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Defect passivation of multicrystalline silicon solar cells by silicon nitride coatings

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The influence of the hydrogenated silicon nitride coatings (SiN_x:H) formed by the plasma enhanced chemical vapour deposition on the electrical activity of interfaces of the grains of mc-Si solar cell was examined. Passivation effects were evaluated by the measurements of light-beam-induced current scan maps. It was found that the SiN_x:H layer obtained under optimized conditions significantly improves local photocurrent at the grain boundaries. The electrical parameters of mc-Si solar cells with and without the SiN_x:H layers were compared.

Key words: *silicon nitride coating; passivation; silicon solar cell*

1. Introduction

Multicrystalline silicon wafers contain a large variety of extended crystallographic defects like grain boundaries or dislocations. These defects reduce effective diffusion lengths of minority carriers. In order to improve the material quality, it is necessary to passivate the defects. It is known that the hydrogenation gives very good results. One of the most promising method is application of the hydrogenated amorphous silicon nitride layers (a-SiN_x:H) deposited by the plasma-enhanced chemical vapour deposition (PECVD). These layers are used as very effective antireflective coatings [1–4], the main interest in these films, however, is attributed to the bulk and surface defect passivation of silicon. It was shown that hydrogen released from the SiN_x:H layer during the thermal treatment of a solar cell can passivate silicon defects [5–13].

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This paper describes the results of investigation of the passivation of grain boundaries by the SiN_x:H layer using light-beam induced current (LBIC) mapping of the surfaces in silicon cells.

2. Experimental

The substrates used in this work were 'as-cut', boron doped p-type, 1 Ω·cm multicrystalline (mc-Si) wafers (Baysix). The thickness of wafers was 320 μm and the area was 10×10 cm^2. The manufacturing sequence for the cell fabrication can be presented in the following steps:

- saw damage removing by the KOH chemical etching;
- emitter formation by the $POCl_3$ diffusion with sheet resistance ≈ 40 Ω/sq;
- parasitic junction removal by chemical etching in acid solution;
- phosphorous silica glass etching (PSG) in HF solution;
- PECVD of the SiN_x:H layer or TiO_x/SiO_2 for the reference cell;
- screen-printing front (Ag paste) and back (Al) contacts;
- co-firing front and back contacts in the infrared (IR) furnace.

The first series of Si wafers (with n^+–p junctions) was covered with SiN_x:H layers in a PECVD system produced by the Elettrorava (AGH University of Science Laboratory). The layers were prepared by direct RF (13.56 MHz) plasma chemical vapour deposition using SiH_4 and NH_3 as source gases. It was shown [3] that the refractive index of SiN_x:H layer depends on the $[SiH_4]/[NH_3]$ flow ratio and it can be changed in a wide range from 1.8 to 2.4. In this work, the refractive index of 2.0 was selected for the best match with air. The thickness of the layer was 80 nm in order to receive the minimum reflectance at the wavelength of 650 nm of the solar spectrum. The other deposition parameters were the following: the substrate temperature 225 °C and the deposition time 7 min 40 sec. In the second series, SiN_x:H layers were deposited on silicon wafers in a direct, low frequency (LF) PECVD system, designed specially for solar cells and for a very large number of wafers in one processing step (IMEC).

The n^+–p junctions and metallization of all the cells were made applying the same process in the Photovoltaic Laboratory of the Polish Academy of Sciences. For comparison, a reference cell with TiO_x antireflection coating, thermally oxidized at 800 °C for the surface passivation have been prepared as well.

The metallization of solar cells was made by the screen-printing process which is commonly used in industrial production. A silver paste PV145, manufactured by DuPont, was used for the front contact. The back contact covering the entire rear surface was deposited with a pure Al paste. The two collection back bus bar contacts were printed with a silver paste containing 3 wt. % of aluminium paste. After screen printing, the pastes were dried by heating at 200 °C and subsequently co-fired in an infrared (IR) belt furnace (LA-310). The silver front contacts were fired through the SiN_x:H layer. The temperature profile and the speed of the belt furnace are very critical parameters. They were optimized in order to receive the optimal values of electrical parameters of the solar cells. The best solar cells were obtained for a very short time of firing (very high speed of the belt) and high temperature in the one zone of the furnace (ca. 900 °C).

3. Measurements

The parameters of the solar cells were measured under standard AM 1.5 (100 mW/cm^2) radiation at 24 °C. The results are presented in Table 1. The measurements of I–V characteristics allow one to determine the basic parameters such as: I_{sc} – the short circuit current, V_{oc} – the open circuit voltage, FF – the fill factor and E_{ff} – the efficiency, and others parameters used for the optimization of firing conditions of the metallization, like: r_s – the series resistance and r_{sh} – the shunt resistance.

