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INFLUENCE OF MATERIAL PROPERTIES ON PARAMETERS OF SILICON SOLAR CELLS*

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Multicrystalline and monocrystalline silicon solar cells are the most popular for commercial applications. Numerous material parameters could affect solar cell performance. The application of antireflective coatings of amorphous silicon based alloys can increase device efficiency. Such coatings due to tunable energy gap and refractive index and non-expensive fabrication method - Plasma Enhanced Chemical Vapour Deposition at 13.56 MHz are good candidates for large scale application. The authors presented the influence of material properties of bulk cell on solar cell efficiency by the use of computer PC-1D simulation program, which solves the fully coupled nonlinear equations for the quasi-one-dimensional transport of electrons and holes in crystalline devices, with emphasis on photovoltaic devices. The temperature, series and shunt resistance, recombination velocity and wafer thickness have the influence on current--voltage photo-characteristics of solar cells and their efficiency. Also the influence of thickness, reflective coefficient and refractive index of antireflective coatings on solar cells performance was examined. The optimal parameters of efficient solar cell were determined.

Key words: silicon solar cell, ARC

1. INTRODUCTION

It is very important for research to have a possibility of theoretical verification of some technological or experimental aspects. PC-1D simulation program is one of the most popular tools among the photovoltaic areas [1]. In the past years, PC-1D was cited at least twenty times in refereed journals [2]. This program is available from the Photovoltaics Special Research Centre at the University of New South

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Wales in Australia [3]. PC-1D is commonly used for interpreting experimental data to determine the structure of a solar cell. PC-1D takes into account the effects of free carrier absorption and trap-assisted tunneling. The new free-carrier absorption model has already been discussed in a journal publication [4].

In this work we propose the use PC-1D program to describe the influence of parameters of antireflective coatings and silicon wafer material parameters on the properties of solar cells.

2. EXPERIMENTAL

The optimization of parameters of solar cells especially their efficiency needs the deposition of antireflective coating (ARC) with strictly defined properties. Additionally a great role plays the structure of cell. The application of PC-1D was very useful for determination of proper correlation between the parameters of films and properties of solar cells.

The physical properties of ARC films taken into account for photovoltaic application are: optimal energy gap, refractive index, low effective reflectivity and thickness. Their values may be predicted by the use of simulation method based on solar cell model. Parameters such as dimension of solar cell, temperature, diffusion length, resistivity of the wafer, dopants profiles, surface recombination were applied in simulation method. Also the antireflective film geometry and optical data are taken into account. The values of all parameters are listed in Tab. 1.

Table 1. Main parameters of silicon solar cells applied in simulation by program PC-1D [5].
Tabela 1. Główne parametry krzemowych ogniw słonecznych zastosowane w programie symulacyjnym PC-1D [5**].**

Parameters applied in simulation and their units	Values
Thickness of solar cell d_c [μm]	300
Area of solar cell A_0 for Θ=0° [cm^2]	100
Temperature T_c [°C]	25
Diffusion length of minority carriers in base L_c [μm]	80
Resistivity of base type p ρ_c [Ω·cm]	1
Donor profile erfc with values: surface resistance R_ρ [Ω/□] surface concentration N_D [1/cm^3] junction depth x_c [μm]	 30 3.688 x 10^{20} 0.3

Parameters applied in simulation and their units	Values
Speed of front-surface recombination in solar cell, for electrons S_n and holes S_p [cm/s]	from 1 to 1 x 10^7
Speed of rear-surface recombination in solar cell, for electrons S_{nR} and holes S_{pR} [cm/s]	1 x 10^5
Serial resistance of solar cell R_s [Ω]	0.015
Global irradiation – AM 1.5 [W/m^2]	1000
Antireflective coating: thickness d_{AR} [nm] refractive index n	80 2
Reflectivity for antireflective coating [%]	8-12
Other parameters	standard values for Si

