Silicon solar cells with antireflecting and protective coatings based on diamond-like carbon and silicon carbide films

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Deposition of single or two-layer diamond like carbon (DLC) antireflecting coatings enables the solar cell (SC) efficiency to be improved 1.35–1.45 time. It is interesting to note that the SC efficiency improvement after DLC films deposition is connected not only with the antireflecting effect. The DLC films deposition also results in short circuit current (J_{SC}) increasing but enhancement of open circuit voltage (V_{oc}) and fill factor (FF) as well. The latter is likely caused by passivation of recombination active centers on the SC surface during DLC film deposition and, possibly, by gettering of the defect and impurities from the SC volume. The improvement in SC' efficiency was also observed for SC covered by thin (50–100 nm) antireflecting SiC coatings.

Keywords: solar cell, silicon carbide film, DLC film, antireflection.

1. Introduction

One of the most efficient ways to improve solar cell (SC) parameters is the deposition of antireflecting coatings on the SC front side [1]. It enables the light reflection from the SC front side to be substantially decreased. This is especially important for SCs fabricated on the base of materials having high refractive index (n) in the range of solar spectra maximum. For example, refractive index of silicon in the spectral range from 400 to 1100 nm is changed from 5.2 to 3.5 [2]. It results in the change of reflection coefficient between ~30–50% [2].

As a rule, silicon wafers with formed p-n junction and contacts are further covered from the working side by the layer that has the functions of antireflection and protection of the surface from the outer factors (contaminations, mechanical influences, etc). Usually used SiO_2 films are non-optimum ones both for antireflection (have insufficiently high refractive index) and for SC protection (the film is transparent for ultraviolet radiation with an energy up to 10 eV and has insufficient hardness to abrasive action of dust). ZnS/MgF_2 and ZnO coatings are also used [3]. Over the last years, the SiN films having refraction coefficient near to an optimal one are used for antireflection and passivation of the silicon SCs. But such films have sufficiently high absorption within the range of SC photosensitivity, especially in the short-wave spectral range. For instance, at the wavelength of 440-450 nm SiN film of 61-nm thickness absorbs up to 5% of the incident light. To insure optimal antireflection the additional MgF_2 film has to be deposited onto work-side of the SC prior to SiN film deposition. Such technology complication leads to the SC cost increase. Diamond-like carbon films may be alternative to the SiO_2 and SiN ones. As some investigations have shown the DLC films have not disadvantages mentioned, provided that the regimes of the film synthesis are optimal [4–7]. It is important to note that two-layer antireflecting coatings for the case of DLC films may be obtained in a single technological cycle only changing parameters of a deposition process.

Moreover, by our preliminary data, DLC can also act as a getter (absorber) of redundant oxygen from subsurface (active) region of silicon improving the SC characteristics. It is well known that ion-plasma treatments are very promising for improvement of parameters of multicrystalline "solar" silicon. The technology of DLC film deposition foresees such treatments before the film synthesis. Besides, presence of hydrogen ions in plasma used for DLC film deposition is an additional factor for improvement in multicrystalline silicon characteristics.

In this work, optical properties of a new type of DLC films, namely amorphous hydrogenated carbon films doped by nitrogen (a-C:H:N), were investigated. The possibility to apply the a-C:H:N films as antireflecting and protective coatings for silicon SCs was also studied.

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2. Experimental

The a-C:H:N films used in this study were deposited by RF plasma decomposition of CH_4:H_2:N_2 gas mixture in a parallel plate reactor. The total pressure in the reaction chamber was varied from 0.2 to 0.8 Torr. Si (100) wafer and Si solar cells were used as a substrate. During deposition process the substrate was kept at room temperature and fixed RF bias voltage (U = 1900 V).

Silicon carbide films were deposited by ion-plasma sputtering of a SiC target in argon-hydrogen vapour atmosphere. A triode system of sputtering was used when plasma discharge was excited by thermoelectric emission and localised as a plane beam by the magnetic field of a permanent magnet.

Optical constants of the films were measured by a laser (λ = 632.8 nm) and spectral ellipsometer. The mechanical properties of the films were studied using a microanalyser (Nano Indenter II, Nano Instruments Inc., Knoxwille, TN, USA) or microhardness tester Shimadzu HMV-2000, Japan). All measurements were carried out at room temperature.

