Letter to the Editor

Investigation of interface and band gap states in amorphous silicon p–i–n solar cells using current deep level transient spectroscopy

R.V.R. Murthy *, V. Dutta

Photovoltaic Laboratory, Centre for Energy Studies, Indian Institute of Technology, New Delhi 110 016, India

Received 14 June 1995; revised 28 November 1995

Abstract

Current deep level transient spectroscopy (DLTS) studies were performed on as-deposited and reverse biased annealed samples of a-Si:H p–i–n solar cells. These studies indicate interface states at p/i and i/n junctions, in addition to the band gap states in the i-layer. The hole and electron trap states are located at 0.8 and 1.12 eV, respectively, above the valence band, whereas the interface states at the p/i junction are located at 0.55 eV and those at the i/n junction at 1.2 eV above the valence band. A decrease in the interface states with reverse biased annealing treatment has been observed.

1. Introduction

The performance of amorphous Si solar cells is dependent on the bulk density of states in the absorber i-layer, as well as the interface states at p/i and i/n junctions [1–4]. Therefore, one needs a device-based characterisation which can reveal the role of these states. Deep level transient spectroscopy (DLTS) is one of the techniques in which a current or capacitance transient is activated by means of an optical or voltage pulse. The transient then contains information regarding band gap states. Optically-induced current DLTS measurements can be used to distinguish between the role of interface and bulk states, since the photons can be absorbed close to interface, depending on the absorption coefficient. In fact, use of blue photons can be very effective, since these photons will be absorbed within 10–20 nm in the i-region from the p-layer. Moreover, if these photons are incident from the p-side, apart from interface states at the p/i junction, information regarding the electron traps will be obtained, because electrons have to traverse the i-layer to reach the contact on the n-side. If blue light is incident from the n-side, one obtains information regarding the hole traps. Reverse biased annealing (RBA) is known to reduce the degradation in these cells [5–8]. Current DLTS studies on RBA samples can also yield information regarding this effect.

In this paper current DLTS experiments on a-Si p–i–n solar cells using blue light are reported. The interface states at p/i and i/n junctions and band gap states in the i-layer of these cells under as-deposited and RBA treatments were studied.

Small area (1 cm^2) a-Si:H solar cells of structure-glass/ITO/p^+ (150 A°)/i (3500 A°)/n^+ (300 A°)-a:Si:H/Ag were used in the measurements.

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* Corresponding author. Tel.: +91-11 685 645; fax: +91-11 686 2037; e-mail: pdp@ces.iitd.ernet.in.

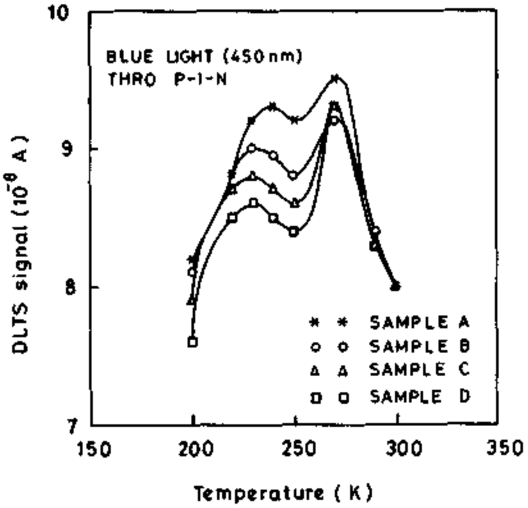

Fig. 1. DLTS spectra of as-deposited (sample A) and reverse biased annealed (samples B, C, and D) samples with blue light incident from the p-side of a-Si:H p–i–n solar cells.