3. RESULTS AND DISCUSSIONS

3.1. Influence of antireflective coatings parameters on solar cell properties

Investigated solar cells structures were obtained on p-type multicrystalline silicon wafers produced by Bayer, 300 μm thick with a resistivity of 1 Ωcm according to the technological method described in [4]. As an antireflector a-Si:C:H films were deposited on upper surface of these solar cells. Using global spectrum sun simulator [5] current-voltage characteristics of cells with and without a-SiC:H films were measured under an AM 1.5 illumination (1000 W/m^2). This experiment allow us to determine the basic solar cells parameters like: I_{SC} – short circuit current, V_{OC} – open circuit voltage, FF – fill factor and E_{ff} – efficiency. The current-voltage characteristics [6] with the use of double exponential relationship allow fitting these parameters (Fig. 1). The model has been thoroughly describe by Appelbaum et al. [7]. The formula has a following form:

$$I = I_{ph} - I_{s1}\left[\exp\left(\frac{V + I \cdot R_S}{A_1 V_t}\right) - 1\right] - I_{s2}\left[\exp\left(\frac{V + I \cdot R_S}{A_2 V_t}\right) - 1\right] - \frac{V + I \cdot R_S}{R_{sh}} \quad (1)$$

where: I – current, V – voltage, I_{ph} – generated photocurrent, R_S – series resistance, R_{sh} – shunt resistance, A_1 and A_2 diode ideality factors, I_{s1} and I_{s2} saturation currents. V_t is equal to kT/e. The A_1 equal 1.0 and A_2 as equal 2.0 was chosen. To obtain high cell efficiency it is necessary to reduce the surface recombination losses. Very effective method is the use of hydrogen rich antireflection coating, which apparently reduces defects concentration in multicrystalline silicon.

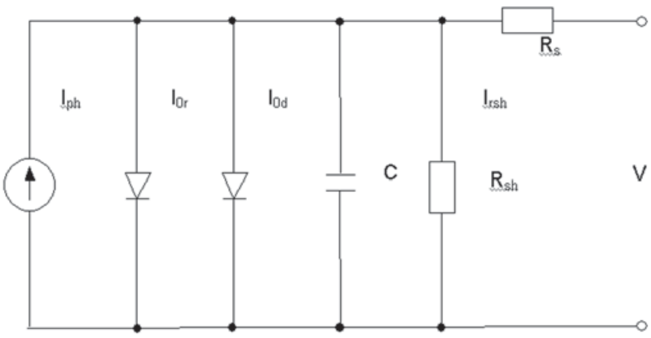

Fig. 1. Scheme of two-diode model of solar cells.
Rys. 1/

In Fig. 2 the generated by PC-1D current-voltage characteristics for silicon solar cells with ARC of various optical refractive indices *n* are presented. It is evident that the recommended *n* value equals 2. PECVD deposition process parameters were chosen to produce a-Si:C:H and a-Si:N:H films of refractive index of about 2, which was confirmed by optical measurements of these films [8-9]. The electrical measurement confirmed that this is the best value of n for silicon solar cells.

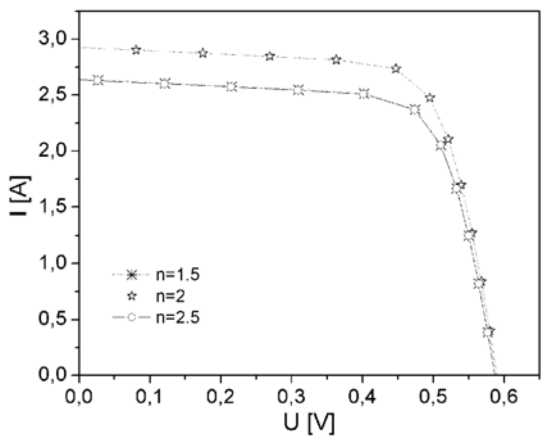

Fig. 2. Simulated I-V characteristics for solar cells with ARC of different refractive index.
Rys. 2. Charakterystyki prądowo-napięciowe I-V ogniw słonecznych z warstwą ARC, symulowane dla różnych współczynników załamania warstwy antyrefleksyjnej.

Fig. 3 shows the generated by PC-1D current-voltage characteristics dependence on the thickness of antireflective films. The highest values of solar cell current were obtained for thickness in the range from 70 to 85 nm, which is optimal for commercial applications. The amorphous silicon based alloys (a-Si:C:H and a-Si:N:H) used for solar cells modification have thickness values of about 80 nm. The influence of ARC thickness on solar cell efficiency was previously experimentally investigated [9-10].

