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Defect characterization of amorphous silicon thin film solar cell based on low frequency noise

Linna HU[1], Liang HE[1*], Hua CHEN[1], Xiaofei JIA[2], Ying HU[1], Hongmei MA[1], Dandan GUO[1] & Yu QIN[1]

[1]*School of Advanced Materials and Nanotechnology, Xidian University, Xi'an* 710126*, China;*
[2]*School of Electronic and Information Engineering, Ankang University, Ankang* 725000*, China*

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Dear editor,
The reliability of solar cells is the key factor to determine the performance and lifetime of photovoltaic products. Compared to the insensitivity of traditional electrical detection and the limitations of in-situ characterization methods, noise measurement has been widely used in semiconductor device reliability characterization for its rapid, sensitive and nondestructive. The energy band structure shows that there are two kinds of defects exist in amorphous silicon solar cells. One is the band-tail states, which concentration will increase with illumination time and will result in $1/f$ noise, the other one is the deep-level traps, which act as recombination centers for the carriers, and they are the origination of generation-recombination (GR) noise.

In this article, through the light-induced attenuation experiment and the deep-level characterization experiment, the correlation between noise and defects is clarified. Furthermore, based on the extraction of the defects' parameters, the failure mechanism is analyzed experimentally and theoretically. Therefore, it will be helpful for improving the preparation process.

Experiments. Two kinds of commercial amorphous silicon solar cells were adopted: ST-3722 (group A) and DJ-L003 (group B). According to the results of initial noise test, three samples were selected for each group, and they were executed light-induced attenuation experiment and deep-level characterization experiment, respectively.

Experimental results and discussion. During the illumination process of samples from group A, it was found that the series resistance of the amorphous silicon cells increase with the illumination time, the short-circuit current and the conversion efficiency of the cells decrease with the exposure time.

The trends mentioned above are mainly caused by the change of intrinsic layer properties for p-i-n architecture. The disordered structure of amorphous silicon enables the valence band and the conduction band to extend their states at the edges. The band-tail states will capture or emit carriers, and their concentration will increase with exposure duration, resulting more and more carriers are captured or emitted in the shallow-level, this process will induce an increase of series resistance and decrease of short-circuit current. The mobility of carrier is reduced intensely by the interaction between carriers and defects through coulomb scattering.

The noise power spectrum density during the exposure duration show that the $1/f$ noise amplitude increases continuously with the exposure time. For hydrogenated amorphous silicon, the position of localized band-tail states are very close to

* Corresponding author (email: xidianhic@163.com)

the mobility edges of conduction band E_c and valence band E_v [1]. Meanwhile these states disturb the carriers transport as traps, so carriers drifting in extended states will be trapped and then released for a while. This trapping-detrapping process can occur many times because of the shallow states, so that the motion ability of carriers will be reduced within the band, at the same time, the traps with carriers will affect the transport in extended states by coulomb scattering, which causes the mobility fluctuation [2].

In order to make a further discussion on how defects affect the noise power spectrum through mobility fluctuation, the voltage noise power spectrum density can be obtained,

$$S_V(f) = \frac{2}{3}\alpha q(\mu_n + \mu_p)\frac{R^3 I^2}{f L^2} \tag{1}$$

with α the empirical constant, q the unit electron charge, μ_n the mobility of electrons, μ_p the mobility of holes, R the equivalent resistance of i layer, f the frequency and L the width of i layer. The amplitude of $1/f$ noise power spectrum is proportional to the number of shallow-level traps in the device. Our result reflects the number of shallow-level (band-tail states) defects in the device increases with the exposure time, the mobility of electrons and holes fluctuate through trapping-detrapping process, which will lead to an increase of $1/f$ noise amplitude.

Through the comparison between noise amplitude and electrical parameters in reliability characterization, the relative change rate of noise amplitude at 1 Hz is much larger than conversion efficiency after 30 h exposure, this indicates the sensitivity of noise measurement is higher than the electrical parameters in characterizing device reliability.

The bias and temperature dependence on noise were performed during the deep-level characterization experiment. The corner frequency of GR noise increases with the positive bias applied on the cells, as shown in Figure 1. For p-i-n architecture, different from the heavy doping p and n regions, the intrinsic layer has lower conductivity, the space charge region basically falls into the i layer, and it should be more sensitive to bias than the heavy doping region, so the result shows that the source of GR noise mainly locates in the depletion region.

