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OPTIMIZATION OF THE ELECTRICAL PARAMETERS OF SILICON HETEROJUNCTION SOLAR CELLS

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Abstract: We used the AFORS-HET simulation program for hetero-junction solar cells modeling to determine how the thickness and material properties of the *n*-, *i*-, and *p*-layers affect the electrical parameters and the device performance. Simulation studies have been carried out on hetero-junction (HJ) amorphous silicon (a-Si)/crystalline silicon (c-Si) solar cells and hetero-junction solar cells with intrinsic thin layer (HIT). The obtained maximum solar energy conversion efficiency is 22.68% for a-Si (*n*)/a-Si(*i*)/c-Si(*p*)/a-Si(p^+) solar cells with a back surface field (BSF) contact on a *p*-type silicon wafer. The open-circuit voltage (V_{OC}) (728.3 mV), short circuit current density (J_{SC}) (37.96 mA·cm^{-2}), and the fill factor (*FF*) (82.06%) of the solar cells are improved by introducing thin layers of intrinsic and doped amorphous hydrogenated silicon, deposited on crystalline silicon, and by optimizing the thickness of the layers. Potential for achieving conversion efficiencies over 20% and current densities higher than 35 mA·cm^{-2} are demonstrated.

Key words*: modeling, simulation, hetero-junction solar cell, efficiency.*

INTRODUCTION

During the last two decades the solar photovoltaic (PV) industry has shown an extraordinary growth, with an average growth rates exceeding 40% per year [1]. The global PV installed capacities of 102 GW at the end of 2012 are expected to exceed 1.5 TWp in 2030 [2,11].

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The wafer-based silicon technology maintains its leading position and the highest market share of around 80%, because of: (i) the technology maturity, which provides a reliable product with commercial module efficiencies ranging from 12 to 20%, and (ii) the existing manufacturing capacities [1,3].

The new generation thin film PV technologies have emerged as a response to the shortage of silicon feedstock and in order to reduce the material use per Wp. Their market share increased more than 3 times (from 6% to16-20%) for the period from 2005 through 2010 [1]. The research efforts have been focused on the development of the solar cells based on hydrogenised amorphous silicon (a-Si:H), copper indium gallium diselenide (CIGS) and cadmium telluride (CdTe). Among the advantages of these technologies are the usage of less material, a monolithically integrated cell, lower cost and large area. However, the reported module efficiency (η) of a-Si (6÷10%), CdTe (10.9%) and CIGS (9.5%), are lower than those of crystalline silicon (c-Si) modules [3-5]. Silicon hetero-junction solar cells (SHJ) and hetero-junction solar cells with intrinsic thin layer (HIT), are a promising hybrid amorphous silicon (a-Si)/crystalline silicon (c-Si) technology developed by Sanyo. As a response to rapidly growing demand, the company increased the production capacity of HIT solar cells more than 3 times for the period from 2006 through 2010, to 600 MW [6]. The HIT solar cells became very attractive due to a unique conversion efficiency (higher than 22% in laboratory cells and 20% in commercially produced cells) combined with a low temperature device processing [7,12]. Compared to conventional diffused solar cells, HIT solar cells have a higher open-circuit voltage (V_{OC}) and a better temperature coefficient due to the reduced carrier recombination at the interface.

Numerical simulations are an important tool for gaining a better insight in material properties and processes in solar cells and hence, for the improvement of the devices. The large numbers of variables that influence the solar cell performance, such as the thickness of the layers and their physical parameters (density of states, a band gap, carrier concentration and mobilities) make it difficult, and economically ineffective to evaluate experimentally the effects of each variable on the cells characteristics. We have employed the numerical program, AFORS-HET v.2.4.1 to investigate the influence of the structure and the material parameters on the solar cell performance. Our previous research showed that an efficiency of 21.63% can be obtained by optimizing of the *n*-emitter layer thickness of the hetero-junction a-Si/c-Si solar cell [8].

In this paper, we present the numerical simulation study of hetero-junction cells (a-Si(*n*)/c-Si(*p*)), hetero-junction cells with intrinsic thin layer (a-Si(*n*)/a-Si(*i*)/c-Si(*p*)) and hetero-junction cells with intrinsic thin layer and back surface field (BSF) layer (a-Si(*n*)/a-Si(*i*)/c-Si(*p*)/a-Si(p^+)), using the software AFORS-HET. The simulations were used to optimize the thickness of the *n*-, *i*-, and *p*-layers and thereby to increase the solar cells efficiency.

