

Anti-reflective microcrystalline silicon oxide p-layer for thin-film silicon solar cells on ZnO

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ABSTRACT

As a result from the development of silicon thin-film solar cells that had been conducted at Applied Materials over the last few years, we present a new kind of microcrystalline silicon oxide (μ c-SiO_x:H) based p-layer for the application in amorphous/microcrystalline (a-Si:H/ μ c-Si:H) tandem solar cells on ZnO substrates. The refractive index of this p-layer can be adjusted in the range 2–3.5 and therefore serves as a refractive index matching layer between ZnO ($n \sim 2$) and silicon ($n \sim 4$). By applying such a layer the reflection of solar cells can be reduced to 3%. This results in a significant short circuit current increase in thin-film solar cells. As a follow up to the recently published results of large area thin film silicon modules by us [1,2], we describe in this paper in detail the material properties of this new silicon oxide p-layer, the optimization of electrical and optical properties in solar cells and also the impact on the light induced degradation of a-Si/ μ c-Si tandem junction cells.

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1. Introduction

One of the most direct approaches to increase the efficiency of thin film solar cells is to increase the cell current by allowing more photons to enter into the active absorber layers. This can be achieved by

- i. Reducing the reflection loss at the interfaces of glass/TCO and TCO silicon absorbers and
- ii. reducing the absorption loss of the TCO and the p-layer.

Several approaches to minimize these losses were reported in the literature, e.g. by introducing an intermediate layer between the TCO and the p-layer. Often sputtered doped TiO₂ is used as such an index-matching layer [3,4]. However, this often results in series resistance losses of the cells due to the low conductivity and the difficulty to implement such a layer in the production sequence. In particular if sputter-etched ZnO [5] is used this requires an additional sputter process. Another approach which is reported in literature is the use of μ c-SiC [6]. With such layers very high cell currents of > 29 mA could be achieved with μ c-Si single junction cells [7]. However, the reported deposition rates for μ c-SiC are low and so far could only be produced by HWCVD, which makes it again difficult to include such layers in the production of large area modules.

In order to avoid the disadvantages of these approaches we have developed a new p-layer based on μ c-SiO_x (μ c-SiO_x(p):H). Promising results have been reported by other groups using a similar p-type layer consisting of microcrystalline or nanocrystalline morphology [8–13]. In this study we demonstrate in detail a newly developed p-layer stack applied on sputter-etched ZnO for large area application. In order to enhance the performance of amorphous and micromorph thin film silicon solar cells on ZnO substrates, the silicon oxide p-layer stack has to fulfill certain requirements:

- The p-layer has to form a good electrical contact with the front electrode.
- Furthermore it has to build up the electric field for the PIN device.
- The light in-coupling has to be maximized.
- The absorption loss has to be minimized.

Balancing these apparently contradicting requirements is one of the key challenges for the development of high efficiency amorphous silicon based solar cells. Using μ c-SiO_x based p-layers can help to fulfill these requirements: the refractive index can be tuned in the range 2–3.5 (at a wavelength of 500 nm). The absorption is significantly lower than for a-SiC and the conductivity can be high.

Such material can be produced in a standard PECVD equipment in large areas because the process is very similar to the μ c-Si p-layers and to μ c-SiO_x based interlayer materials. In single and

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tandem junction silicon solar cells we use a triple p-layer stack consisting of (Fig. 1):

- A microcrystalline $\mu\text{-Si(p):H}$ layer with a thickness of few nanometers. Although it has a high refractive index and acts therefore as an optical barrier, the microcrystalline p-layer is needed in order to provide a good contact to the crystalline and textured ZnO:Al.
- A microcrystalline silicon oxide p-layer ($\mu\text{-SiO}_x\text{(p):H}$) with a thickness of the same magnitude as the $\mu\text{-Si:H(p)}$ layer. The refractive index is in between the refractive index of the front contact (ZnO:Al) and the amorphous silicon absorber. It works as an antireflection layer due to the better refractive index matching.
- A silicon oxide p-layer with low crystallinity ($\text{nc-SiO}_x\text{(p):H}$) with again a similar thickness as the $\mu\text{-Si(p):H}$ layer. This antireflection layer with reduced crystallinity is needed for providing a good contact to the a-Si(i):H layer. Furthermore the refractive index is in between the refractive index of the $\mu\text{-SiO}_x\text{(p):H}$ and of the a-Si(i):H layer. Thus graded crystallinity and refractive index matching from the $\mu\text{-Si(p):H}$ layer to the a-Si(i):H layer is provided.

