Journal of Non-Crystalline Solids 137&138 (1991) 1181-1184
North-Holland

JOURNAL OF
NON-CRYSTALLINE SOLIDS

TEMPERATURE DEPENDENCE OF THE PHOTOCURRENT IN pin AND nip SOLAR CELL STRUCTURES MADE FROM a-Si:H

Martin HOHEISEL, Elke REICHLE*, Hauke HARMS, and Josef KOTSCHY

SIEMENS AG, Corporate Research and Development, Otto-Hahn-Ring 6, W-8000 München 83, F.R.Germany
* Fachhochschule der Naturwissenschaftlich-Technischen Akademie Isny, W-7972 Isny, F.R.Germany

In connection with the development of solar cells made from amorphous silicon (a-Si:H), we investigated the temperature dependence of the photocurrent under reverse bias of different diodes. From the saturation behavior of the current-voltage characteristics we conclude that the reverse-bias photocurrent is of primary nature. Therefore, it is expected to be independent of temperature. A slight decrease with rising temperature might be due to increasing absorption within the p^+ layer.

Surprisingly, we found an increase of the photocurrent with temperature in all samples investigated. The dependence of this effect on bias voltage, illumination wavelength and intensity suggests the following picture. Using weakly absorbed light, temperature dependent absorption can explain the positive temperature coefficient ($>5\cdot10^{-3}$/K). Strongly absorbed light leads to a small temperature coefficient of the order of $+10^{-4}$/K. The photo-generated carriers influence the internal field distribution and may thus cause an additional increase of the current.

1. INTRODUCTION

Solar cells made from amorphous silicon (a-Si:H) are developed. They show the well known decrease in efficiency with temperature. Recently the influence of the open-circuit voltage on the efficiency decrease has been investigated[1].

Other applications of a-Si:H, i.e. image sensors[2], also make use of photodiodes. The temperature coefficient TC of the photocurrent must be low to ensure a stable signal, if a high grey-scale resolution[3] is required.

We attempted to find out the physical basis of the observed temperature dependence of the photocurrent under reverse bias of different pin and nip junctions. From simple considerations, no pronounced temperature dependence would be expected. Under reverse bias, the photocurrent is of primary nature and thus proportional to the incident photon flux. Every absorbed photon yields one electron-hole pair and hence contributes likewise to the steady-state photocurrent.

An influence of the temperature can arise for three reasons: absorption and reflection of the incident light and carrier recombination inside the diode. Due to the absorption of the bulk a-Si:H, the TC of the optical gap has an influence on the photocurrent as long as only part of the light is absorbed. The TC of the reflection enters directly into the temperature dependence of the photocurrent. If it is a primary photocurrent, no recombination should occur. If, on the other hand, some of the electron-hole pairs recombine, this process contributes its temperature behavior to the TC of the photocurrent.

2. EXPERIMENTAL

The pin diodes were deposited on SnO_2-covered glass substrates, followed by p^+-a-Si:C:H/i-a-Si:H/n^+-a-Si:H and a Cr electrode 20mm^2 in size. The nip diodes were deposited on stainless steel followed by n^+-a-Si:H/i-a-Si:H/p^+-a-Si:C:H and an indium-tin-oxide (ITO) electrode.

The diodes were reverse-biased between 0V and -12V and illuminated with 10^{11}-10^{14}photons/cm^{2}s of weakly and strongly absorbed light. The wavelengths were 707nm and 519nm, respectively. The diodes were measured on a heated sample holder between 25°C and 105°C under vacuum. The pin diodes must be illuminated through the substrate. This makes it difficult to establish good thermal contact to the sample holder. As pin and nip diodes showed the same behavior, most measurements were carried out on nip samples.

