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Simulation of the optimized performance of thin-film silicon solar cells with nano-hole surface structures

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Abstract In this study, the optical generation rate and surface recombination velocity (SRV) of the emitter layer of a thin-film silicon solar cell, which depend on the depth, width, and number of nano-holes on the cell's surface, were simulated and investigated. The trade-off between the optical generation rate and SRV was examined in terms of short-circuit current density (J_{sc}), open-circuit voltage (V_{oc}), and conversion efficiency (η) using a two-step simulation. The simulated results indicated that a thin-film solar cell with a proper nano-hole structure on the emitter layer can be used to achieve much higher J_{sc} and η performances.

Keywords Nano-hole structures · Optical generation rate · Surface recombination velocity (SRV) · Simulation · Thin-film solar cell

1 Introduction

In order to reduce the reflectivity of silicon surfaces, antireflection coating (ARC) (Zhang et al. 2013) and subwavelength surface structures (Li et al. 2014) have been applied in silicon photovoltaic devices. In addition, a number of simulation methods, including finite-difference time-domain (FDTD) methods (Das and Islam 2014), rigorous coupled-wave analysis (RCWA) (Semenikhin et al. 2012), and the finite element method (FEM) (Xavier

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and Becker 2014), have been used to examine the photovoltaic performance enhancement of cells with subwavelength surface structures. Furthermore, APSYS (advanced physical models of semiconductor devices) based on two-dimensional/three-dimensional (2D/3D) finite element analysis of the electrical and optical properties of semiconductor devices is also a powerful simulation tool.

In this study, a commercial software APSYS was used to simulate the optical generation rate and surface recombination velocity (SRV) (Xiong et al. 2010) which were created on the emitter layer of a solar cell by a nano-hole structure. The detailed fabrication of nano-hole surface structures of thin-film Si solar cells was reported on in two previous studies (Ho et al. 2015a, b). To achieve high efficiency in thin-film Si solar cells, the trade-off between the optical generation rate and the SRV are simulated and discussed.

2 Simulation setup and sequence

Two-step 2D model simulations are proposed in this study, the simulation flow chart as shown in Fig. 1. In the first step, various SRV values (0–9000 m/s) are applied on the fabricated bare plane-type Si solar cell to simulate a short-circuit current density (J_{sc}). The J_{sc} will decrease with increases in the SRV values. First, a simulation was used to determine the SRV value required to produce the J_{sc} obtained experimentally using photovoltaic J-V measurement under one-sun AM 1.5G illumination; this value could then be referenced for further simulations. In this study, the simulation model of the bare plane-type Si solar cell, in the Y-direction, consisted of a 0.87 μm-thick p^+-Si emitter layer, a 5.0 μm-thick n^--Si base layer, a 675 μm-thick n^+-Si substrate, and front/back-side electrodes. In the X-direction, it consisted of two front contact electrodes with an electrode width of 27 μm and an illuminated area between the two electrodes of 590 μm.

In the second step, nano-hole structures on the emitter layer with various hole-depths, hole-widths, and hole-numbers were proposed for simulations. The simulation sequence in this step consisted of varying the hole-depths first, then varying the hole-widths, and finally varying the hole-numbers. Initially, a value of 3 was settled on for the number of holes and a value of 0.2 μm was settled on for the hole-width for the initial simulation. The obtained optimized result from that simulation was then used to determine the parameters of the subsequent simulations. Therefore, the optimized performance of a thin-film Si solar cell with a proper nano-hole surface structure would be achieved.