3. Results and discussion

Figure 1 shows the refractive index dependencies of a-C:H:N films on nitrogen content in gas mixture and total gas pressure. It can be seen that the dependencies are non-monotonous and refractive index can be changed from 1.6 to 2.2. Thus, under certain conditions the films with n = 2.0 can be grown. Evidently, this value satisfies completely the condition of optimal antireflecting effect [$n_{film} = (n_{substrate})^{1/2}$] for silicon which have n = 3.96 at λ = 632.8 nm. It should be noted that Si extinction coefficient at λ = 632.8 nm did not exceed 0.10 and 0.005 for the films with n = 2.0 and n = 1.6, respectively. Optical bandgap (E_{opt}) values determined from the optical constants spectra is 2.2 and 3.96 eV for the films obtained at P = 0.4 and 0.8 Torr, respectively (see Table 1).

As noted above, the optimal antireflecting effect for silicon SC will be achieved by using the films having n ~2.0. Thus, the a-C:H:N films grown at low nitrogen content in gas mixture should be used. Figure 2 shows reflection spectra of Si covered by DLC antireflecting coatings of different thickness and refractive index. For comparison, the spectrum of Si with SiO_2 antireflecting coating is also presented. It is seen that the antireflecting effect is much more pronounced when the DLC coatings are used. So, the reflection spectra of SC with the DLC antireflecting coating show significant decreasing of reflection coefficient, which can attain ~1% in the minimum of reflection band (~600 nm) (Fig. 2).

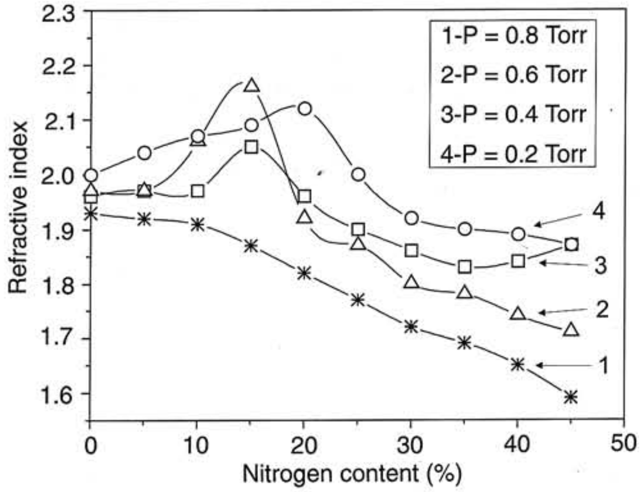

Fig. 1. Refractive index of DLC films measured at λ = 632.8 nm as a function of nitrogen content in gas mixture (P is total gas pressure in reaction chamber).

Parameters of Si SCs with and without DLC coatings are presented in Table 1. One can see, that deposition of single or two-layer a-C:H:N antireflecting coatings enables the SC efficiency to be improved 1.3–1.43 times (samples 1a and 2a).

The current-voltage characteristics of the initial (bare) SC and the SC with two-layered DLC-antireflecting coating are presented in Fig. 3. In insert to Fig. 3 some characteristics of the SCs are also given. It is interesting to note that the SC efficiency improvement after DLC films deposition is connected not only with the antireflecting effect. Indeed, as it can be seen from insert in Fig. 3, the DLC films deposition results in not only short circuit current (J_{SC}) increasing but enhancement of open circuit voltage (V_{oc}) and fill factor (FF) as well. The latter is likely caused by passivation of recombination active centers on the SC

Table 1. a-C:H:N film parameters and Si SCs efficiency with and without DLC antireflecting coatings.