MATERIAL AND NUMERICAL SIMULATION METHODOLOGY

Solar Cell Structures

Numerical simulation of a-Si/c-Si hetero-junction solar cells was carried out by AFORS-HET, version 2.4.1, computer software with the aim to investigate the effects of

the layers' thickness on the solar cell performance. In this work we investigated three types of hetero-junction solar cell structures, shown in Fig. 1. In Fig. 1(a) is shown a simple hetero-junction structure consisting of a transparent conducting ZnO layer used as a front contact, an *n*-type amorphous silicon layer deposited on a *p*-type crystalline silicon wafer and a metal back contact.

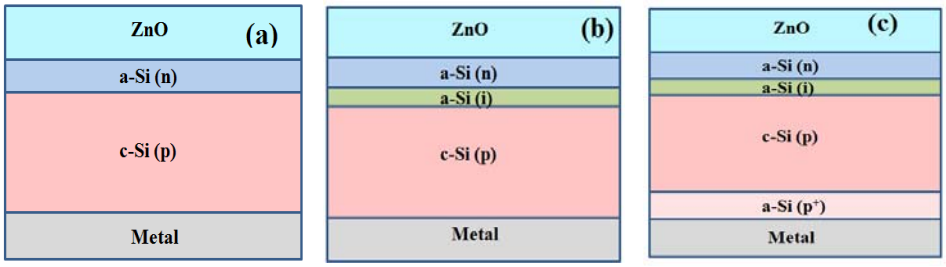


Figure 1. Structures of the simulated cells (a) a HJ a-Si(n)/c-Si(p) solar cell; (b) a HIT a-Si(n)/a-Si(i)/c-Si(p) solar cell, and (c) a HIT with BSF a-Si(n)/a-Si(i)/c-Si(p)/a-Si(p^+) solar cell

The hetero-junction structure with an intrinsic layer is obtained when an intrinsic a-Si layer is inserted at the *n*/*p* interface (Fig. 1(b)). By inserting of this layer, the defects on the c-Si surface can be effectively passivated, and a high Voc can be obtained. Fig. 1(c) represents a hetero-junction solar cell with a back surface field (BSF).

AFORS-HET is a numerical simulation tool, which can be used for modeling of homo-junction and hetero-junction photovoltaic devices. The software uses Shockley-Read-Hall recombination statistics to solve the one dimensional semiconductor equations for: (a) thermodynamic equilibrium (b) for steady-state conditions under an external applied voltage or current and/or illumination; (c) for small additional sinusoidal modulations of the external applied voltage/illumination; and (4) for transient conditions [13,14].

The simulations were performed under illumination at solar AM1.5 radiation with a power density of 1000W/m^2. The flat band front and back contacts are chosen to ignore the contact potential influence. Band-to-band and Auger recombination are considered. The band gap was set to 1.7 eV for all the a-Si layers in the cell. In table 1 are listed parameters of the solar cells used for the simulations with the AFORS-HET such as, thickness, conduction and valence band density of states, doping concentrations and electron and hole mobilities.

The variable parameter for numerical simulations was the thickness of the *n*-, *i*-, or *p*-layers. The changes in *Voc*, *Jsc*, *FF* and efficiency η were obtained and recorded.

RESULTS AND DISCUSSION

The optimum thickness of an *n*-type a-Si emitter layer was obtained at constant thicknesses of 3 nm, 300 μm and 5 nm of the a-Si (*i*), c-Si (*p*) and a-Si (p^+) layers respectively. Fig. 2 shows *Voc*, *Jsc*, *FF* and the efficiency plotted as a function of the *n*-emitter (a-Si) layer thickness.

Maximum values of *Voc*, *Jsc* and efficiency were obtained for a thickness of the *n*-type a-Si layer of 5 nm for all studied cells.

The open circuit voltage, short circuit current density, fill factor and efficiency as a function of the *n*-type a-Si layer thickness for a hetero-junction a-Si(n)/c-Si(*p*) solar cell are plotted in Fig.2(a). For thicknesses up to 12 nm *Voc* remains constant (627.9 mV) and after that decreases to 626.4 mV.

