Optica Applicata, Vol. XLI, No. 2, 2011

The role of antireflective coatings in silicon solar cells – the influence on their electrical parameters

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In this work, the authors compared the properties of multicrystalline silicon solar cells which depended on the kind of following antireflective layers: a-Si:C:H, a-Si:N:H and TiO_x. Current–voltage characteristics for multicrystalline silicon solar cells were measured by the use of a computer controlled global spectrum sun simulator under an AM 1.5. The measurements of *I–V* characteristics allow the determination of basic electrical parameters and efficiency using the double exponential relationship from a two-diode solar cells model. Two key parameters: refractive index and thickness of the film affect the final features of the antireflective coating. Optimisation of these parameters and afterwards the experimental verification lead to the minimalisation of the reflection coefficient that decides about the quality of the antireflective layer. A high quality reflective layer can improve the efficiency of the solar cell even by 30%.

Keywords: antireflective coatings (ARC), solar cells, *I–V* characteristics.

1. Introduction

The basic factor that affects the efficiency of a solar cell is the reflection of light from its front surface. The reflection coefficient can be reduced by covering the top of the solar cell surface by antireflective coatings (ARC) – Fig. 1. The surface of the silicon substrate can be covered with single or double antireflective coatings.

Various techniques can be used to deposit antireflective coatings: the chemical vapour deposition (CVD), spray, spin-on or screen printing. The spin-on is the simplest technique which is very efficient and does not need an expensive equipment [1, 2], however this method can be used only on smooth, polished surfaces. For textured surfaces, the thickness of the ARCs deposited by the spin-on method becomes uneven. Another method – plasma enhanced chemical vapour deposition (PECVD) is

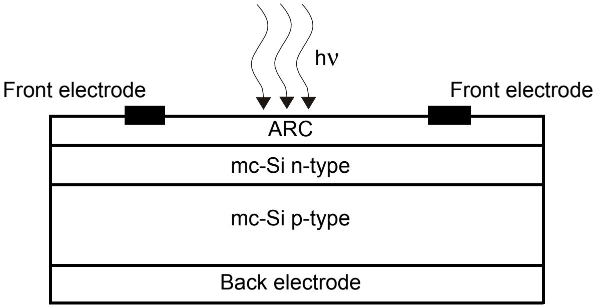

Fig. 1. Scheme of photovoltaic solar cell on the base of multicrystalline silicon (mc-Si) with antireflective coating.

more expensive, but it enables the deposition of layers with very good parameters (reflection coefficient, chemical contents) – very uniform and of controlled thickness. The following materials are used as reflective coatings: TiO_2 (refractive index $n = 2.3$), Si_3N_4 ($n = 1.9$), Al_2O_3 ($n = 1.8–1.9$), SiO_2 ($n = 1.4–1.5$), Ta_2O_5 ($n = 2.1–2.3$) [3]. Recently the amorphous layers a-SiN_x:H [4] and a-Si:C:H [5] have been applied as ARCs. In solar cell production process during diffusion, on the surface of silicon substrate, phosphorous silicate glass (PSG) is formed which can also operate as a low quality antireflective layer [6] which does not need any additional processes and costs. For this reason it is removed just after the diffusion process with the use of H_2F_2 and then the above mentioned antireflective layers are coated on the top surface of solar cells.

The proper choice of thickness of the ARC is important for the metallisation process of electrical contacts. Excessively thick ARC makes the process of pad metallisation more difficult, and additionally decreases optical parameters and efficiency of the solar cell.

The authors obtained a-Si:C:H and a-Si:N:H films by PECVD and applied them as ARC in multicrystalline silicon solar cells. Films of TiO_x are deposited by the use of the spray technique.