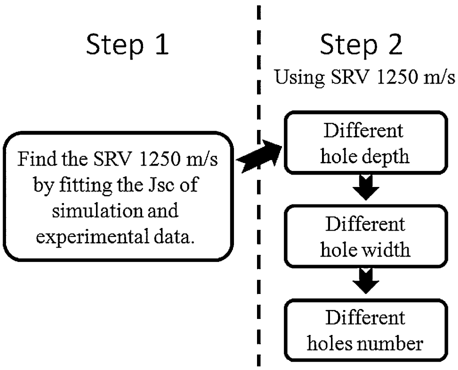

Fig. 1 The simulation flow chart for the two-step 2D model simulations

3 Results and discussion

The photovoltaic results of the simulated and experimental measurements for the bare plane-type Si solar cell in the first step are listed in Table 1, which indicates that the simulated J_{sc} of 15.31 mA/cm^2 was equal to the measured J_{sc} of 15.31 mA/cm^2 when the SRV was given a value of 1250 m/s. The open-circuit voltage (V_{oc}) and conversion efficiency (η) values obtained by the simulation were higher than the experimentally measured values, difference which were attributed to the ideal series resistance ($R_s = 0\ \Omega$) and shunt resistance ($R_{sh} = \infty\ \Omega$) characteristics of the solar cell using in the simulation case.

The simulated photovoltaic J–V curves of the solar cells with various depths for the holes (ranging from 0 to 0.87 μm) and with the SRV set at 1250 m/s are shown in Fig. 2, and the simulated photovoltaic performances are summarized in Table 2. The J_{sc} increased slightly (from 18.42 to 18.58 mA/cm^2) because the surface reflection was reduced when the depth of the holes was increased (from 0 to 0.8 μm). On the other hand, the V_{oc} decreased (from 575.94 to 563.17 mV) as the depth of the holes was increased (from 0 to 0.8 μm) due to the increases in the surface area of recombination. In particular, the V_{oc} dropped significantly to 505.65 mV when the depth of the holes was 0.87 μm, which caused the interface of the emitter and base layers to have numerous interface recombination centers and a larger surface area of recombination. The changes in the magnitudes

Table 1 The simulation and experimentally measured photovoltaic results of the bare plane-type Si solar cell obtained in the first step, when the SRV was set at 1250 m/s

	Experiment	Simulation
J_{sc} (mA/cm^2)	15.31	15.31
V_{oc} (V)	0.532	0.581
η (%)	5.64	7.55

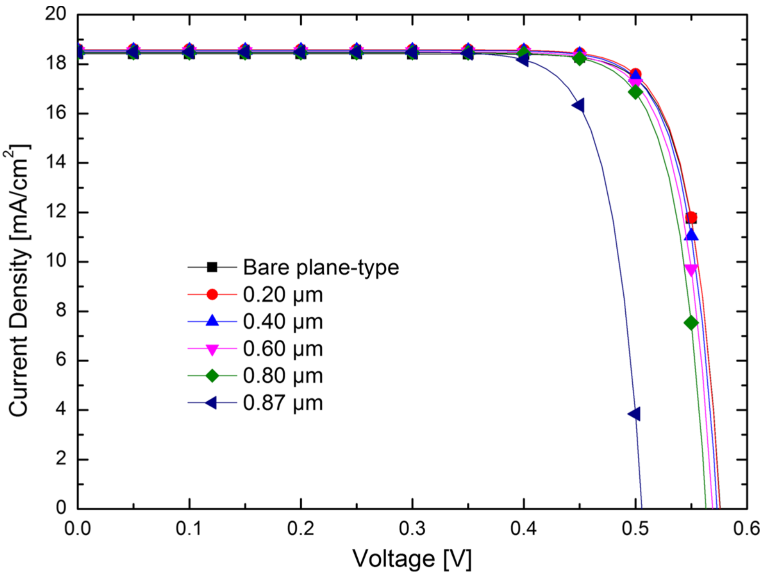

Fig. 2 Simulated photovoltaic J–V curves of the solar cells with various depths for the holes (from 0 to 0.87 μm), under SRV of 1250 m/s

of J_{sc} and V_{oc} depending on the depth of the holes are summarized in Table 2. Because η of a solar cell is proportional to the product of J_{sc} and V_{oc}, the maximum η of 9.12 % was exhibited for the cell with holes with a depth of 0.2 μm. Thus, the simulated J_{sc} and V_{oc} results show that, when the depth of the holes was increased, the effect of increasing the surface area of recombination was exceeded by decreasing the surface reflection.