Table 1. Material parameters used for the simulations with AFORS-HET

Parameter	*Unit*	*c-Si(p)*	*a-Si(p)*	*a-Si(i)*	*a-Si(n)*
Thickness	*[nm]*	*variable*	*variable*	*variable*	*variable*
Dielectric constant	*-*	*11.9*	*11.9*	*11.9*	*11.9*
Electron affinity	*[eV]*	*4.05*	*3.9*	*3.9*	*3.9*
Band gap	*[eV]*	*1.12*	*1.72*	*1.72*	*1.72*
Effective conduction band density	*$[cm^{-3}]$*	*$2.8\cdot10^{19}$*	*10^{20}*	*10^{20}*	*10^{20}*
Effective valence band density	*$[cm^{-3}]$*	*$2.7\cdot10^{19}$*	*10^{20}*	*10^{20}*	*10^{20}*
Electron mobility	*$[cm^2\cdot V^{-1}s^{-1}]$*	*1041*	*20*	*20*	*20*
Hole mobility	*$[cm^2\cdot V^{-1}s^{-1}]$*	*413*	*5*	*5*	*5*
Acceptor concentration	*$[cm^{-3}]$*	*$1.5\cdot10^{16}$*	*$9\cdot10^{19}$*	*0*	*0*
Donor concentration	*$[cm^{-3}]$*	*0*	*0*	*1000*	*$5\cdot10^{19}$*
Thermal velocity of electrons	*$[cm\cdot s^{-1}]$*	*10^7*	*10^7*	*10^6*	*10^7*
Thermal velocity of holes	*$[cm\cdot s^{-1}]$*	*10^7*	*10^7*	*10^6*	*10^7*
Layer density	*$[g\cdot cm^{-3}]$*	*2.328*	*2.328*	*2.328*	*2.328*
Auger recombination coefficient for electron	*$[cm^6s^{-1}]$*	*$2.2\cdot10^{-31}$*	*0*	*0*	*0*
Auger recombination coefficient for hole	*$[cm^6s^{-1}]$*	*$9.3\cdot10^{-32}$*	*0*	*0*	*0*
Direct band-to-band recombination coefficient	*$[cm^3s^{-1}]$*	*0*	*0*	*0*	*0*

The increase of the layer thickness causes the decrease in *Jsc* (35.6÷33.56 $mA\cdot cm^{-2}$) and consequently, the reduction of the cell efficiency from 18.52 to 17.3% due to the increase photons absorption in the thicker layer. The *FF* reduces from 82.88 to 82.32%.

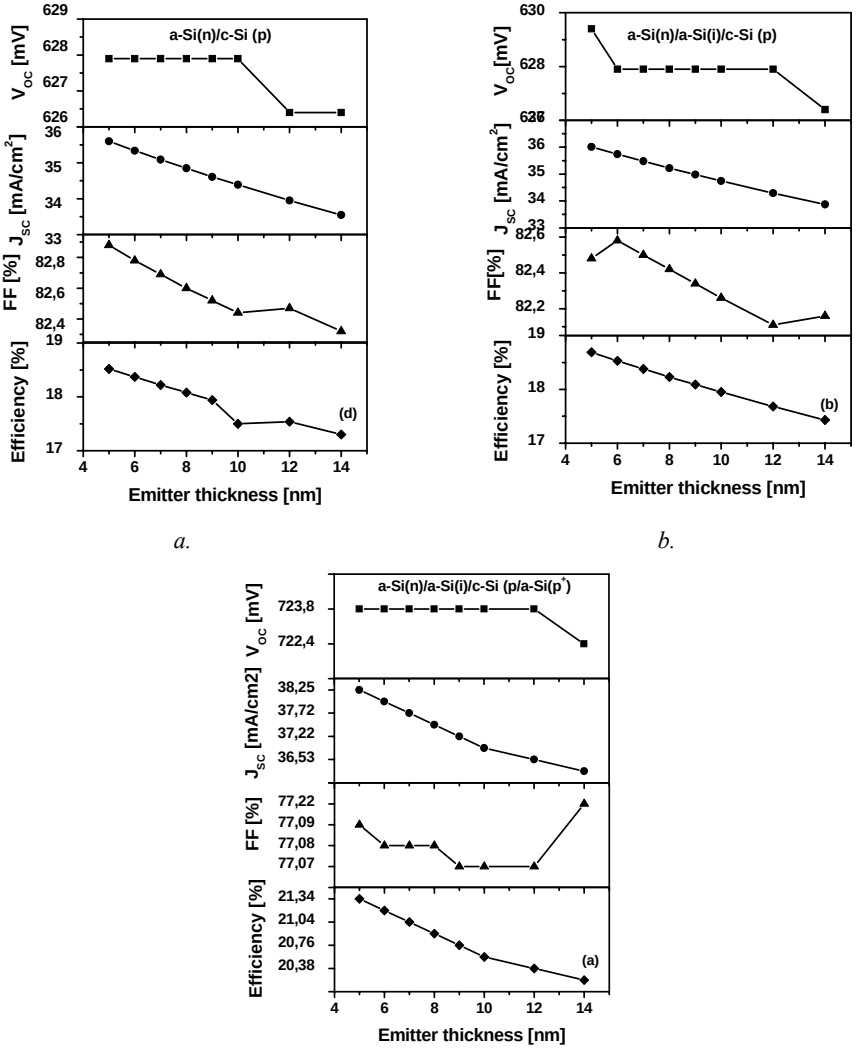
For the HIT solar cell from Fig.1(b) the optimum *n*-layer thickness of 5 nm resulted in the highest *Voc*, *Jsc* and efficiency of 629.4 mV, 36.01 $mA\cdot cm^{-2}$ and 18.69% respectively (Fig. 2(b)). As can be seen, the open circuit voltage decreases to 626.4 mV with increasing of the *n*-layer thickness above 13 nm. First, the fill factor raises slightly (82.48÷82.58% with the increasing *n*-layer thickness from 5 to 6 nm then decreases (82.04%) for the thickness range 6÷13 nm.