0022-3093/91/$03.50

3. RESULTS AND DISCUSSION

Fig.1 displays the current-voltage characteristics of an nip diode in the dark and under illumination. Strongly absorbed light leads to excellently saturated curves, i.e. a rise in applied voltage from -1V to -8V causes an increase in the photocurrent of only 3.4%. In the case of weakly absorbed light, in contrast, the photocurrent tends to decrease near 0V.

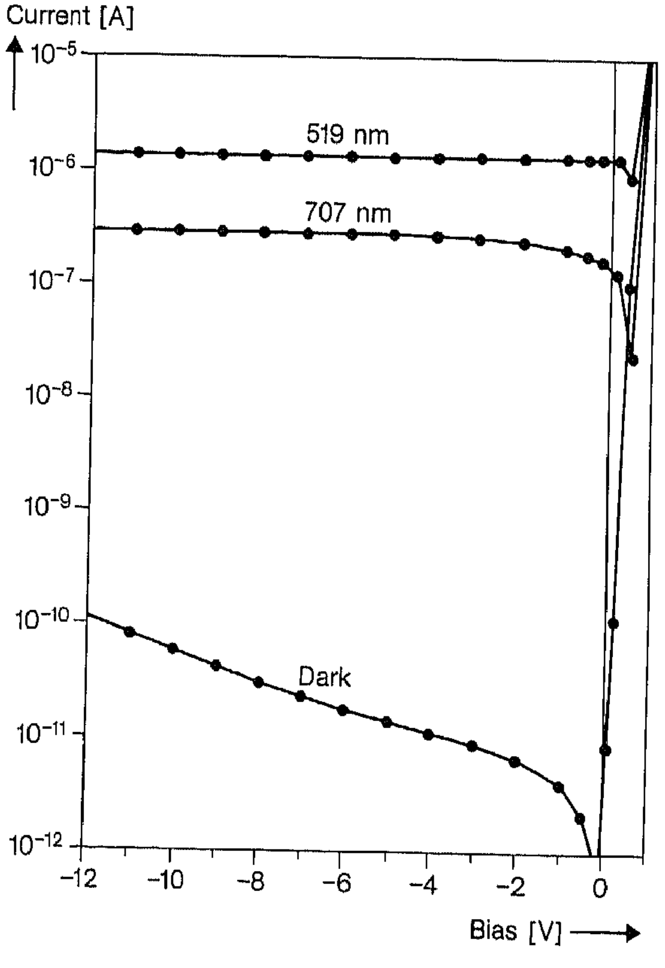

FIGURE 1
Current-voltage characteristics of an nip diode in the dark and illuminated with $4\cdot10^{13}$phot/cm^{2}s of green (519nm) and red (707nm) light.

Green light is absorbed in a thin region of some 100nm. The created electron-hole pairs are separated by the electric field. Holes travel the short distance to the transparent electrode, electrons have to traverse the sample to reach the opposite contact. Hence the spatial overlap between electron and hole distribution is small and recombination can be excluded.

Red light is absorbed throughout the volume of the diode (α=10^3cm^{-1} at 707nm). As a result, recombination can occur in the whole sample. The dependence of the drift velocity of the carriers on the electric field influences the recombination rate thus causing an increase of the photocurrent with voltage (Fig.1).