The simulated optical generation rate and effective SRV as a function of the depth of the holes are presented in Fig. 3. In this study, the observed point of the optical generation simulation was chosen at the point of $x = 1.25$ μm and $y = 680$ μm, as shown in the inset for Fig. 3. The optical generation rate and the effective SRV were increased as the depth of the holes was increased. Here, an effective SRV is defined as one which is assumed to have an equivalent recombination effect on a flat surface. In this study, an effective SRV was introduced to evaluate the effects of the surface recombination for surfaces with various hole-depths. The effective SRV was linearly increased with the increasing hole-depths beginning from an SRV value of 1250 m/s. Since the optical generation rate of electron–hole pairs (EHPs) is based on multiple reflections and transmissions of the incident light

Table 2 The simulated photo-voltaic performances of the solar cells with various depths for the holes (from 0 to 0.87 μm) and SRV set at 1250 m/s

Depth of hole (μm)	J_{sc} (mA/cm^2)	V_{oc} (mV)	η (%)
Flat	18.42	575.94	9.05
0.2	18.58	575.69	9.12
0.4	18.56	573.06	9.06
0.6	18.50	569.22	8.96
0.8	18.47	563.17	8.84
0.87	18.50	505.65	7.80

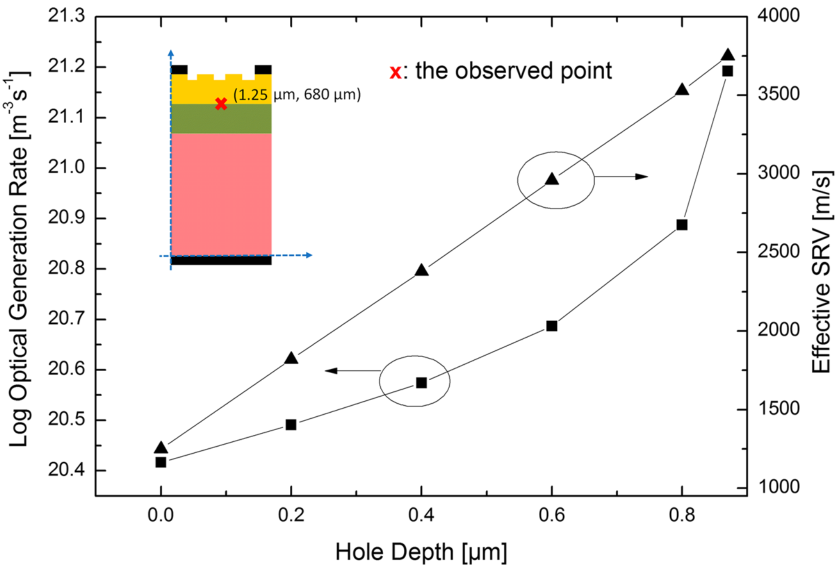

Fig. 3 The simulated optical generate rate and SRV as a function of the depth of hole, based on the SRV of 1250 m/s

within a nano-hole structure, higher optical generation rate values were obtained for the solar cells with deeper holes in the absorbing semiconductor layer.

With the SRV set at 1250 m/s and the hole-depth set at 0.2 μm, the simulated photovoltaic J–V curves of the solar cells with various widths for the holes (from 0.05 to 0.5 μm) are shown in Fig. 4, and the simulated photovoltaic performances are summarized in Table 3. The J_{sc} and V_{oc} values first increased and then decreased as the widths of the holes were increased from 0.05 to 0.5 μm. *The* J_{sc} and V_{oc} increased because the surface reflection was reduced when the width of the holes was increased. The maximum J_{sc} of 19.01 mA/cm^2 and the maximum V_{oc} of 576.27 mV were obtained for the cell with a hole-width of 0.15 μm and a hole-width of 0.3 μm, respectively. The minimum J_{sc} of 17.64 mA/cm^2 was obtained for the cell with a hole-width of 0.5 μm because the surface reflection increased as the surface approached a flat plane. The maximum η of 9.33 % was obtained for the cell with a hole-width of 0.15 μm. Therefore, the optimized depth and