Maximum *Voc of* 723.8 mV, *Jsc* of 38.25 $mA\cdot cm^{-2}$ and a conversion efficiency of 21.34% were obtained for a HIT solar cell with a BSF layer, which consists of 5 nm a-Si(n), 3 nm a-Si(i), 300 μm c-Si(p) and 5 nm a-Si(p^+). *Voc*, *Jsc*, *FF* and the efficiency dependence on the *n*-layer thickness is displayed in Fig. 2(c).

The obtained optimum thickness of the *n*-type a-Si layer of 5 nm for the simulated solar cell structures is in good agreement with the findings of other groups [9,10].

As in case of the *n*-type a-Si layer, the optimum thickness of 3 nm of the front *i*-type a-Si layer was found to be one and the same for all solar cells from Fig. 1. The simulations were performed at constant thicknesses of 5 nm, 300 μm and 5 nm of the a-Si (*n*), c-Si (*p*) and a-Si (p^+) layers respectively.

The optimum thickness of the *p*-type c-Si wafer varies, depending on the solar cell structure. Maximum conversion efficiency of 22.68% (*Voc of* 728.3 mV, *Jsc* of 37.25 mA·cm^{-2} and FF of 82.06%) were obtained for a HIT solar cell with a BSF layer and a wafer thickness of 250 μm.



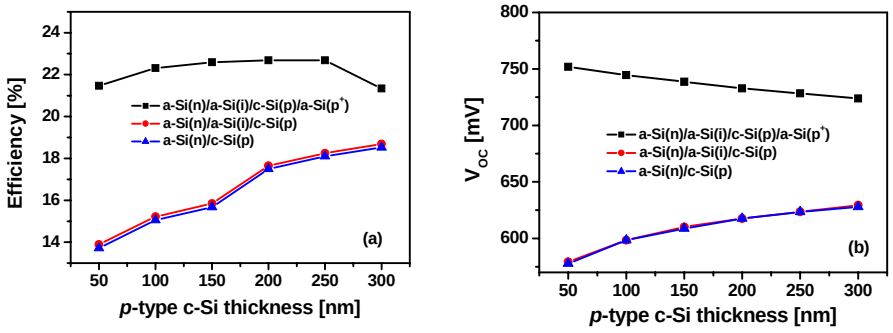
a. *b.*

c.

Figure 2. Dependence of V_{OC}, J_{SC}, FF and efficiency on the n-emitter layer thickness for: a. a HJ a-Si(n)/c-Si(p) solar cell; b. a HIT a-Si(n)/a-Si(i)/c-Si(p) solar cell; c. a HIT with BSF a-Si(n)/a-Si(i)/c-Si(p)/a-Si(p$^+$) solar cell

The conversion efficiency as a function of the thickness of the *p*-type c-Si wafer for a HJ a-Si(n)/c-Si(p) solar cell, a HIT a-Si(n)/a-Si(i)/c-Si(p) solar cell, and a HIT with BSF

a-Si(n)/a-Si(i)/c-Si(p)/a-Si(p^+) solar cell is plotted in Fig. 3(a). In Fig 3(b) are displayed plots of V_{OC} as a function of the thickness of the *p*-type c-Si wafer for three solar cell structures.



