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Influence of a back side dielectric mirror on thin film silicon solar cells performance

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Back side p^+ emitter thin silicon solar cells have been constructed using vapor phase epitaxy. Double porous structure on a c-Si substrate was used as a seed substrate in order to enable active layer separation after vapor phase epitaxy growth. Structure of the back side emitter solar cell was obtained *in situ* during the epitaxy process. In order to enhance solar cell response to light from a range of 700–1200 nm wavelength, the back side dielectric mirror was developed and optimized by means of a computer simulation and deposited by plasma enhanced chemical vapor deposition. At the same time, a reference sample was fabricated. Comparison of solar cells performance with or without the back side mirror was performed and clearly shows that the quality of solar light conversion into the electricity by means of solar cells, can be improved by using the structure proposed in this article.

Keywords: thin film silicon solar cells, back side emitter, back side mirror, vapor phase epitaxy, Bragg mirror, IMD optical properties simulation.

1. Introduction

Increasing energy demand of the modern world and fossil fuels depletion have stimulated the world's economy, industry and scientific centers to invest in alternative sources of energy development. One of the main paths that modern science is taking to develop an efficient way of producing electrical energy is photovoltaics. The Sun is the main source of energy in our planet and the amount of energy reaching the Earth is equivalent to 10000 times the world's energy requirements [1]. Moreover, for the humanity, the Sun can be considered as the inexhaustible source of energy. All of this makes the Sun a very promising alternative source of energy.

Photovoltaics is the science that develops the direct conversion of solar radiation into electricity. In order to make solar cells more common, one has to decrease their price to make them more competitive on the energy market. It can be achieved by increasing their efficiency or by reducing production costs. Thin film silicon solar cells fit in the second trend – reducing costs of production, by means of reducing the amount of material needed to fabricate solar cells.

Silicon has a low absorption coefficient due to an indirect band gap structure, therefore it requires a thicker absorber layer to effectively absorb incoming light [2]. Since thickness of thin film silicon solar cells varies from a few nanometers to tens of micrometers, increasing the optical thickness of an absorber should be taken into account in order to improve its performance. There are many ways to achieve it, *e.g.* texturisation of a front or rear side of a solar cell [3]. Other way is to fabricate a back side mirror [4, 5] in order to enhance the solar cell response for a low energy photons, which would otherwise go through the solar cell without absorption.

This work presents a comparison of a thin film silicon solar cell which contains a rear side dielectric mirror designed to reflect light from the wavelength range 700–1200 nm with a solar cell with similar structure except the dielectric mirror. That kind of approach allows us to determine the impact of the dielectric mirror on the solar cells performance.

2. Experimental details

2.1. Experimental methods

Vapor phase epitaxy (VPE) was chosen as a method to deposit a silicon active layer [6]. This method enables to fabricate the whole solar cell structure *in situ* (Fig. 1). The constructed solar cells had 40 μm *n*-type absorber with phosphorous as a *n*-type dopant, 3 μm *p*-type emitter with boron as a *p*-type dopant and 300 nm thick n^+ front side field (FSF). The *p*-type (100) monocrystalline Si (c-Si) seed substrate had a double porous layer on the top in order to detach active layer after VPE deposition [7]. In order to obtain a monocrystalline layer on the porous Si, restructuration process has to take place. Prior to epitaxy, the sample was annealed at 1100°C under hydrogen atmosphere

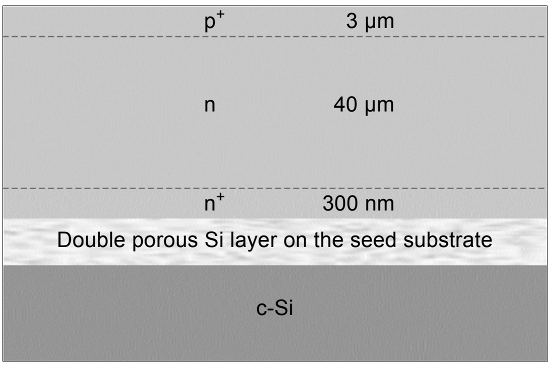

Fig. 1. Structure of an active layer after VPE growth.

during 5–15 minutes. This process closes the silicon pores on a low porosity layer and leads to the formation of a very thin monocrystalline layer at the surface [8].