Table 1. Electrical parameters of mc-Si solar cells with SiN_x and TiO_x/SiO_2 layers

No.	ARC	r_s [Ω·cm^2]	r_{sh} [kΩ·cm^2]	I_{sc} [A]	V_{oc} [V]	FF [%]	E_{ff} [%]
1	SiN_x (IMEC)	0.70	2.2	3.17	0.596	75.2	14.2
2	SiN_x (AGH)	1.15	>10	3.05	0.589	72.5	13.0
3	TiO_x/SiO_2	0.72	10.2	2.79	0.589	76.5	12.6

In order to investigate the effect of the SiN_x:H layers on defect passivation, the technique LBIC was used. The method is based on the excitation of material with a light beam with a specified wavelength and intensity and measuring the current response for this excitation. As a result of focusing the light beam with defined shape, the light spot with a specified diameter on the tested sample is obtained. Based on the assumption of power density distribution on a sample surface and inside the material, the carriers generated in a time unit is determined. All the minority carriers generated by the illumination which do not participate in the recombination process create the induced signal.

The LBIC images of induced photocurrent distribution were obtained using the experimental set-up described in Ref. [14]. The optical systems consisting of a LED light source (650 nm), a diaphragm with 100 μm aperture and a glass objective were used in formation of the light beam. The diameter of light spot obtained with this system was 10 μm. Two computer-controlled translation stages provided the x–y scanning capability with 0.25×1.0 μm^2 step size. Steady state current induced in the external circuit was recorded for each position of the light beam spot. The LBIC images were obtained as the maps of values of induced photocurrent in the function of the x–y light beam position.

4. Results and discussion

The electrical parameters of solar cells are presented in Table 1. The SiN_x:H layers in cells 1 and 2 have been deposited in the IMEC (Inter-University Microelectronics

Centre in Leuven, Belgium) and the AGH Laboratory, respectively. The parameters of the reference cell with the TiO_x /SiO_2 coating are given for comparison. It is seen in Table 1 that the I_{sc} value of the solar cell with SiN_x:H layer deposited in the AGH Laboratory is improved in comparison with the reference cell but the V_{oc} values are still similar. The solar cell with the SiN_x:H made in the IMEC Laboratory is the best, a considerable improvement of I_{sc}, V_{oc} and efficiency (E_{ff} = 14.2 %) was obtained. One can notice that the fill factor of cell 2 is smaller than for other cells due to its high series resistance.

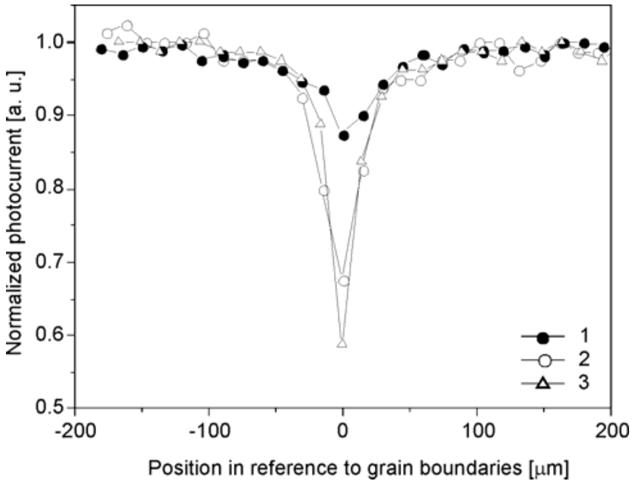

Fig. 1. The cross-section of the current signal across the interface of grains for the cells with SiN_x:H (1 – IMEC, 2 – AGH) and the reference cell with TiO_x/SiO_2 (3)

Figure 1 shows the cross-section current signals across the interface of grains for the cells 1–3 obtained in the LBIC measurements. One can see that the photocurrent of the cell in the grains interface with SiN_x:H deposited in IMEC is the highest. The improvement of photocurrent by the SiN_x:H deposited in the AGH Laboratory is smaller due to non-optimized conditions of PECVD deposition of this layer.

5. Conclusions

Both kinds of the SiN_x:H layers used as the antireflection and passivating coatings improve electrical parameters of the solar cells in comparison with the TiO_x/SiO_2 coating. The best parameters of the solar cells were obtained for the SiN_x:H deposited in the IMEC Laboratory. Investigation using the light beam induced current maps shows that this layer gives a significant increase of the photocurrent in the grains interface. In the case of the SiN_x:H layer deposited in the AGH Laboratory, the improvement in the LBIC signal is very small. Thus, one can conclude that the deposition conditions of the layers should be further optimized in order to improve the defect passivation. In addition, the firing parameters of metallization should be changed in order to decrease the series resistance and improve the fill factor of cells as well.

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