According to the double-diode equivalent circuit model, the current-voltage characteristics of solar cells can be expressed as [3]

$$I = I_{SC} - I_{01}(\gamma - 1) - I_{02}(\gamma^{1/2} - 1) \tag{2}$$

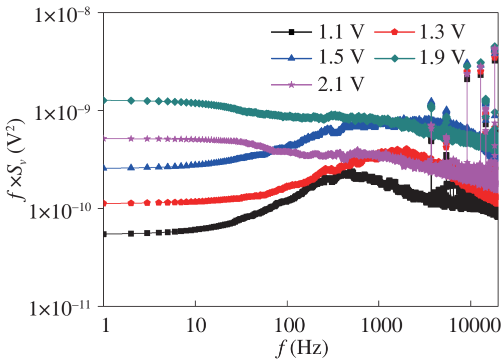

Figure 1 (Color online) The normalized noise power spectrum density under different bias.

with $\gamma = e^{qV/k_BT}$, V the applied voltage, k_B the Boltzmann constant, T the absolute temperature, I_{SC} the short-circuit current, I_{01} the saturated current associated with recombination in n and p regions, I_{02} the saturated current associated with recombination in the depletion region. I_{02} was extracted from (2) through polynomial fitting, the result reflects that the presence of the GR noise source promotes the recombination in the depletion region and leads to a greater I_{02}. As we known, GR noise can only be inspired by deep-level traps near the Fermi-level, so this result proves that deep-level traps exist in the depletion region again.

According to the noise theory [4], the corner frequency f_0 of GR noise can be described as

$$f_0 = \frac{\sigma v n}{2\pi}\left[1 + \exp\left(-\frac{E_F - E_t}{k_B T}\right)\right] \tag{3}$$

with v, n, σ, E_F and E_t are the carrier velocity, the carrier concentration, the trapping section of traps, the Fermi-level and trap energy level, respectively. Eq. (3) shows that the corner frequency of GR noise is related to the relative position between defects energy level and Fermi-level, and their intersection will change with the bias. The traps at the intersection have the largest recombination probability for carriers. The GR noise in semiconductor devices is caused by the random fluctuation of the carriers' number in the energy band, the variance ΔN can be written as [4]

$$\overline{\Delta N^2} = \frac{B N_t(p)\exp\left(-\frac{E_F - E_t}{k_B T}\right)}{\left[1 + B\exp\left(-\frac{E_F - E_t}{k_B T}\right)\right]^2}, \tag{4}$$

where N_t the concentration of deep-level traps, B the spin degeneracy of deep-levels. From (4), it is found that only the defects near the intersection of E_F and E_t can contribute to GR noise, the voltage power spectrum of the GR noise can be written as

$$S_V(f) = a^2 \frac{4BN_{\rm t}(p)}{(1+B)^2} \frac{\tau}{1+\omega^2\tau^2} \tag{5}$$

with w the angular frequency, τ the time constant. The distribution of deep-level traps concentration $N_{\rm t}$ in the depletion region is not homogeneous, and the intersection p of defect energy level and the Fermi-level change with bias. When the positive bias keeps to increase above 1.7 V, the intersection will move to the side with lower doping concentration continuously, and once it moves out of the defect region, the GR noise will disappear.

From the temperature dependence test, the activation energy of deep-level traps could be derived from the relationship between f_0 and T by the form of the equivalent noise power spectrum density at different temperatures, as follows:

$$\ln(\tau T^2) = \frac{E_{\rm c} - E_{\rm t}}{k_{\rm B}T} + \ln\left(\frac{h^3}{\Gamma}\right), \tag{6}$$

in which $\Gamma = 4k_{\rm B}^2\sigma\sqrt{6\pi^3 M_{\rm c} m_{\rm e}^{*1/2} m_{\rm h}^{*3/2}}$, h is the Planck's constant, $M_{\rm c}$ is the equivalent minimum of conduction band, and $m_{\rm e}^*$ and $m_{\rm h}^*$ are the effective transport quality of electron and hole, respectively. Obviously, the activation energy of the defect can be obtained from the slope [5, 6].

The Arrhenius plots indicate that the activation energies of deep-level traps in our samples are around 0.37 eV. According to [1, 4, 6], this energy level is related to metal Cu.

Conclusion. $1/f$ noise is related to the carrier mobility fluctuation caused by band-tail states, and through the noise model, the effect of the defects originated in the process of light-induced attenuation is analyzed. Furthermore, the effectiveness and sensitivity of the noise characterization are verified. The study of GR noise shows that the noise source is in the depletion region, and through the activation energies extracted from Arrhenius plot, the GR noise can be attributed to Cu impurities.

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