After restructuration, the growth of an epitaxial layer could be initiated. At the same time, due to high temperature, a high porosity layer is being degraded but remained mechanically stable until the detachment step.

In order to increase the absorbance of the active layer in the 700–1200 nm wavelength range, a back side mirror was developed [9, 10].

Dielectric mirror was deposited using plasma enhanced chemical vapor deposition (PECVD) reactor (Fig. 2).

Mirror side is the rear side of the solar cell; hence, in order to enable an electrical contact and good bonding to a supporting substrate, holes in SiN_x/SiO_x mirror had to be made. It was achieved using a photolithography technique. A 500 nm thick aluminum layer was deposited on the top of the dielectric mirror. This metallic layer has two tasks: it is a rear electrical contact and it enables to bond an active layer to a low-cost sintered silicon supporting substrate. After the bonding procedure, a detaching step enables to separate the active layer from the seed substrate (Fig. 3).

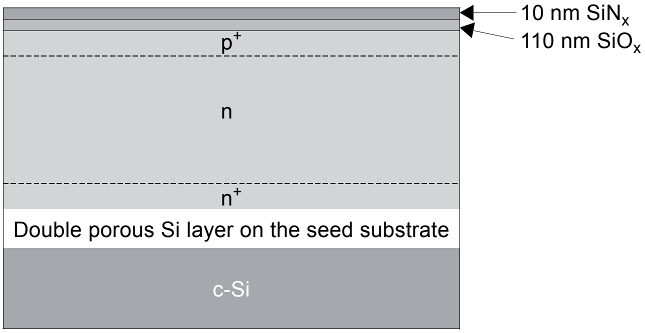

Fig. 2. Structure of an active layer after dielectric mirror deposition, prior to detachment.

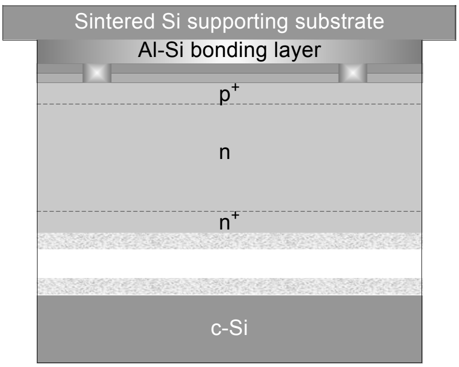

Fig. 3. Bonding and detaching step.

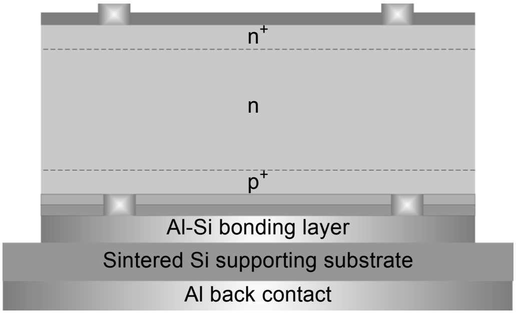

Fig. 4. Final structure of the analyzed solar cells.

After additional cleaning, the crystal seed substrate can be reused in a next epitaxy process. The active layer, bonded and cleaned from remaining porous silicon, may be subjected to further solar cell production process.

The following step was an antireflective coating (ARC) deposition to reduce reflection at a front side of the solar cell. SiN_x layer of 70 nm thick deposited in PECVD reactor, not only lowers reflection from the front surface but also ensures good passivation of the silicon surface.

After opening the ARC by means of photolithography and HF etching, front metallic contact (Ti/Pd/Ag) was deposited by evaporation.

The final structure of fabricated solar cells is shown in Fig. 4.

At the same time, a reference sample was made with the same structure but without a dielectric mirror.

2.2. Examination methods

Computer simulation with IMD software [11] has been performed in order to establish the reflectance from the back surface of the solar cell in the wavelength range between 700 and 1200 nm. Four different cases were taken into account:

– Single SiN_x layer as a dielectric mirror;
– Single SiO_x layer as a dielectric mirror;
– Single pair of SiO_x/SiN_x layer as a dielectric mirror;
– Multiple pairs of SiO_x/SiN_x layer as a dielectric Bragg mirror.