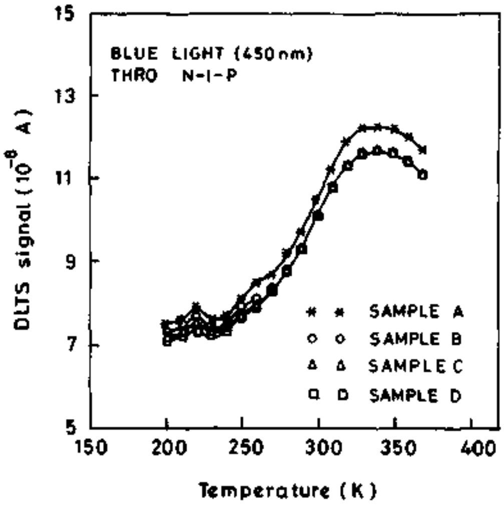

Fig. 2. DLTS Spectra of as-deposited (sample A) and reverse bias annealed (samples B, C, and D) samples with blue light incident from the n-side of a-Si:H p–i–n solar cell.

Typical doping ratios, dark and photo conductivities of individual layers, are mentioned in Table 1. Samples were annealed under reverse biases of 0 V, −1 V, and −2 V in a light shielded chamber at 10^{-6} Torr at 170°C for half an hour and then slowly cooled under bias. The as − deposited sample is referred to as sample A, and zero, −1 V, and −2 V bias annealed samples as samples B, C, and D, respectively. Mechanically chopped blue light (450 nm) was used as excitation source in the measurement, giving a ~ 1 ms pulse of light. The DLTS signal was measured using a PAR 124A lock-in amplifier.

The DLTS spectra of the as-deposited (sample A) and reverse biased annealed samples (samples B, C, and D) are shown in Fig. 1 with blue light incident from the p-side. Two peaks, one at 240 K and the other at 270 K, were observed. The peak at 240 K decreases from sample A to sample D. Only a slight variation was observed in the peak at 270 K. Fig. 2 shows the DLTS spectra of the same samples by illuminating the cell from the n-side. A broad peak at 350 K, along with a small sharp peak at 240 K, was observed in all samples. As before, the peak at 240 K decreases and the peak at 350 K is the same for samples B, C, and D.

In this method, the variation of current transient, $\Delta I(\tau)$, is obtained by differentiating the variation of charge with respect to the response time, τ:

$$\begin{aligned}\Delta I(\tau) &= \mathrm{d}(\Delta Q)/\mathrm{d}\tau\\ &= qAL\,\mathrm{d}/\mathrm{d}\tau\left[\int_0^{E_\mathrm{T}} g(E)f(E)\,\mathrm{d}E\right], \qquad (1)\end{aligned}$$

where q is the electronic charge, A is area of the cell, L is the thickness of the i-layer, $g(E)$ is the density of trap states, $f(E)$ is the probability function of a carrier for a trap level at energy, E, and E_T is the demarcation energy which is related the temperature scale as

$$E_\mathrm{T} = kT\ln(\nu\tau) \qquad (2)$$

where ν is the attempt-to-escape frequency for a

Table 1

	Doping ratio	Dark and photo conductivities (Ω^{-1} cm^{-1})	E_g (eV)
p-layer	SiH_4:CH_4:B_2H_6 ≈ 1:1:0.006	5×10^{-5}	1.94
i-layer	SiH_4 (undoped)	1×10^{-10}, 5×10^{-5}–10^{-4}	1.77
n-layer	SiH_4:PH_3 ≈ 1:0.004	1×10^{-10}	1.80

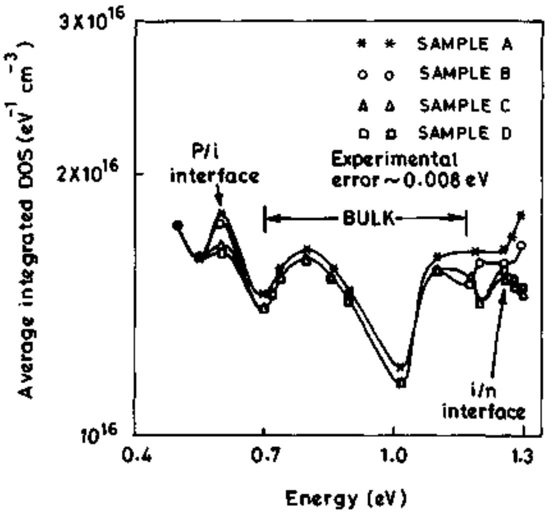

Fig. 3. Integrated average density of states distribution as a function of the energy, E, for as-deposited (sample A) and reverse bias annealed (samples B, C, and D) samples of a-Si:H p–i–n solar cell calculated from the DLTS measurements.

