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Open-Circuit Voltage Decay (OCVD) Measurement Applied to Hydrogenated Amorphous Silicon Solar Cells

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A small-signal open-circuit voltage decay (OCVD) method has been applied for the first time to measure carrier lifetime in hydrogenated amorphous silicon solar cells under dc bias illumination. The observed decay has multiexponential time dependence with the time constants between 0.7 μs and 20 μs. In the n-i-p type cells investigated in this paper, these time constants correspond to deep trapping hole lifetimes near the n-layer/i-layer interface of the cell. The light-induced changes in the OCVD signal have been observed.

KEYWORDS: carrier lifetime, OCVD method, a-Si:H solar cells, light-induced changes

Carrier lifetime is one of the most important parameters in photovoltaic materials because it determines solar cell characteristics. A variety of methods[1-4] have been proposed to determine the carrier lifetime in hydrogenated amorphous silicon (a-Si:H). Among them are time-of-flight (TOF)[1] and delayed field (DF)[2] methods, photothermal displacement (PTD)[3] measurement, and carrier collection measurement[4] as a function of wavelength and applied bias voltage. TOF[1] and DF[2] methods have been applied to thick (>2 μm) samples, but it is difficult to use these methods in actual solar cell structures with thin (~ 0.5 μm) undoped layers. Moreover, one cannot determine, in principle, the carrier lifetime under dc bias illumination with these methods. The PTD measurements[3] have been carried out in single film samples, and it is unclear whether they can be applied to solar cell structures. The carrier collection measurements[4] were made without dc bias illumination, and the obtained quantity is usually the mobility-lifetime product instead of the carrier lifetime. The carrier lifetime in a-Si:H depends on the level of dc bias illumination,[5] and the surface and the interface of the sample affect trapping and recombination of carriers in a-Si:H.[5] It is therefore necessary to consider a method that enables us to determine the carrier lifetime in actual a-Si:H solar cells under dc bias illumination.

In this paper, we propose, for the first time, a small-signal open-circuit voltage decay (OCVD) method to determine the carrier lifetime in a-Si:H solar cells under dc bias illumination. The observed decay has multiexponential time dependence with time constants between 0.7 μs $\sim$ 20 μs. From the observed changes in OCVD induced by the prolonged illumination of visible light with different wavelengths, we conclude that these time constants correspond to the deep trapping hole lifetimes near the n-layer/i-layer interface of the n-i-p type cells investigated in this paper.

Samples with an n-i-p structure were prepared on stainless steel substrates by glow discharge decompositiom of silane (SiH_4). The substrate temperature during growth was 250°C and the doping concentration in the gas phase was $B_2H_6/SiH_4=2\%$ for p-type doping and $PH_3/SiH_4=0.09\%$ for n-type doping. The thicknesses of the n, i, and p layers were 100 A, 5000 A, and 300 A, respectively. One-thousand-angstrom thick indium tin oxide (ITO) dots with an area of 0.01 cm^2 were evaporated on the n layers as top electrodes. The details of the sample preparation were described elsewhere.[6]

Light from a dye laser at the wavelength of 650 nm or light from an Ar ion laser at the wavelength of 488 nm was modulated with an AO modulator, and this pulsed light was introduced to the sample from the n-layer side which was set in a wafer cryostat (Sanwa Radio Measurement Works Inc., Model WM-365). The period and the width of the light pulse were 2 ms and 0.3 ms, respectively. The fall time and the intensity on the sample surface of the light pulse were less than 100 ns and 5 mW/cm^2, respectively. During the OCVD measurements, the samples were illuminated with dc white light from a tungsten halogen lamp with an intensity of 100 mW/cm^2 (equivalent to AM1.5 spectrum).[7] The dc bias illumination was necessary to (1) reduce the effect of the *CR* time constant of the sample on the OCVD measurements and to (2) set the sample in the actual illumination condition. The *CR* time constant of the sample under the dc bias illumination was shorter than 0.5 μs, and it did not affect the observed decay. The OCVD signal was stored in and analyzed with a Tektronix 7854 processing oscilloscope. All the measurements were carried out at room temperature.