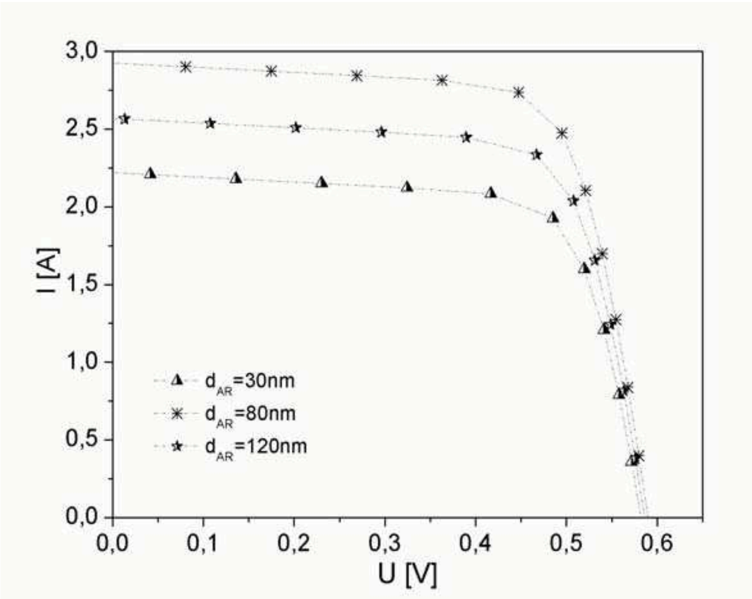

Fig. 3. Simulated I-V characteristics for solar cells with ARC of different thickness.
Rys. 3. Charakterystyki prądowo-napięciowe I-V ogniw słonecznych z warstwą ARC, symulowane dla różnych grubości warstwy antyrefleksyjnej.

The role of an antireflective film is to decrease the effective reflectivity of the upper cell surface. The theoretical prediction of the influence of ARC reflectivity on I-V characteristics of solar cells is presented in Fig. 4. In real measurements the highest efficiency of solar cells we can observe for effective reflectivity of ARC between 5 and 9% [10]. The electrical measurement of mc-Si solar cells with an ARC revealed good agreement with simulation results.

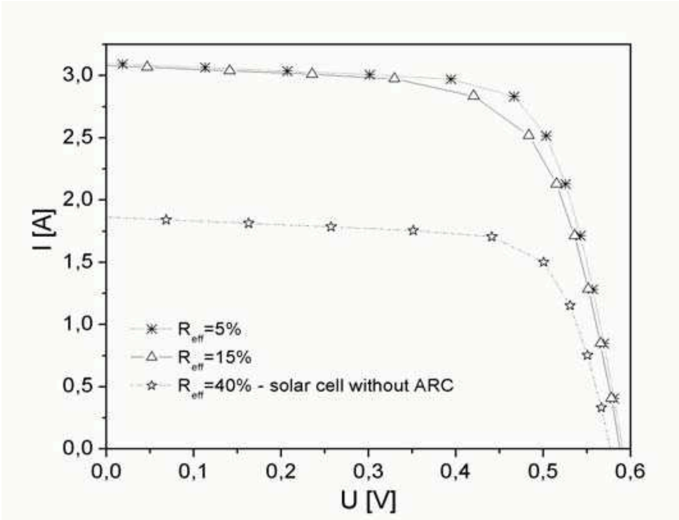

Fig. 4. Simulated I-V characteristics for solar cells without and with ARC of various reflectivity.
Rys. 4. Charakterystyki prądowo-napięciowe I-V ogniw słonecznych bez i z warstwą ARC, symulowane dla różnych współczynników odbicia warstwy antyrefleksyjnej.

3.2. Influence of silicon wafers parameters

In Fig. 5 the dependence of Si wafer resistivity on final efficiency of silicon solar cell is presented. One can observe the linear decrease of such dependence. This simulation result indicates that low resistivity of Si wafers are preferable. From the technological literature announcements [11] it is know that the optimal resistivity value is 1 Ωcm. Also the solar cell industry enterprises prefer such base resistivity value in large scale production. The resistivity of the basis of all modified in our University solar cells equals 1 Ωcm.