2. Experiment

Amorphous a-Si:C:H and a-Si:N:H thin films were deposited by PECVD in an ultra high vacuum reactor at 13.56 MHz in gaseous mixtures $SiH_4 + CH_4$ and $SiH_4 + NH_3$ with various CH_4 and NH_3 content in plasma [7]. In PECVD method, the probability of dissociation of nitrogen is very low and the silane ammonia mixture should be used to produce a-Si:N:H thin films. Other technological parameters: RF power of 5 W, substrate temperature of 180 °C and total pressure of 80 Pa were kept constant. The TiO_x films were deposited by the spray technique at 280 °C with tetraethylorthotitanat $(C_2H_5O)_4Ti$ using purified air as a carrier gas [8]. Polished crystalline (Cz-Si) and multicrystalline (mc-Si) silicon wafers were used as substrates. All these films were deposited before contacts were screen-printed. Such procedure is important for good soldering of the solar cells and good connecting them in a module. TiO_x films produced at the temperature below 300 °C are primarily amorphous like a-Si:C:H and a-Si:N:H, which makes the metallisation of the front contacts easier.

Structural properties were detected by means of Fourier transform infrared spectroscopy (FTIR – Biorad FTS-60V) and film morphology using scanning electron microscope (SEM – NOVA NANO SEM 200, FEI Company). Optical measurements of films deposited on silicon substrates were done by the use of Perkin–Elmer Lambda 19 double beam spectrophotometer. The method of characterisation and details of the experiment were thoroughly described in [5]. Current–voltage photocharacteristics of solar cells with and without antireflective coatings were measured using a computer controlled global spectrum sun simulator (I–V Curve Tracer For Solar Cells Qualification, v 4.1.1) [9].

3. Results and discussion

SEM method makes possible a quantitative analysis of elemental composition of a-Si:N:H and a-Si:C:H films. The obtained results confirm that the increase in ammonia content in $SiH_4 + NH_3$ and methane content in $SiH_4 + CH_4$ causes the increase in nitrogen w_N and carbon w_C content in a-Si:N:H and a-Si:C:H films ($w_N = N/(Si + N)$; $w_C = C/(Si + C)$), respectively. These two elements of the layers – nitrogen and carbon – had the crucial influence on their optical properties: refractive index, energy gap and effective reflectivity coefficient [7].

The presence of hydrogen in the films used for photovoltaic application is very important for passivation of defects in multicrystalline silicon. These defects play the role of recombination centers in the bulk and at the surfaces of mc-Si. FTIR measurements, which were carried out in the spectral range from 400 to 4000 cm^{-1} in an absorption mode, confirmed the presence of numerous diverse hydrogen bondings both in a-Si:N:H as well as a-Si:C:H layers [7]. Exemplary bondings are: SiH_n, NH_n, CH_n, $Si–CH_n$, $H–SiN_n$, *etc.*

The measurement of optical transmission and reflection of films enabled us to calculate a refractive index n, optical absorption α and Tauc optical energy gap E_g using relations given in [10, 11]. The refractive index of a-Si:N:H apparently decreases with an increase in nitrogen content in films, whereas the energy gap increases with an increase in w_N. For a-Si:C:H films we observed a similar dependence: n decreases with an increase in carbon content, E_g increases with an increase in w_C.

From the position of the reflectivity minimum λ_{min}, the film thickness d can be evaluated as [12]:

$$d = \frac{\lambda_{min}}{4n} \tag{1}$$

where n is the real part of light refractive index in ARC ($k \approx 0$) and:

$$n^2 = n_0 n_2 \tag{2}$$

where: n_0 – refractive index of air which is equal to 1; n_2 – refractive index of base material; d – thickness of antireflective coating; λ – wavelength from the area of maximum photosensitivity (400–1100 nm).

The refractive index for silicon for the wavelength $\lambda = 600$ nm is equal to $n_2 = 3.6$. It is worth to remind that the effective reflectivity coefficient R_{eff} for the monocrystalline silicon is in the range of 30–35%, while for the multicrystalline silicon – in the range of 25–30%. For the wavelength equal to 600 nm and the refractive index of silicon $n_2 = 3.6$, the optimal thickness of the ARC is about 80 nm. As can be seen from the Eq. (2), the optimal refractive index n for the ARC layer deposited on a silicon solar cell should be about 1.9. The antireflective layer in dependence to its chemical contents enables also the passivation of defects in multicrystalline silicon. Multicrystalline silicon is a highly defected material with a large number of dangling bonds at the boundaries of grains. Some technological steps, such as cutting of silicon substrates and phosphorous diffusion, are the source of further defects. The presence of hydrogen in ARC layers is in this case useful.

