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Band gap optimization of the window layer in silicon heterojunction solar cells

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Abstract

The properties of silicon heterojunction solar cells differ with the band gap of the window layer. The analytical model of the open-circuit voltage for silicon heterojunction solar cells is first derived. Based on the analytical model and the carrier transport, the effect of the band gap of the window layer (E_{g2}) on the properties of silicon heterojunction solar cells and the mechanism are explored by a set of AMPS simulations. At non-negligible interface states, the increase of E_{g2} leads to increase of the electric field in the c-Si depletion region, and then causes decrease of the effective interface recombination. The open-circuit voltage increases with E_{g2} increasing, and the fill factor *FF* increases with E_{g2} increasing at $E_{g2} \leqslant 1.8$ eV. However, at $E_{g2} \geqslant 1.9$ eV, the valence band offset barrier limits the carrier transport, and the *S*-shape in the *J–V* characteristics occurs. It results in the decrease of *FF*. The optimum band gap of the window layer is obtained $\Delta E_V \approx 0.5$ eV for silicon heterojunction solar cells, especially at $E_{g2} = 1.8$ eV for the offset ratio 3:1. And the effect of E_{g2} on the properties of silicon heterojunction solar cells operates by: (1) decreasing photons absorbed in the window layer; (2) the recombination due to the interface traps is reduced due to enhanced electric field with increase in the band gap; and (3) the increase of the valence band offset influencing the electron transport.

Keywords: Silicon heterojunctions; Solar cells; Band gap; The window layer

1. Introduction

Amorphous hydrogenated silicon and crystalline silicon (a-Si:H/c-Si) heterojunctions are of great interest for photovoltaic applications due to the high conversion efficiencies of solar cells achieved so far up to 22% and the possibility of complete fabrication at low temperature process (Tsunomura et al., 2009). With the development of the thin film deposition technique, various silicon thin films, such as a-Si:H, microcrystallite silicon (uc-Si:H), silicon carbide (a-SiC$_x$:H), nanometer hydrogenated silicon (nc-Si:H) and polymorphous silicon (pm-Si:H), have been deposited as the window layer (namely the emitter) of silicon heterojunction solar cells (Kim et al., 2008; Ling et al., 2012; Mueller et al., 2007; Page et al., 2011; Yamamoto et al., 2002; Wu et al., 2009; Hamashita et al., 2012). The combination of silicon thin films with crystalline silicon is one of the most promising solar cells. However, since the band gap of the window layer is different with the deposition technique of silicon thin films. And the properties of silicon heterojunction solar cells differ with the band gap of the window layer. It is reported (Mueller et al., 2007)

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that a certain amount of carbon and hydrogen, which widens the band gap of the a-Si layers, increases the open circuit voltage as well as the short circuit current. To further improve the open-circuit voltage and reduce absorption in the a-Si:H layers, Sanyo is developing high-quality wide-gap alloys such as a-SiC:H as the window layer in their so-called HIT structure solar cells (Tsunomura et al., 2009).

In this paper, by integrating the equation of the electron current density at the depletion region under illumination and at open circuit, an analytical model of the open-circuit voltage for silicon heterojunction solar cells is derived. Based on the analytical model of the open-circuit voltage and the carrier transport, the effects of the band gap of the window layer on the properties of silicon heterojunction solar cells and the mechanism are explored by a set of simulations.

2. Calculation of the open-circuit voltage

Silicon heterojunction solar cells of TCO/10 nm (p^+) TF-Si:H /300 μm (n) c-Si/Al type structure are considered, where TF-Si:H denotes silicon thin film. The front and back contacts were assumed to be ohmic. The schematic diagram of the hole electron density distributions in silicon heterojunctions at thermal equilibrium, and under illumination and at open circuit, is shown in Fig. 1. Under illumination, as there exist a gradient of carrier concentration and the electric fields including the built-in electric field and the photogenerated electric field at the depletion region, the total hole current density is

$$J_p = qD_p\frac{dp(x)}{dx} + q\mu_p p(x)\varepsilon(x) = qD_p\frac{dp(x)}{dx} + q\mu_p p(x)(\varepsilon_{built} - \varepsilon_{opt}) \quad (1)$$

where D_p is the hole diffusion constant, μ_p is the hole mobility, ε is the total electric field in the x-direction, ε_{built} is the built-in electric field in the x-direction and ε_{opt} is the photogenerated electric field opposite to the x-direction. Furthermore, at open circuit, $J_p = 0$ at any point and we can get

$$\frac{D_p}{\mu_p}\frac{dp(x)}{p(x)} + (\varepsilon_{built} - \varepsilon_{opt})dx = 0. \quad (2)$$