The carriers generated in solar cells before reaching the contacts recombine with defects, impurities, surface defects and the current output is diminished. Minority--carrier lifetime (τ) is a quantitative measure of such phenomena. Characterization of lifetime is frequently used to qualify the crystalline Si material before it is used in device processing. Quality of PV material is strongly connected with τ. In Fig. 6 the simulation of dependence of solar cells efficiency on minority carrier lifetime is shown. One can see that the higher values of lifetime are preferable.

Our earlier investigations concerned the measurements of decay rates of the photovoltage and photocurrent for the determination of minority-carrier lifetime and surface recombination velocity of solar cell, the most important transport phenomena in solar cells. The decays were obtained from experiments using specially designed measurement setup where a laser diode controlled from the pulse generator and specially designed modulator circuit is used [6].

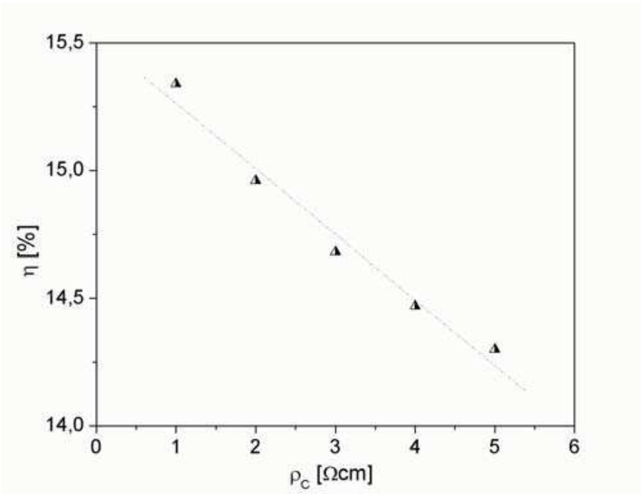

Fig. 5. Simulated dependence of solar cells efficiency on the resistivity of Si basis generated by PC-1D.
Rys. 5. Zależności sprawności ogniw słonecznych od rezystywności bazy, wygenerowane za pomocą symulacji PC-1D.

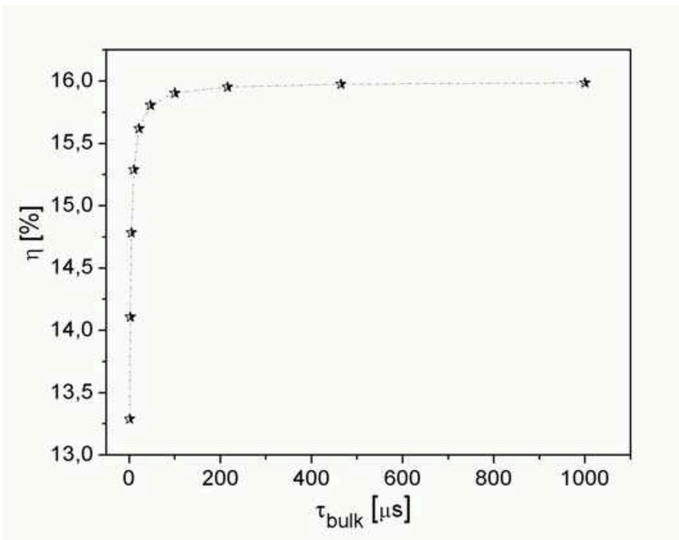

Fig. 6. Simulated dependence of solar cells efficiency on minority carrier lifetime generated by PC-1D.
Rys. 6. Zależności sprawności ogniw słonecznych od czasu życia nośników mniejszościowych, wygenerowane za pomocą symulacji PC-1D.

Photocurrent decays are generally nonexponential, but the decay time could be determined as the initial logarithmic slope after termination of the light pulse at $t = 0$ [12]

$$\frac{1}{\tau_{\tau}} = -\frac{1}{I_{ph}} \frac{dI_{ph}}{dt}\bigg|_{t=0} \tag{2}$$

The typical photovoltage decay curve is presented in Fig. 7. It is clearly seen that only after the switching off the light the exponential like decay exists. From the decay – time curves it is possible to calculate the lifetime, using above mentioned formula, which was of about 40 μs. This value is in the range where the achievement of solar cell of higher efficiencies is possible [6].