Figure 1 shows a semilogarithmic plot of a typical OCVD obtained for an a-Si:H n-i-p solar cell before and after the prolonged illumination of 488 nm light from an Ar ion laser. The intensity of the 488 nm light was 200 mW/cm^2, and the illumination time was 2 hours. The cell was kept in the open circuit condition during the illumination. The observed OCVD signal was less than 10 mV and much smaller than the open-circuit voltage (820 $\sim$ 850 mV) induced by the dc bias illumination. Thus, the small-signal condition[8] is fulfilled in the present measurements. The observed decay has multiexponential time dependence, which contrasts with the OCVD in laser recrystallized poiy-Si[9] where single exponential decay was observed. While the red light pulse

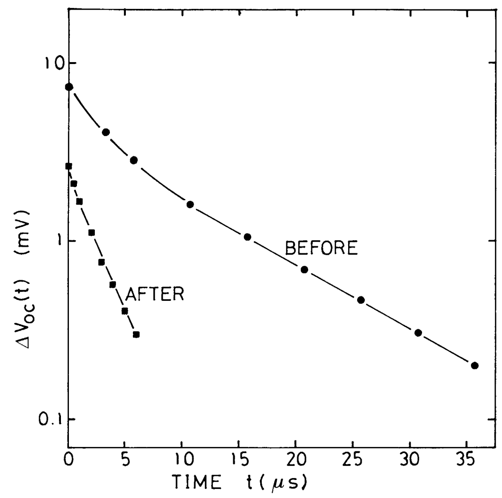

Fig. 1. A semilogarithmic plot of a typical open-circuit voltage decay (OCVD) signal obtained for an a-Si:H n-i-p type solar cell before and after the prolonged illumination of 488 nm light from an Ar ion laser with the intensity of 200 mW/cm^2. The illuminating time was two hours. The red light pulse at the wavelength of 650 nm was used for the OCVD measurements.

Table I. Time constants, τ_1 and τ_2, and photovoltaic parameters, J_{SC}, FF and V_{OC}, obtained for a-Si:H n-i-p type solar cells before and after the prolonged illumination of blue, red and air mass(AM) 1.5 light.

illumination condition		τ_1(μs)	τ_2(μs)	J_{SC} (mA/cm^2)	FF	V_{OC} (mV)
blue(λ=488 nm)	before	2.88	12.2	7.51	0.510	851
(200 mW/cm^2, 2 hours)	after	0.76	3.05	6.02	0.446	823
red(λ=650 nm)	before	2.91	19.1	7.55	0.526	855
(200 mW/cm^2, 2 hours)	after	2.83	20.7	5.95	0.449	825
AM1.5	before	2.89	20.2	7.97	0.638	855
(100 mW/cm^2, 4 hours)	after	2.64	16.1	7.53	0.582	837

was used for the present measurement, almost the same decay was observed when the blue light pulse was used for excitation. The multiexponential decay reflects the distribution of carrier lifetime in a-Si:H due to the gap states with continuous energy distribution.[10] The decay observed in the time range in Fig. 1 can be fitted with the superposition of two exponential transients:

$$\Delta V_{OC}(t)=A_1 \exp(-t/\tau_1)+A_2 \exp(-t/\tau_2). \quad (1)$$

Here A_1 and A_2 are constants. Time constants, τ_1 and τ_2 ($\tau_1<\tau_2$), obtained from the fitting are summarized in Table I (see the second and third lines labeled with "blue"). Both τ_1 and τ_2 are longer than the CR time constant ($\sim$0.5 μs) of the sample. The prolonged illumination of the 488 nm light decreases τ_1 and τ_2 to a quarter of the initial values before the illumination. These light-induced changes are reasonable and confirm that we are observing the quantities related with the material properties of a-Si:H. Berry and Longrigg[11] applied a large-signal OCVD method to a-Si:H modules and obtained an extremely long decay time in the order of 100 ms which is much longer than the time constants reported here. They carried out the OCVD measurements without the dc bias illumination, which might be the reason for the extremely long decay.