The results of these simulations enabled to select the optimal dielectric structure in terms of reflection and economic issues.

The constructed solar cells were tested under STC (standard test conditions: cell temperature of 25°C, irradiation of 1000 W/m^2, air mass 1.5) in order to establish the main electrical parameters characterizing the given semiconductor structure. Parameters such as short circuit current density J_{sc}, open circuit voltage V_{oc}, and fill factor (FF) were extracted from *I-V* characteristics.

Moreover, external quantum efficiency (EQE) was measured to provide additional information concerning the back side dielectric mirror performance.

3. Results and discussion

IMD software enables to model the optical properties of multiple thin films. The parameter which had to be taken into account in order to optimize the dielectric mirror was the reflection from the Si/dielectric mirror/Al interface. As a dielectric material, the PECVD deposited SiN_x and SiO_x were chosen. Input data for simulations containing optical indexes of the given materials were measured by ellipsometry and introduced to IMD software. Four different cases were considered, the results of simulations are presented in Figs. 5–8.

Maximal reflectance from the interface of $Si/SiO_x/Al$ layer (Fig. 5) is given for 110 nm SiO_x layer and it varies from 0.7 to 0.84 in the considered wavelength range.

For the interface of $Si/SiN_x/Al$ layer (Fig. 6), maximal reflectance is given for 70 nm thickness of SiN_x layer and it varies from 0.58 to 0.76 in the considered wavelength range.

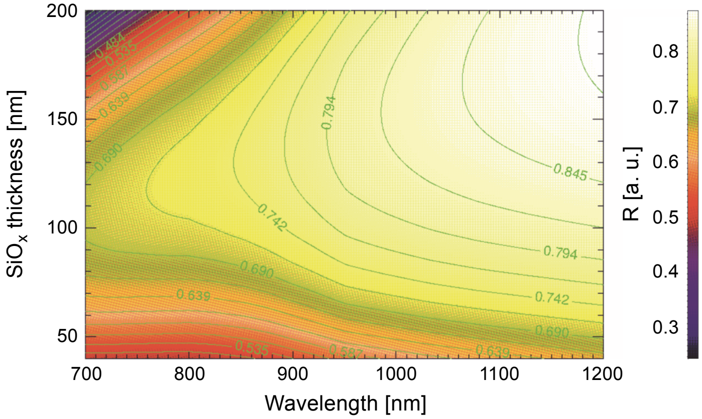

Fig. 5. Reflectance from the interface of silicon and one SiO_x layer, with Al on the backside.

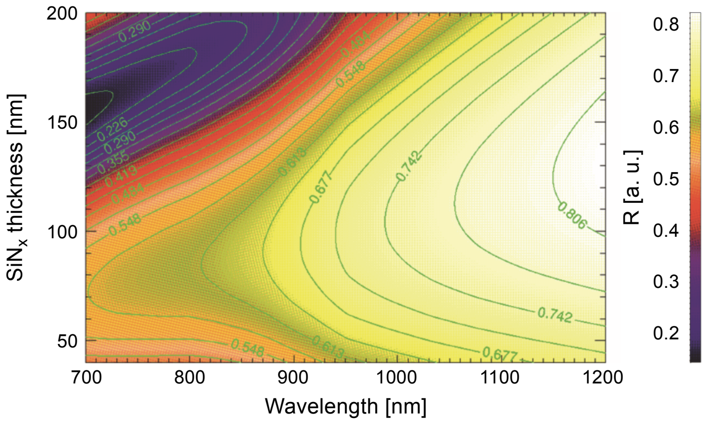

Fig. 6. Reflectance from the interface of silicon and one SiN_x layer, with Al on the backside.