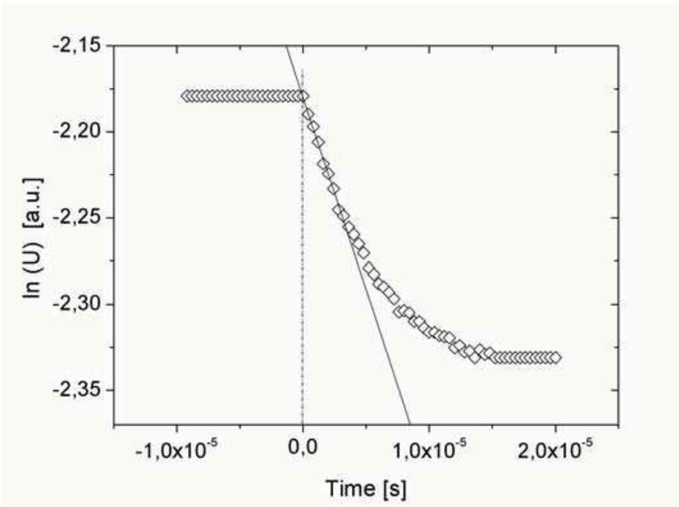

Fig. 7. Time dependence of the photovoltage after switching off the light for silicon solar cell (after [6]). See that just after the termination of the light pulse the decay trend is exponential.
Rys. 7. Przebieg zaniku fotonapięcia na otwartym ogniwie Cz-Si [6]. Zaraz po zgaszeniu oświetlenia zależność przyjmuje charakter eksponencjalny.

4. CONCLUSIONS

The possibility of the simulation of working parameters of solar cells with a-Si:C:H and a-Si:N:H antireflective was of a great importance for possible applications of these films. The simulation results fully confirmed a strong relation between the cell efficiency and the thickness refractive index and reflectivity coefficient of ARCs. All investigated solar cells have material parameters values predicted by PC-1D simulation program as preferable in photovoltaics. The theoretical simulation provides quantitative values of the main parameters of the antireflective coating which is very important for designing advance solar cell structure. Later investigations of solar cells confirmed the theoretical predictions.

Experiments on high quality c-Si cells give decay times that are comparable to the results obtained in other laboratories [13-14].

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WPŁYW WŁAŚCIWOŚCI MATERIAŁOWYCH NA PARAMETRY EKSPLOATACYJNE KRZEMOWYCH OGNIW SŁONECZNYCH

Światowa produkcja ogniw słonecznych opiera się przede wszystkim na krzemie mono- i multikrystalicznym. Właściwości materiałowe istotnie wpływają na jakość, a przede wszystkim na ich parametry użytkowe. Wydatny wzrost sprawności ogniw można uzyskać poprzez zastosowanie warstw ARC. Tego typu powłoki, z możliwością optymalizacji współczynnika załamania oraz przerwy optycznej, można otrzymywać metodami Chemicznego Osadzania z Fazy Gazowej (RFCVD – *Radio Frequency Chemical Vapour Deposition*). Autorzy zbadali wpływ właściwości materiałowych na sprawność ogniw korzystając z metody numerycznej – program PC-1D. Program umożliwia wyznaczenie końcowych parametrów ogniw z uwzględnieniem zarówno stałych materiałowych podłoża, jak i elementów modyfikujących to ogniwo. Na kształt charakterystyki prądowo-napięciowej I-V (model dwudiodowy) i sprawność ogniwa mają wpływ: temperatura, rezystancja szeregowa i zwierająca, szybkość rekombinacji oraz grubość podłoża. W przypadku warstw antyrefleksyjnych, decydujące są: grubość, współczynnik załamania oraz współczynnik odbicia. Program symulacyjny pozwolił określić optymalne parametry wydajnych ogniw słonecznych na bazie krzemu, z uwzględnieniem bardzo istotnego wpływu warstw ARC.

Słowa kluczowe: ogniwo słoneczne, ARC