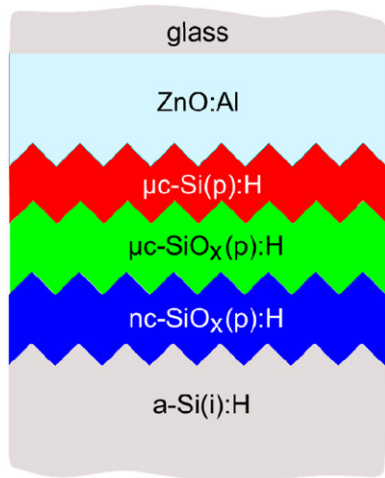


Fig. 1. The p-layer stack used in single and tandem junction devices with the adjacent ZnO:Al on glass (top) and the a-Si:H absorber (bottom).

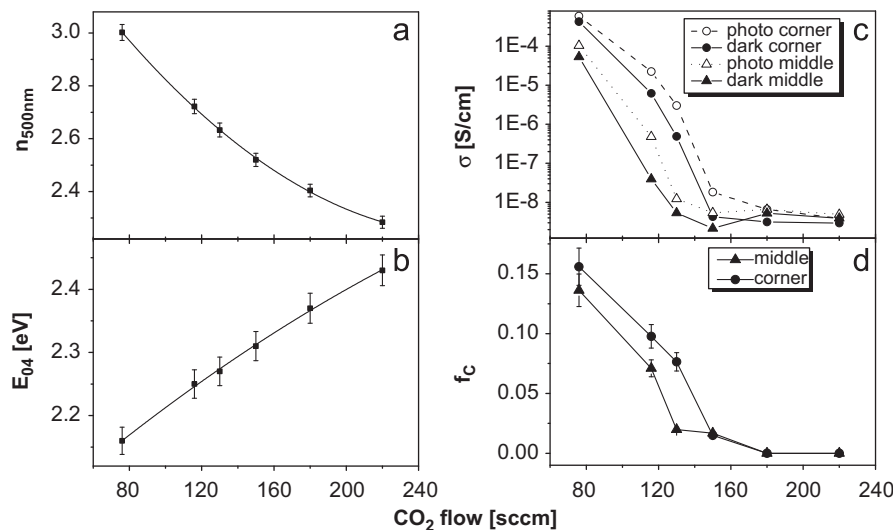


Fig. 2. Single layer properties like refractive index in (a) band gap E_{04} , (b) conductivity σ and (c) crystalline fraction f_c (d) of the $\mu\text{-SiO}_x\text{(p):H}$ as a function of CO_2 gas flow.

2. Experimental details

In the SunFabTM Technology Center (SFTC) Gen5 modules ($1.1 \times 1.3 \text{ m}^2$) can be produced on commercial substrates as well as on in-house produced ZnO substrates. The ZnO is either produced in a horizontal Gen5 laboratory coater [5] or in a prototype Gen8.5 production tool [14]. The silicon layers are deposited in a multi-chamber CVD cluster tool produced by Applied Materials flat panel display division AKT. All CVD layers are made using standard 13.56 MHz PECVD processes. The deposition rates for the i-layers were around 3 Å/s for the top cell and ~ 5 Å/s for the bottom cells. The SiO_x -layers were made by adding CO_2 to the process gas, trimethylboron (TMB) and phosphine diluted in hydrogen was used to make the doped layers.

As back contact a sputtered ZnO/Ag stack was used.

The same equipment is also used to make small cells (1 cm^2), defined by laser scribing.

The solar cells were measured on a class A large area flasher by HALM. Light soaking was carried out at 50 ± 5 °C and a class C AM1.5 light source under open circuit conditions.

Single layers were deposited on large area glass substrates. The refractive index and the optical absorption were determined by reflection and transmission mapping of the substrates. The crystallinity of the films was measured by Raman spectroscopy using a 473 nm excitation wavelength and calculated by fitting the Raman spectra by 5 components representing the different phonon modes [15]. In-plane conductivity of the layers was measured with sputtered coplanar Al contacts.

3. Material results

The influence of the CO_2 gas flow at $\mu\text{-Si}$ p-layer on various material properties is shown in Fig. 2. By increasing the CO_2 gas flow the refractive index can be reduced significantly and the band gap E_{04} increases up to 2.43 eV. The absorption coefficient α is, depending on the energy of incident light, up to 60% lower for the microcrystalline silicon oxide p-layer ($\mu\text{-SiO}_x\text{(p):H}$) than for the $\mu\text{-Si(p):H}$ layer (Fig. 3). As shown in Fig. 4 the thickness uniformity and deposition rate of the silicon oxide p-layer improve by using more CO_2 . Nevertheless one has to consider that above a certain CO_2 flow (here 150 sccm) the $\mu\text{-SiO}_x\text{(p):H}$ gets fully amorphous, which causes a drastic conductivity drop of five orders of magnitude down to 10^{-8} S/cm . From the single

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