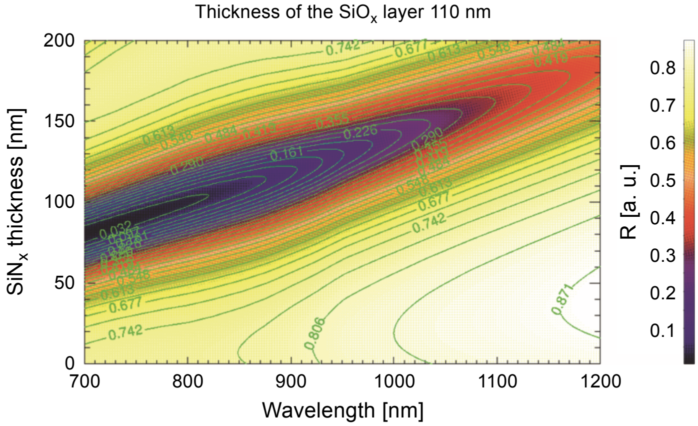

Fig. 7. Reflectance from the interface of silicon and one period of SiN_x/(110 nm SiO_x) layer, with Al on the backside.

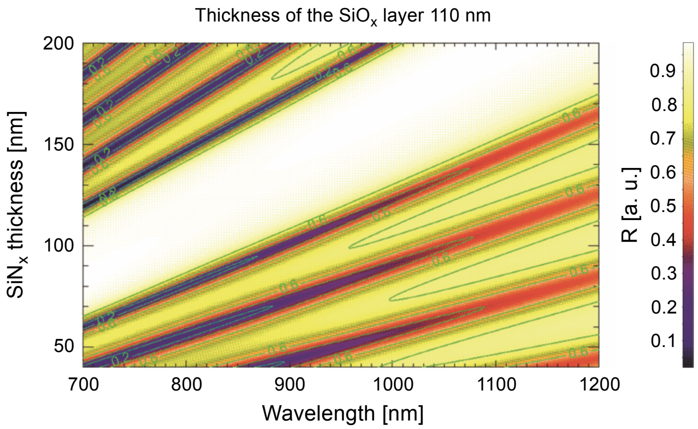

Fig. 8. Reflectance from the interface of silicon and seven periods of SiN_x/(110 nm SiO_x) layer, with Al on the backside.

Maximal reflectance from the interface of Si/SiO_x 110 nm/SiN_x/Al layer (Fig. 7) is given for 10 nm of SiN_x layer and it varies from 0.74 to 0.88 in the considered wavelength range.

Maximal reflectance from the interface of Si/7(SiO_x 110 nm/SiN_x)/Al layer (Fig. 8) is given for thickness of 110 nm of SiN_x layer and it varies from 0.2 to 0.99 in the considered wavelength range. The maximal reflectance is much higher comparing to the previous cases, but at the same time, the width of the high reflectance area in terms of wavelength is narrow comparing to less complex structures. Considering this fact, the complexity, costs and time of producing a Bragg mirror with 7 periods, it can be concluded from the simulations that the most suitable dielectric mirror is the 110 nm thick SiO_x with 10 nm SiN_x layer.

These results were used to fabricate thin film, silicon solar cells.

T a b l e. Main electrical parameters of the examined solar cells.

Sample	V_{oc} [mV]	J_{sc} [mA/cm^2]	FF [%]
Solar cell with the mirror	558	23	61.2
Solar cell without the mirror	547	19.4	63.3

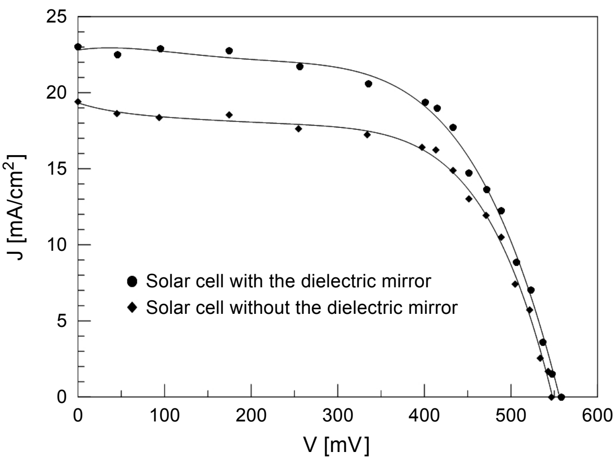

Fig. 9. The *I-V* characteristics of a solar cell with a dielectric mirror and reference sample.