Since trapping and detrapping of carriers occur in the open-circuit condition, the observed time constants correspond to deep trapping lifetime.[1] However, it is unclear whether the time constants are electron or hole lifetime in the bulk of the undoped (i) layer or near the interfaces. To clarify these points, we have examined the changes in τ_1 and τ_2 by prolonged illumination with different wavelengths. The results are summarized in Table I. The prolonged illumination of blue (488 nm) light significantly decreased the time constants, as described in the last paragraph. On the other hand, almost no changes were induced by two hour illumination of red (650 nm) light with the intensity of 200 mW/cm^2. Four hour illumination of air mass (AM) 1.5 light with the intensity of 100 mW/cm^2 induced small changes in τ_1 and τ_2. Here the penetration depth of the 488 nm light and that of the 650 nm light in the undoped a-Si:H layers of the present samples are about 0.1 μm and about 1 μm, respectively. The blue light illumination, thus, can change the electrical properties near the n-layer/i-layer (n/i) interface, while the red light illumination can induce the changes in the properties of the entire i layer. This speculation is supported by the observed changes in carrier collection efficiency; the blue light illumination decreased the efficiency of the short wavelength region ($\lambda<550$ nm) while the red light illumination caused the decrease in the efficiency in the whole wavelength range (400 nm$<\lambda<$700 nm) investigated. Drift and/or diffusion of carriers could make the distribution of light-induced defects different from that of photogeneration of carriers. These effects were, however, not so large when the cell was kept in the open-circuit condition during the prolonged illumination. The present experimental results indicate that the observed time constants, τ_1 and τ_2, correspond to the deep trapping lifetime of minority carriers, i.e., holes near the n/i interface of the n-i-p type cell.

To our knowledge, this is the first report of the deep trapping hole lifetime near the n/i interface of an a-Si:H solar cell under illumination. Karg *et al.*[2] applied the delayed field method to a-Si:H p-i-n solar cells and reported that the electron lifetime at the p-layer/i-layer (p/i) interface is between 50 ns and 600 ns depending on the preparation conditions of the interface. These values are much shorter than the time constants reported in this paper. The difference might be ascribed to the difference in the carrier type, to that of the interface, and to that in the measuring method. Further study is, however, necessary to clarify the reason for the difference.

Light-induced changes in the short circuit current (J_{SC}), the fill factor(FF), and the open circuit voltage (V_{OC}) of the n-i-p solar cells are listed in Table I as well. These photovoltaic parameters were measured under AM1.5 light with the intensity of 100 mW/cm^2. Here the experiments of the prolonged illumination with the blue and red light were made in the same sample while the experiments with AM1.5 light were carried out in the another sample prepared under similar conditions. The initial photovoltaic properties before the AM1.5 illumination are, thus, different from those of other illumination conditions. Since the shadow of the probe on a small ITO dot affects the value of J_{SC}, the observed light-induced changes in J_{SC} can contain experimental error resulting from the inaccuracy of the probe position. We, thus, discuss the changes in FF and V_{OC} which are almost independent of the probe position. Similar changes were observed in FF and V_{OC} when different (blue and red) light was used for the prolonged illumination. This contrasts with the changes in τ_1 and τ_2. For the red light illumination, the values of FF and V_{OC} exhibited considerable decrease while almost no changes were observed in τ_1 and τ_2. The light-induced degradation in FF and V_{OC} by the red light illumination implies that the properties of the undoped (i) layer bulk changed with the illumination. It is, however, unclear at present why the OCVD signal does not reflect the change in the properties of the i layer bulk. Experiments on samples with different structure are necessary to answer this problem.

In summary, we have applied a small-signal open-circuit voltage decay method to a-Si:H n-i-p type solar cells. The observed decay had multiexponential time dependence with time constants between 0.7 μs and 20 μs. From the observed changes in OCVD induced by the prolonged illumination of visible light with different wavelengths, it has been shown that these time constants correspond to the deep trapping hole lifetime near the n/i interface of the n-i-p cells under illumination.

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