The total reflectivity in the wavelength range extending from 400 nm to 1100 nm of mono- and multicrystalline silicon substrates with and without ARC films was measured by the Perkin–Elmer spectrophotometer equipped with the integrating sphere. From the spectral dependence of the reflectivity $R(\lambda)$, the effective reflectivity coefficient R_{eff} was calculated [13].

TiO_x layers are characterized by excellent optical properties as ARCs for silicon solar cells due to the refractive index value of about 2.38 at the wavelength of 600 nm and the extinction coefficient remaining near zero at the wavelength of 400 nm [14].

Main optical parameters of chosen antireflective coatings, obtained by described methods, are collected in Tab. 1.

Table 1. Main parameters of ARCs: d – film thickness, n – refractive index, E_g – energy gap, R_{eff} – effective reflectivity coefficient.

	Parameters of ARC – best results			
Kind of ARC	d [nm]	n	E_g [eV]	R_{eff} [%]
a-Si:C:H	75	1.92	2.6	6.5
a-Si:N:H	80	1.97	2.7	8.3
TiO_x	35	2.28	3.1	7.5

Solar cells parameters were calculated by fitting of a two diode model to the experimental data [15]. Examined solar cells were made on multicrystalline silicon wafers of 300 μm thickness, 1 Ωcm resistivity, p-type (boron doped). The measurements of I–V characteristics allow us to determine the basic parameters like: I_{SC} – short circuit current, V_{OC} – open circuit voltage, FF – fill factor and η – efficiency.

Each of tested layers has the beneficial influence on electric parameters of solar cells on the base of the multicrystalline silicon – Tab. 2. In every case, an improvement

Table 2. Main parameters of mc-Si solar cells of area 100 cm^2: I_{SC} – short circuit current, V_{OC} – open circuit voltage, FF – fill factor, η – efficiency; for different kinds of ARC (*I–V* measurements in standard test conditions – STC).

Kind of solar cells	Parameters of solar cells			
	I_{SC} [A]	V_{OC} [mV]	FF [%]	η [%]
mc-Si solar cell without ARC	2.43	566.7	71.1	9.84
mc-Si solar cell with a-Si:C:H ARC	3.12	578.3	70.8	12.22
mc-Si solar cell with a-Si:N:H ARC	3.29	612.4	73.1	14.25
mc-Si solar cell with TiO_2 ARC	3.24	593.4	72.7	14.00

in the efficiency of solar cells was observed. With the decrease in R_{eff}, the increase in the efficiency η and short circuit current were observed.

As can be seen in Tab. 2, most favourably a-Si:N:H layer influences the parameters of solar cells, but very comparable results are being achieved through using a titanium oxide layer. Probably, it is a result of additional influence of many hydrogen bondings, present in the structure of a-Si:N:H antireflective coatings [13].

The output parameters of multicrystalline silicon solar cells with and without antireflective coatings were simulated using a computer program PC1D and the results compared with the measurement [7]. The obtained results are in good agreement with the measured output parameters of analysed solar cells.

4. Conclusions

In common opinion it is not possible to produce efficient solar cells without any antireflective coatings. The profitable influence of ARC is particularly exhibited by the values of the short circuit current and the efficiency of cells. Moreover, the ARCs have good protective properties of solar cells surface, before assembling them into the panel.

PECVD is the most effective method of ARC preparation due to good reproducibility of material properties. Additionally, this method guarantees the hydrogen presence suitable for passivation of silicon defects, especially in multicrystalline substrates.

The numerical prediction of *I–V* characteristics of solar cells was confirmed by the results of measurements.

Acknowledgements – The research was supported by EEA Financial Mechanism and the Norwegian Financial Mechanism Grant PL0081.

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Received September 25, 2010