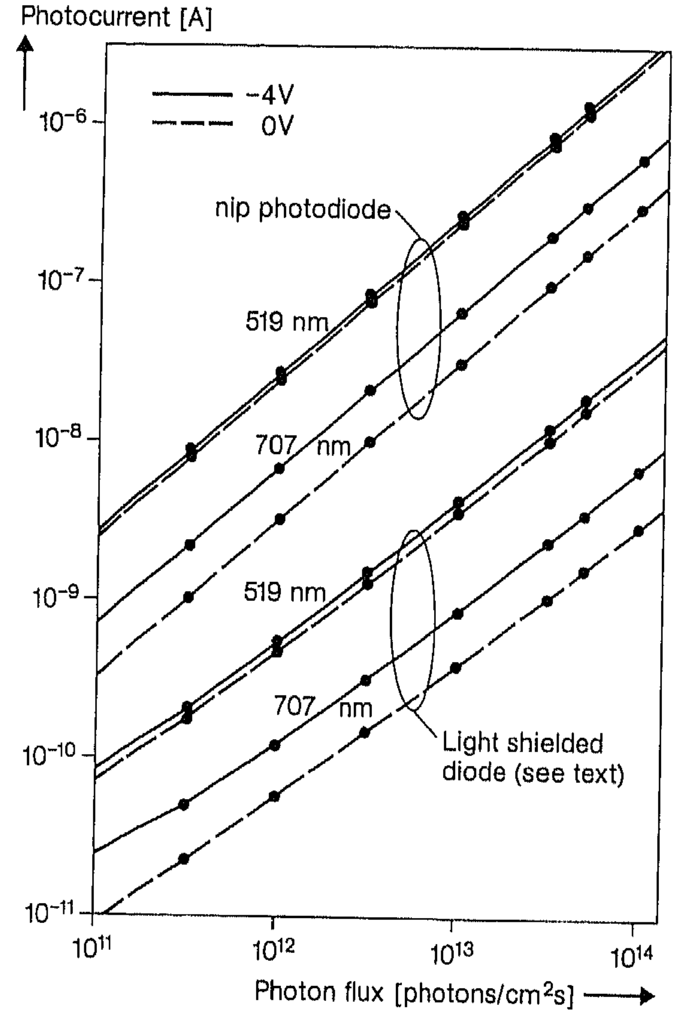

FIGURE 2
Intensity dependence of the photocurrent with green and red light. Power-law exponents n are 1. A light-shielded diode exhibits n=0.8.

In Fig.2 the intensity dependence of the photocurrent indicates that strongly and weakly absorbed light yield similar exponents n close to unity. In the case of weak absorption the photocurrent is diminished by monomolecular recombination, which also exhibits n=1.

The typical dependence of the dark current on temperature is shown in Fig.3. The Arrhenius plot yields E_a=0.93eV. The dark current density at room temperature is $3\cdot10^{-11}$A/cm^2. At higher temperatures the dark current has to be subtracted from the photocurrent. Otherwise the strong TC of the dark current may incorrectly be interpreted as a temperature dependent photocurrent.

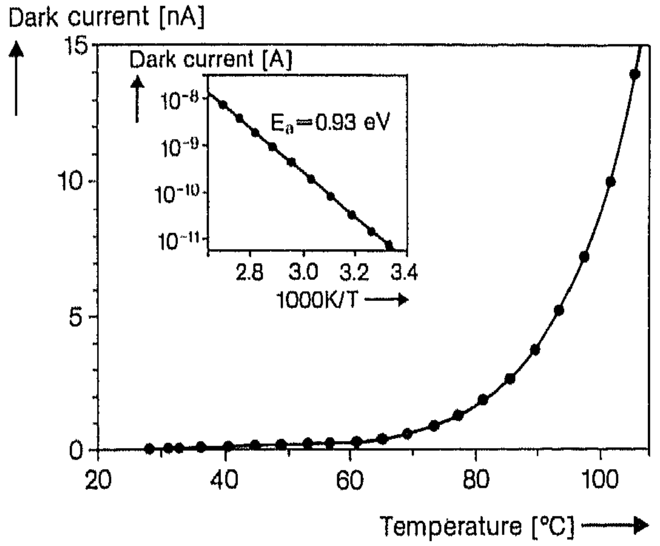

FIGURE 3
Temperature dependence of the dark current with -4V bias. Inset: Arrhenius plot with E_a=0.93eV.

Fig.4 displays a selection of temperature dependences of the photocurrent. With green light, the TC is small (100-300ppm/K, i.e. $1\text{-}3\cdot10^{-4}$/K) whereas with red light the photocurrent rises more strongly with temperature (6000-9000ppm/K).

