a), (b) and (c) under the illumination show the straight lines between $(A-B)/[A(I_{sc}-I)-V]$ as ordinate and B as abscissa with satisfing eq. (5). Figure 4 shows the straight lines between $(B-A)/(V+AI)$ and B in the dark with satisfing eq. (7). Consequently, R_s, R_{sh}, n and FF are obtained as shown in Table I. As light intensity increases

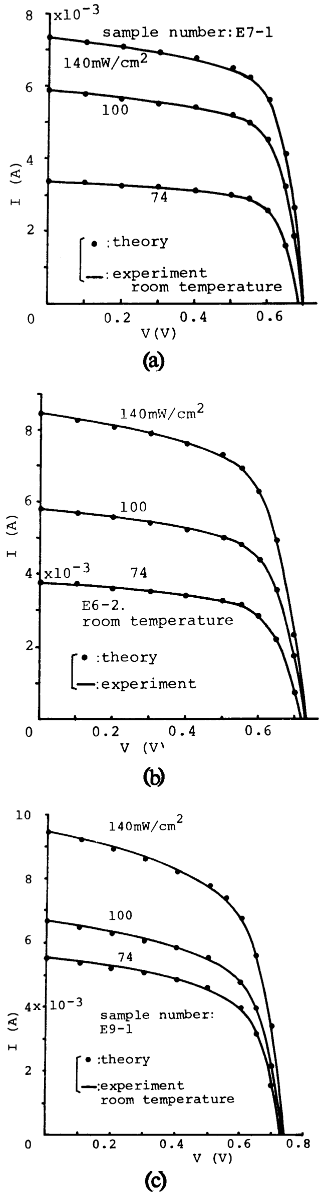

Fig. 1. *I-V* curves of p-i-n type a-Si: H cells under illumination. (a): sample number E7-1, (b): sample number E6-2, (c): sample number E9-1.

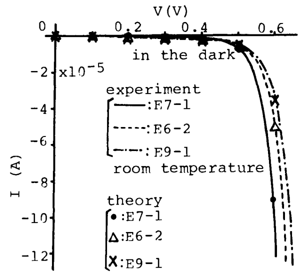

Fig. 2. *I-V* curves of p-i-n type a-Si: H cells in the dark.

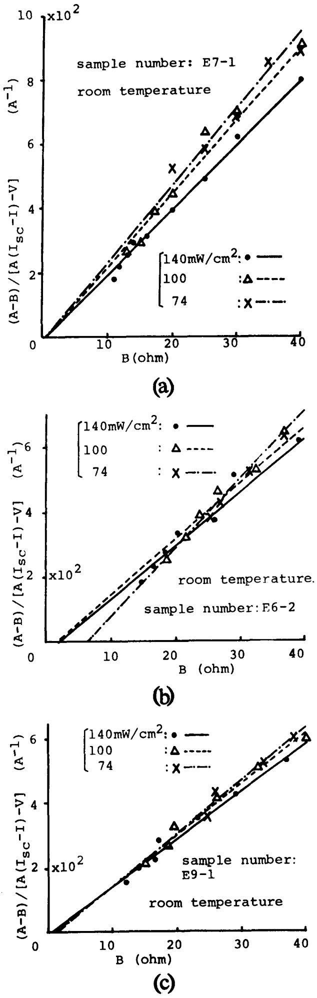

Fig. 3. Straight lines in order to determine R_s, R_{sh} and n of p-i-n type a-Si: H cells under illumination. (a): sample number E7-1, (b): sample number E6-2, (c): sample number E9-1.

from zero to 140 mW/cm^2, it is found that the series resistance R_s decreases from 47.3 ohm to 0.1 ohm and that the shunt resistance R_{sh} decreases from 2.2×10^5 ohm to 7×10^2 ohm,

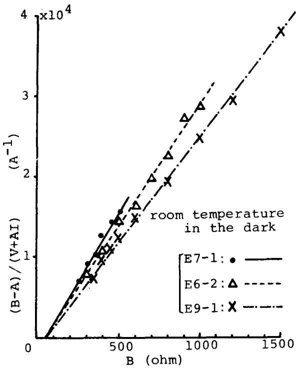

Fig. 4. Straight lines in order to determine R_s, R_{sh} and n of p-i-n type a-Si: H cells in the dark.

for example, in the case of E7-1 cell. It is known that the a-Si: H cells have more conductive property with increasing light intensity. The decrease in R_s with increasing light intensity is due to the decrease in the bulk resistance caused by increase in photogenerated carriers. It is found that n-value increases from 1.1 to 1.9 as the light intensity increases from zero to 140 mW/cm^2 in the case of E7-1 cell. From the increase in n-value as shown in Table I, it seems that the a-Si: H cell shows a tendency toward the property due to the recombination current in the space charge region near the p-i junction with increasing light intensity, and that the high value of n above 2 may be due to non-uniformities in the distribution of recombination centers.[8] Otherwise, it seems that the n-value above 2 suggests the property due to tunneling current or hopping current through trap centers. It is expected that the dc current under illumination is influenced by the light intensity through the plasma screening effect and charge trapping effect[9] originated from an increase in the density of gap states by exposure to light. It is considered that the voltage dependence[10] of I_L is modified by the light intensity. It seems that this voltage dependence results in the light intensity dependence of R_{sh} as shown in Table I.

§4. Conclusion

It is shown that the a-Si: H p-i-n type solar cells become more conductive as the light intensity increases. The new methods are proposed in order to determine the series resistance R_s, the shunt resistance R_{sh} and the diode factor (n-value) from the measured dc current I—dc

Table I. Light intensity dependence of R_s, R_{sh} and n of a-Si: H solar cell by this evaluation method.

Sample number	I_{inc} (mW/cm^2)	FF	n	R_s (ohm)	R_{sh} (ohm)	I_s (A)	I_L (A)
	140	0.670	1.94	0.131	700	5.68×10^{-9}	7.35×10^{-3}
E7-1	100	0.676	1.71	0.063	780	7.77×10^{-10}	5.87×10^{-3}
	74	0.688	1.62	0.286	1450	2.52×10^{-10}	3.38×10^{-3}
	0	—	1.10	47.3	220000	9.85×10^{-14}	—
	140	0.622	2.35	1.960	528	4.59×10^{-8}	8.47×10^{-3}
E6-2	100	0.631	2.26	1.325	739	1.94×10^{-8}	5.85×10^{-3}
	74	0.644	1.86	6.053	1144	1.06×10^{-5}	3.77×10^{-3}
	0	—	1.26	47.0	180000	6.03×10^{-13}	—
	140	0.586	2.63	0.301	350	1.43×10^{-7}	9.47×10^{-3}
E9-1	100	0.595	2.48	0.467	500	5.53×10^{-8}	6.68×10^{-3}
	74	0.605	2.38	1.014	639	3.35×10^{-8}	5.53×10^{-3}
	0	—	1.45	49.5	170000	4.68×10^{-12}	—

voltage V curve under the illumination of a fixed light intensity. Consequently, as the light intensity increases from zero to 140 mW/cm^2, it is found that R_s decreases from 47.3 ohm to 0.1 ohm and that R_{sh} decreases from 2.2×10^5 ohm to 7×10^2 ohm in the case of E7-1 sample as well as the other samples. The increase of the n-value with increasing light intensity suggests that the a-Si: H cells show a tendency toward the property due to the recombination current in the space charge region near the p-i junction. In the case of dark, the n-value which approches to unity suggests that the a-Si: H cells show a tendency toward the property due to injection current.

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