Sample No.	a-C:H:N films						SC eff. (%)	Illumination conditions
	PN2 (%)	P (Torr)	D (nm)	n	k	E_{opt} (eV)		
1							10.6	AM1.5
1a	5	0.4	63	1.98	0.09	2.2	14.3	AM1.5
2							9.96	AM1.5
2a	5/40	0.2/0.8	70/108	2.04/1.65	0.124/0.005	2.0/3.96	14.2	AM1.5

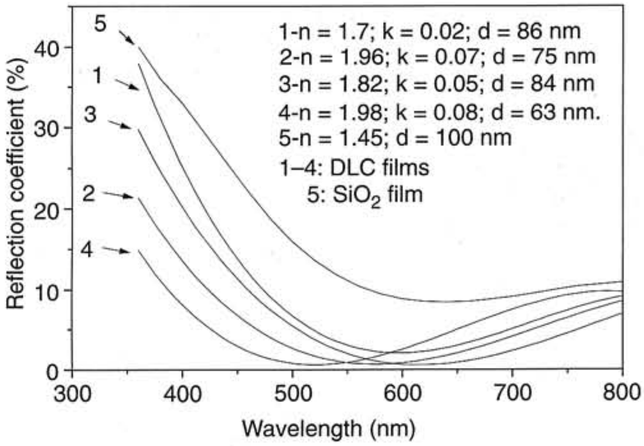

Fig. 2. Reflection spectra of silicon SCs covered by various antireflecting coatings.

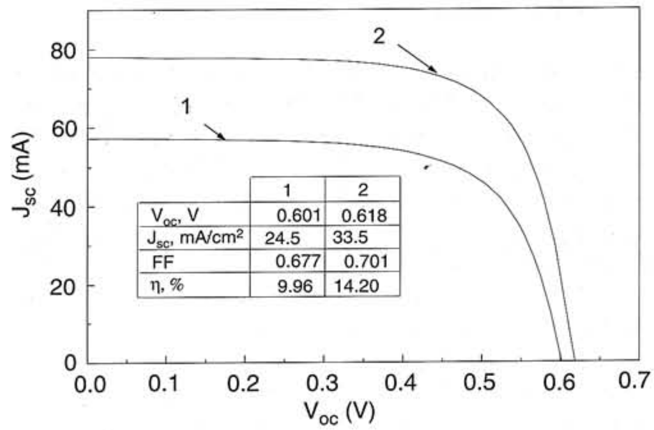

Fig. 3. J–V characteristics of silicon SCs without (1) and with (2) two-layer DLC antireflecting coatings.

surface during DLC film deposition and, possibly, by gettering of the defect and impurities from the SC volume.

The results obtained for Si SCs with silicon carbide antireflecting coatings are presented in Table 2. Some parameters of the SiC films are also given. We can conclude that deposition of SiC films allows us to increase the SC efficiency 1.2–1.3 times. The best results were obtained for the sample 3a when the film thickness was closer to the optimal one than that for the sample 4a. It should be pointed out that extinction coefficient of the SiC films is substantially lower than that for a:C:H:N films having the practically same refractive index. It is probably connected with some differences in structure of the films. In particular, an amorphous carbon film consists on sp^2 clusters embedded into sp^3 coordinated matrix [8], whereas an amorphous SiC film contains mainly tetrahedral coordinated bonds [9]. However, improvement in SC efficiency, after deposition of the SiC films, is connected with antireflecting effect mainly (only slight increase in fill factor and open circuit voltage was observed) while, as it was mentioned above, for a-C:H:N films the effects of gettering of impurities and passivation of recombination active centres took place. It is most likely caused by high deposition temperature for the SiC films and, as a result with the lower hydrogen content in the films in comparison with a-C:H:N ones. It should be also noted that hardness of the SiC films was high (up to 20 GPa) that is substantially higher than that for a-C:H:N films (up to 10 GPa). On the other side, the SiC film deposition rate was high enough (3.5 micrometers per hour) that can be important in case that thick protective coating should be deposited. Both a-C:H:N and SiC films show high wear resistance that is determined by good elastic properties of the films. The measurements were carried out using "Taber tester" device.

In conclusion, it has been shown that owing to possibility to vary optical properties of a-C:H:N and SiC films by changing of deposition conditions and their good mechanical characteristics the films can be successfully used as antireflection and protective coatings for silicon solar cells.

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Table 2. SiC film parameters and Si SCs efficiency with and without SiC antireflecting coatings.

Sample No.	a-C:H:N films						SC eff. (%)	Illumination conditions
	t_{dep} (s)	T_{substr} °C	D (nm)	n	k	E_{opt} (eV)		
3							11.1	AM1.5
3a	80	350	71	1.99	0.015	2.2	14.4	AM1.5
4							10.8	AM1.5
4a	60	150	54	1.97	0.01	2.25	12.7	AM1.5

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