Combining with the equilibrium band diagram of (p) a-Si:H/(n) c-Si heterojunctions shown in Fig. 2, and integrated at the depletion region ($-x_p \to x_0$ and $x_0 \to x_n$) with

$$\int_{-x_p}^{x_0}\varepsilon_{built} = V_{D2},\ \int_{-x_p}^{x_0}\varepsilon_{opt} = -V_{OC2},\ \int_{x_0}^{x_n}\varepsilon_{built} = V_{D1},\ \int_{x_0}^{x_n}\varepsilon_{opt} = -V_{OC1},$$

Eq. (2) becomes

$$V_D - V_{OC} = \frac{kT}{q}\left[\ln\frac{p(-x_p)}{p(x_n)} + \ln\frac{p_1(x_0{}^+)}{p_2(x_0{}^-)}\right] \quad (3)$$

with

$$\frac{p_1(x_0^+)}{p_2(x_0^-)} \approx \frac{p_{10}(x_0^+)}{p_{20}(x_0{}^-)} = \frac{p_{n0}}{p_{p0}}\exp\left(\frac{qV_D}{kT}\right) = \frac{N_{V2}}{N_{V1}}\exp\left(\frac{\Delta E_V}{kT}\right) \quad (4)$$

and

$$\frac{p(-x_p)}{p(x_n)} = \frac{N_{A2}}{p_{n0} + \Delta p(x_n)}, \quad (5)$$

where V_D is the diffusion potential of the heterojunctions, V_{D1} and V_{D2} are the diffusion potentials on the c-Si and TF-Si:H layers, V_{OC} is the open-circuit voltage, V_{OC1} and V_{OC2} are the photogenerated potentials on the c-Si and TF-Si:H layers, N_{V1} and N_{V2} are the effective densities of

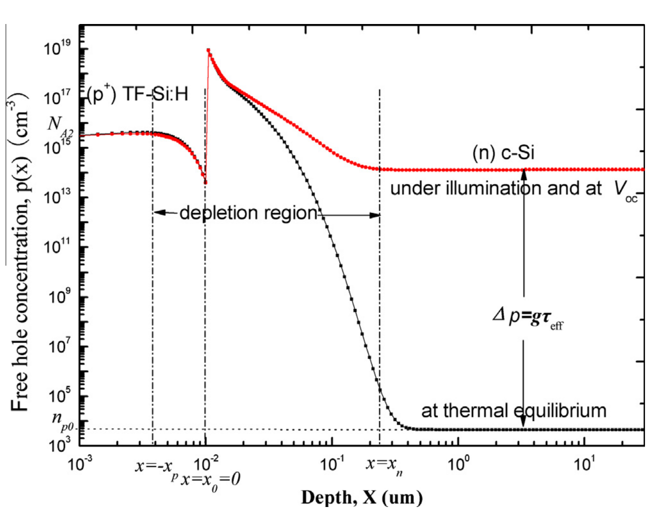

Fig. 1. Schematic diagram of the free electron distributions under illumination and at open circuit, and at thermal equilibrium.

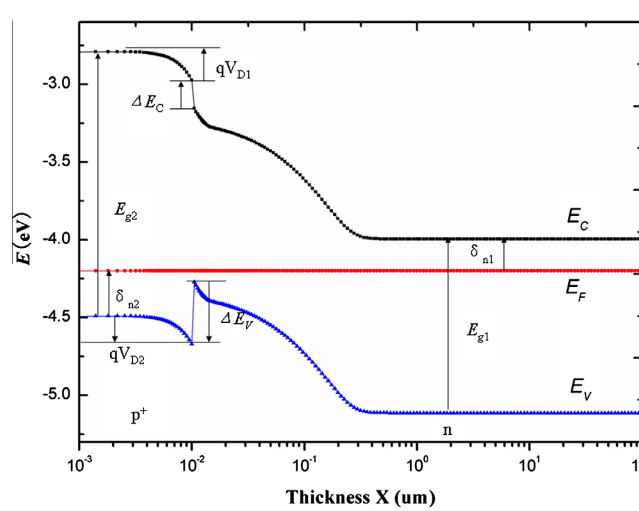

Fig. 2. Energy band diagram of (n^+) TF-Si:H/(p) c-Si heterojunctions at equilibrium.