a. *b.*

Figure 3. a. Conversion efficiency as a function of the thickness of the p-type c-Si wafer b. Open circuit voltage V_{OC} as a function of the thickness of the p-type c-Si wafer

Although, the surface defects can be passivated by the deposition of a thin (3 nm) *i*-type layer on the front side of the c-Si wafer, it does not have a significant impact on the cell parameters (Fig. 3). On contrary, the deposition of a BSF layer strongly affected these parameters (Fig. 3). Some authors [10] attributed the influence of the p^+-type BSF layer on the solar cell parameters to the formation of a barrier for the opposite polarity charge carriers.

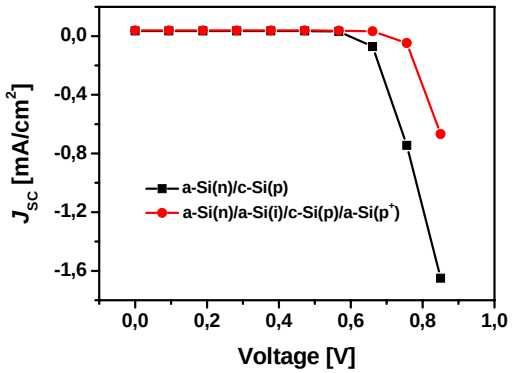


Figure 4. Current-voltage characteristics of a HJ a-Si(n)/c-Si(p) solar cell and a HIT a-Si(n)/a-Si(i)/c-Si(p)/a-Si(p^+) solar cell with a BSF layer

A plot of the short circuit current density as a function of the applied voltage is shown in Fig. 4 for two solar cells with optimized thicknesses of the layers building the structure, a HJ a-Si(n)/c-Si(p) solar cell and a HIT a-Si(n)/a-Si(i)/c-Si(p)/a-Si(p^+) solar cell with a BSF layer. It is obvious that the introduction of the p^+-type BSF layer improves the solar cell characteristics, resulting in higher values of *Voc*, *Jsc*, *FF* and the efficiency.

CONCLUSIONS

The AFORS-HET program was utilized for optimizing the thickness of the *n*-, *i*- and *p*-layers of a simple HJ solar cell (a-Si(*n*)/c-Si(p)), a HIT solar cell (a-Si(n)/a-Si(i)/c-Si(p)), and a HIT solar cell with BSF (a-Si(n)/a-Si(i)/c-Si(p)/a-Si(p^+)) toward the aim to improve the device performance and to obtain a high efficiency solar cell.

The obtained optimum thicknesses of the *n*-type a-Si layer (5 nm) and of the t *i*-type a-Si layer (3 nm) were found to be one and the same for all studied solar cells. The optimum thickness of the *p*-type c-Si wafer varies, depending on the solar cell structure. Maximum conversion efficiency of 22.68% (*Voc of* 728.3 mV, *Jsc* of 37.25 mA·cm^{-2} and FF of 82.06%) were obtained for a HIT solar cell with a BSF layer and a wafer thickness of 250 μm.

It was found that although the surface defects can be passivated by the deposition of a 3 nm *i*-type layer on the front side of the c-Si wafer, it does not have a significant impact on the cell parameters. On contrary, the deposition of a BSF layer strongly affected these parameters due to maybe, the formation of a barrier for the opposite polarity charge carriers. The introduction of the p^+-type BSF layer improves the solar cell characteristics, resulting in higher values of *Voc*, *Jsc*, *FF* and the efficiency.

BIBLIOGRAPHY

[1] Jager-Waldau, A. 2011. Quo Vadis photovoltaics, *EPJ Photovoltaics*, 2, 20801, 1-10.

[2] Delbos, S. 2012. Këwhile thin films for photovoltaics: a review. *EPJ Photovoltaics* 3, 35004, 1-13.

[3] Green, M.A., Emery, K., Hishikawa, Y., Warta, W. 2009. Solar Cell Efficiency Tables (Version 33). *Progress in Photovoltaics: Research and Application*, 17, 85–94.

[4] Radue, C., Dyk, E.E. 2007. Pre-deployment evaluation of amorphous silicon photovoltaic modules. S*olar Energy Materials & Solar Cells*, 91, 129–136.