carrier, k is Boltzmann's constant, and T is absolute temperature.

Thus, Eq. (1) finally becomes

$$\Delta I(\tau) = qkTAL/\tau\left[g(E_T)f(E_T)\right] \quad (3)$$

and the density of states (DOS) at energy, E_T, can be written as

$$g(E_T) = \Delta I(\tau)\,\tau/qkTALf(E_T). \quad (4)$$

The τ value has been selected to be 20 ms from the lock-in amplifier and attempt-to-escape frequency, to be a constant $\sim 10^{14}$ s^{-1}.

Since for light incident from the p-side the electron traps will be involved, the energy, E, will be the energy difference of the trap states from the conduction band, whereas for light incident from the n-side, it will refer to the hole trap state energy from the valence band. The DOS spectrum for blue light through the n-side, as calculated from the DLTS data, shows a peak at 0.8 eV ($E_v = 0$), corresponding to hole traps, and for blue light through the p-side shows a peak at 0.65 eV ($E_C = 0$) corresponding to electron traps. Fig. 3 shows an integrated average DOS distribution for the entire device as calculated from the DLTS data. These DOS spectra yield a complete picture with hole and electron traps, as described earlier. The same experiment has been repeated on five sets of similar samples in order to determine the probable experimental error. The presence of four peaks has been observed at energies 0.55 ± 0.008, 0.8 ± 0.008, 1.12 ± 0.008 and 1.2 ± 0.008 eV from the valence band in almost all samples.

Samples B, C, and D also show similar peaks but with a decrease in peak height. This is expected since annealing results in a decrease in the number of trap states. And the additional peaks at 0.55 and 1.2 eV depend on the annealing treatment. Results show that the reduction of the peak is more in sample D. Therefore, the observed difference in the DOS distribution for samples B, C, and D has to be explained by additional trap states which are influenced by reverse bias applied during the annealing treatment. It has been reported previously that RBA reduces the number of interface states at the junctions because of the hydrogen ion movement towards the interfaces in the presence of the electric field under annealed treatment [5,9,10]. The interface states at the p/i junction at the same energy location have also been observed by de Cesare et al. [11]. Thus, we suggest these peaks arise due to the interface states at p/i and i/n junctions. In fact, our results suggest that under RBA the density of interface states in both the junctions is affected.

2. Conclusions

In conclusion, current DLTS studies have been performed on as-deposited and reverse biased annealed samples of a-Si:H p–i–n solar cells in order to observe the interface states at p/i and i/n junctions and band gap states in the i-layer. The hole and electron trap state densities are estimated to be 1.8×10^{16} eV^{-1} cm^{-3} and 1.6×10^{16} eV^{-1} cm^{-3}, respectively, at 0.8 and 1.12 eV above the valence band. The existence of interface states at 0.55 and 1.2 eV above the valence band, respectively, for p/i and i/n junctions have been determined. A decrease in interface state density with RBA treatment was observed.

Acknowledgements

The authors would like to thank the staff of the Amorphous Silicon Pilot Plant, Bharat Heavy Electrical Limited, Gurgaon (India) for supplying samples for their studies. They are indebted to Professor L.K. Malhotra, Thin Film Lab., I.I.T., New Delhi, for providing the experimental facilities for these studies. The financial assistance by University Grants Commission, New Delhi is gratefully acknowledged.

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