The solar cells were tested under STC in order to establish the main electrical parameters characterizing the given semiconductor structure. The results are given in the Table and Fig. 9.

While analyzing the *I-V* characteristics (Fig. 9), it can be noticed that the open circuit voltage (V_{oc}) and fill factor (FF) are not changing in a significant way (see the Table). While V_{oc} is the measure of the amount of recombination in the solar cell, the same values for both solar cells mean that the qualities of the active areas of both samples are comparable – they have the same recombination rate.

Parasitic resistances (R_s – series resistance, R_{sh} – shunt resistance) have a significant influence on the shape of the *I-V* curve since FF is not changing. One can conclude that also parasitic resistances are comparable in the examined solar cells.

The main difference between the solar cell with the dielectric mirror and the reference sample is the value of the short circuit current density J_{sc} – as seen in Fig. 9 and the Table. The difference reaches 18.5% in favor of the solar cell with the dielectric mirror. Short circuit current is strictly connected to the number of absorbed photons. Since the solar cells have the same semiconductor structure, they are made with the same material during the same process. Analyzing values of the J_{sc}, one can conclude that the back side dielectric mirror reflects photons, which in other case would pass through the solar cell without absorption.

Another performed examination was the external quantum efficiency (EQE) shown in Fig. 10.

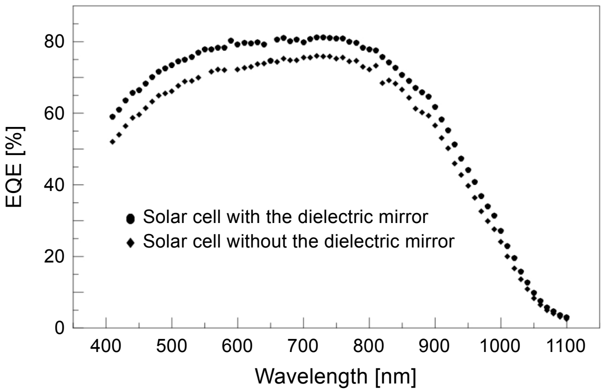

Fig. 10. External quantum efficiency of the examined solar cells.

The quantum efficiency is the ratio of the number of collected photons to the number of photons of given energy that reached the solar cell surface. The difference visible in Fig. 10 shows that there are more photons that are absorbed in the active layer in the solar cell with the dielectric mirror. That means that the dielectric mirror reflects additional photons in the front surface direction what increases collection probability.

4. Conclusions

The influence of the back side dielectric mirror on the back *p*-type emitter solar cell performance was studied. In order to increase the reflectance from the back side mirror in the wavelength range 700–1200 nm, computer simulations have been performed by means of IMD software enabling to simulate optical properties of thin films. According to the results, taking into account reflectance, complexity and economical aspects, the best dielectric mirror was: 110 nm of SiO_x/10 nm of SiN_x PECVD deposited on a p^+ back side silicon emitter (Fig. 2). This result was introduced to further solar cell fabrication process. The active layer of examined solar cells was deposited using vapor phase epitaxy. The final structure of the solar cell is shown in Fig. 4. A reference sample without dielectric mirror was also constructed.

In order to compare and analyze the influence of the dielectric mirror on solar cell performance, *I-V* characteristics and EQE were measured. Electrical parameters extracted from *I-V* curve clearly show that the back side dielectric mirror has a positive influence on the thin solar cell performance. The parameter that is directly connected with the number of collected photons is a short circuit current density J_{sc} and the difference between these parameters reaches 18.5% in favor of the solar cell with the dielectric mirror. Higher J_{sc} means higher number of photons collected, which in turn means higher reflection from the back dielectric mirror.

External quantum efficiency curve (Fig. 10) also confirms this conclusion – in the solar cell with the dielectric mirror there are more photons collected in the active layer.

Carried out analysis shows that the VPE method based on the reusable monocrystalline silicon seed substrate is an efficient method to produce thin film, monocrystalline silicon solar cells. Moreover, introducing the described dielectric mirror on the back side of the solar cell is an effective way to increase photon collection probability. So, combining the VPE process with porous silicon properties along with a carefully designed back side mirror can be an innovative and interesting method to produce thin film silicon solar cells.

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