One contribution to the temperature dependence is the TC of the bandgap[4], as at 707nm only part of the incident light is absorbed in the i-layer. We calculated a TC of about 8700ppm/K, which nicely explains the observed behavior.

Another influence on the TC is due to the reflection. The temperature dependence of the reflectivity[6] leads to a TC of -100ppm/K. As this TC has a negative sign compared to the measured +250ppm/K, it cannot explain our observations.

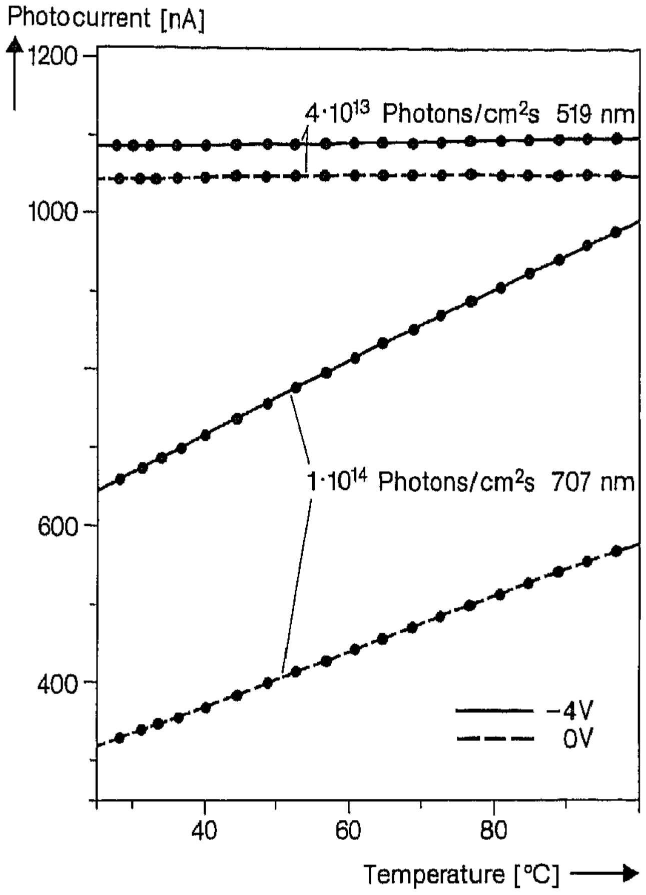

FIGURE 4
Temperature dependences of the photocurrent with 0V and -4V bias and with green and red light.

In most applications, illumination of fringe regions of the sample cannot be avoided[5]. In these regions the electric field is considerably lower. To investigate the influence of this fringe on the TC, we prepared a sample with a metal electrode instead of ITO to light-shield the diode area. This sample exhibits a photocurrent which is a factor of 50-100 lower, with a power-law exponent around 0.8 (Fig.2) indicating recombination-controlled photoconduction in the fringe region. By comparing the samples, we can separate the influence of the fringe areas on the total photocurrent. Only ≈100ppm/K of the positive TC observed can be explained by the contribution of the fringes, whereas the major effect is due to other reasons.

To investigate the influence of the density of states on the TC, we aged a diode by light-soaking (16h, AM1). Fig.5 shows the temperature dependences. While the TC with -4V bias is somewhat greater than in the as-deposited case (700ppm/K and 250ppm/K, respectively), the photocurrent at 0V rises strongly with temperature (TC=13000ppm/K). This result indicates recombination near the p^+ contact because the electric field does not penetrate the whole a-Si:H. Correspondingly, the current-voltage characteristic shows poor saturation (see inset).