[5] Shah, A., Meier, J., Buechel, A., Kroll, U., Steinhauser, J., Meillaud, F., Schade, H., Dominé, D. 2006. Towards very low-cost mass production of thin-film silicon photovoltaic (PV) solar modules on glass. *Thin Solid Films*, 502, 292 – 299.

[6] Tsunomura, Y., Yoshimine, Y., Taguchi, M., Baba, T., Kinoshita, T., Kanno, H., Sakata, H., Maruyama, E., Tanaka, M. 2009. Twenty-two percent efficiency HITsolar cell. *Solar Energy Materials & SolarCells*, 93, 670–673.

[7] Como, N. H., Acevedo, A. M. 2010. Simulation of hetero-junction silicon solar cells with AMPS-1D. *Solar Energy Materials & Solar Cells*, 94, 62–67.

[8] Zheliyazova, V., Shtereva, K. 2013. Optimization of the Parameters of Solar Cells through Numerical Simulations, *Proceedings of 5th conference on Energy Efficiency and Agricultural Engineering,* 17-18 May 2013, Ruse, Bulgaria, 488-495.

[9] Schmidt, M., Korte, L., Laades, A., Stangl, R., Schubert, Ch., Angermann, H., Conrad, E., Maydell, K. 2007. Physical aspects of a-Si:H/c-Si hetero-junction solar cells. *Thin Solid Films*, 515, 7475–7480.

[10] Dwivedi, N., Kumar, S., Bisht, A., Patel, K., Sudhakar, S. 2013. Simulation approach for optimization of device structure and thickness of HIT solar cells to achieve ~27% efficiency. *Solar Energy*, 88, 31–41.

[11] European Photovoltaic Industry Association, Global Market Outlook for Photovoltaics 2013-2017. 2013. Available through: http://www.epia.org/news/publications/ [6 May 2013].

[12] Levi, D., Iwaniczko, E., Page, M., Wang, Q., Branz, H., Wang, T. 2006. Silicon Heterojunction Solar Cell Characterization and Optimization Using *In Situ* and *Ex Situ* Spectroscopic Ellipsometry "Preprint". 2006. Conference Paper NREL/CP-520-39932. Available through: www.nrel.gov/docs/fy06osti/39932.pdf [14 April 2013].

[13] Stangl, R., Geipel, T., Dubiel, M., Kriegel, M., El-Shater, Th., Lips, K. AFORS-HET 3.0: First Approach to a Two-Dimensional Simulation of Solar Cells. Available through: dubielnet.de/max/BachelorThesis/aforshetpaper.pdf [12 March 2013]

[14] Froitzheim, A., R. Stangl, L. Elstner, M. Kriegel, W. Fuhs, AFORS-HET: A Computer-Program for the Simulation of Heterojunc-Tion Solar Cells to be Distributed for Public Use. Available through: www.helmholtz-berlin.de/media/media/...HET/...het/published1.pdf. [12 March 2013].

OPTIMIZACIJA ELEKTRIČNIH PARAMETARA SILIKONSKIH HETERO-SPOJNIH SOLARNIH ĆELIJA

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Sažetak: Program za simulaciju AFORS-HET za modeliranje hetero-spojnih solarnih ćelija upotrebljen je za određivanje uticaja debljine i karakteristika materijala *n*-, *i*-, i *p*-slojeva na električne parametre i karakteristike uređaja. Simulacije su izvođene na hetero-spojnim (HJ) solarnim ćelijama od amorfnog silikona (a-Si)/kristalnog silikona (c-Si) i hetero-spojnim solarnim ćelijama sa intrinsičnim slojem (HIT). Postignuta je maksimalna efikasnost konverzije sunčeve energije od 22.68% za a-Si (*n*)/a-Si(*i*)/c-Si(*p*)/a-Si(p^+) solarne ćelije sa zadnjim površinskim (BSF) kontaktom na *p*-tipu silikonske obloge. Napon otvorenog kola od (V_{OC}) (728.3 mV), gustina struje kratkog kola (J_{SC}) (37.96 mA·cm^{-2}) i faktor punjenja (*FF*) (82.06%) solarnih ćelija su unapređeni uvođenjem tankih slojeva intrinsičnog i obogaćenog amorfnog hidrogenizovanog silikona, deponovanog na kristalnom silikonu i optimizacijom debljine slojeva. Predstavljen je potencijal za postizanje efikasnosti konverzije veće od 20% i gustine struje veće od 35 mA·cm^{-2}.

Ključne reči*: modeliranje, simulacija, hetero-spojna solarna ćelija, efikasnost.*

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