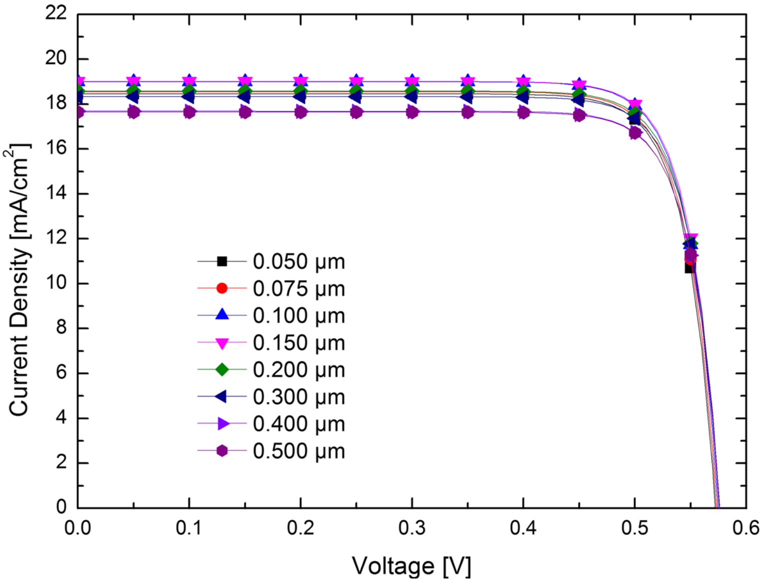

Fig. 4 Simulated photovoltaic J–V curves of the solar cells with various widths for the holes (from 0.05 to 0.5 μm), based on the SRV of 1250 m/s and a hole depth of 0.2 μm

Table 3 The simulated photovoltaic performances as a function of the hole width (d), based on an SRV of 1250 m/s and a hole-depth of 0.2 μm

Width (μm) of hole	J_{sc} (mA/cm^2)	V_{oc} (mV)	η (%)
0.05	18.46	572.17	8.99
0.075	18.56	573.23	9.06
0.1	19.00	574.52	9.31
0.15	19.01	575.57	9.33
0.2	18.58	575.69	9.12
0.3	18.33	576.27	9.01
0.4	17.68	575.86	8.69
0.5	17.64	576.18	8.67

Table 4 The simulated photovoltaic performance as a function of the number of hole, based on the SRV of 1250 m/s, hole depth of 0.2 μm, and hole width of 0.15 μm

Number of hole	J_{sc} (mA/cm^2)	V_{oc} (mV)	η (%)
3	19.01	575.57	9.33
4	19.03	576.69	9.36
5	19.03	577.49	9.37
6	19.06	578.08	9.40
7	19.06	578.53	9.41
8	19.06	578.89	9.41
9	19.07	579.14	9.42
10	19.02	579.14	9.40

width of the holes for achieving a higher efficiency of the proposed thin-film solar cell with a nano-hole surface emitter layer would be between 0.15 and 0.2 μm.

Finally, holding the depth at 0.2 μm, the width at 0.15 μm, and the SRV at 1250 m/s for simulation, the simulated results of J_{sc}, V_{oc}, and η as a function of the number of holes are presented in Table 4. The J_{sc}, V_{oc} and η values were increased as the number of holes was increased. The optimal number of holes was 9, which yielded the highest J_{sc} of 19.07 mA/cm^2, the highest V_{oc} of 579.14 mV, and the highest η of 9.42 %.

4 Conclusion

Optimized performances of thin-film Si solar cells with a nano-hole surface layer were simulated using a commercial software APSYS. The optical generation rate, SRV, and photovoltaic performance of a cell with a nano-hole structure emitter layer were demonstrated, as were the degrees to which those values depend on the depth, width, and number of holes. The highest simulated efficiency of 9.42 % was obtained when a cell with a structure emitter layer with a hole-depth of 0.2 μm, a hole-width of 0.15 μm, and a total of 9 holes was used, indicating a significant improvement compared with the 9.05 % efficiency of a bare-plane type Si solar cell.

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