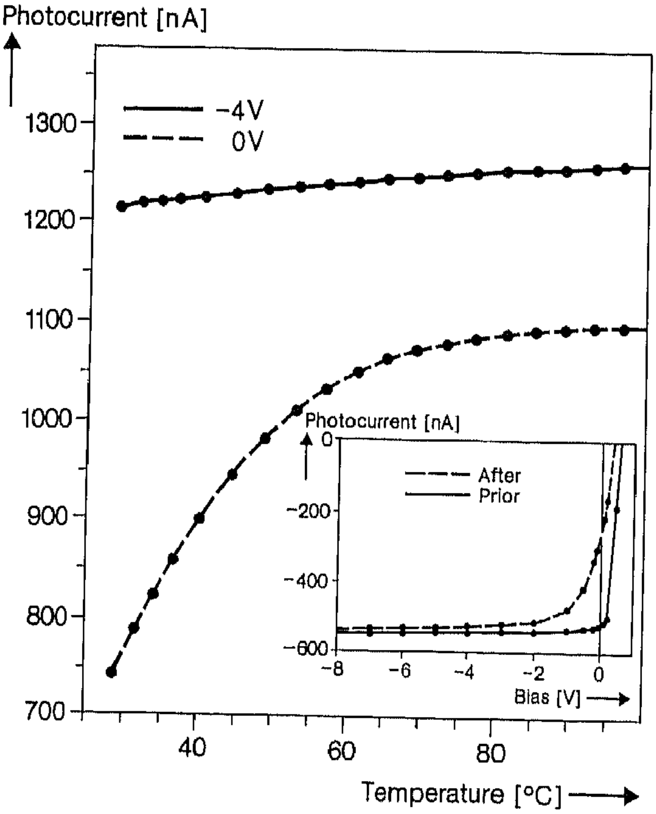

FIGURE 5
Temperature dependences of the photocurrent of an aged diode with 0V and -4V bias with green light. Inset: Current-voltage characteristics at 25°C prior to and after light-soaking.

4. CONCLUSIONS

The TCs of the photocurrents of reverse-biased pin and nip diodes unexpectedly show a positive sign. This cannot be entirely explained by optical absorption, reflection or by recombination. We therefore propose an alternative model. Under illumination, charge carriers are trapped in the i-layer. These carriers screen the internal field and thus alter the band profile. Wieczorek and Fuhs[7] demonstrated on Schottky diodes that holes are trapped mainly near the negatively-biased contact. This hole concentration near the p^+ contact (in our case) can induce electron injection, as suggested by Street[8]. The total current I_{ill} under illumination as the sum of the (primary) photocurrent I_{ph} and the dark currrent I_d which is strongly temperature dependent (see Fig.3). Illumination of the p/i interface enhances electron injection by lowering the barrier height, resulting in an increase of I_d. This leads to a TC of the total current I_{ill} with a positive sign.

ACKNOWLEDGEMENTS

We would like to thank R. Carius, B. Ebersberger, W. Krühler, W. Kusian, and H. Wieczorek for fruitful discussions.

REFERENCES

1. Jin Jang, C. Lee, D. Adler, Y. Hamakawa, and A. Madan, Mat. Res. Soc. Symp. Proc. Vol. 70 (1986) 543

2. M. Hoheisel, G. Brunst, and H. Wieczorek, J. Non-Crystalline Solids 90 (1987) 243

3. G. Brunst, S. Griep, H. Harms, K. Rohleder, and K. Rosan, Mat. Res. Soc. Symp. Proc. Vol. 118 (1988) 249

4. G. Weiser, and H. Mell, J. Non-Crystalline Solids 114 (1989) 298

5. M. Hoheisel, H. Wieczorek, and K. Kempter, J. Non-Crystalline Solids 77&78 (1985) 1413

6. J.M. Berger, F. de Chelle, J.P. Ferraton, A. Donnadieu, J. Beichler, and G. Weiser, Solar Energy Materials 9 (1983) 301

7. H. Wieczorek, W. Fuhs, phys. stat. sol. (a) 109 (1988) 245

8. R.A. Street, Phys. Rev. B 27 (1983) 4924