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# Microcrystalline silicon–oxygen alloys for application in silicon solar cells and modules

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ABSTRACT

Microcrystalline silicon oxide (μc-$SiO_x$:H) alloys prepared by plasma enhanced chemical vapor deposition (PECVD) represent a versatile material class for opto-electronic applications especially for thin-film and wafer based silicon solar cells. The material is a phase mixture of microcrystalline silicon (μc-Si:H) and amorphous silicon oxide (a-$SiO_x$:H). The possibility to enhance the optical band gap energy and to adjust the refractive index over a considerable range, together with the possibility to dope the material p-type as well as n-type, makes μc-$SiO_x$:H an ideal material for the application as window layer, as intermediate reflector (IR), and as back reflector in thin-film silicon solar cells. Analogously, μc-$SiO_x$:H is a suitable material for p- and n-type contact layers in silicon hetero junction (SHJ) solar cells. The present paper gives an overview on the range of physical parameters (refractive index, optical band gap, conductivity) which can be covered by this material by variation of the deposition conditions. The paper focuses on the interdependence between these material properties and optical improvements for amorphous silicon/microcrystalline silicon (a-Si:H/μc-Si:H) tandem solar cells prepared on different substrates, such as Asahi (VU) and sputtered ZnO:Al. It gives a guideline on possible optical gains when using doped μc-$SiO_x$:H in silicon based solar cells. As intermediate reflector in a-Si:H/μc-Si:H tandem cells μc-$SiO_x$:H leads to an effective transfer of short circuit current generation from the bottom cell to the top cell resulting in a possible thickness reduction of the top cell by 40%. Within another series of solar cells shown in this paper a short circuit current density of 14.1 mA/cm² for an a-Si:H/μc-Si:H tandem solar cell with a μc-$SiO_x$:H intermediate reflector is demonstrated. A SHJ solar cell on a flat (non-textured) wafer using p- and n-type doped μc-$SiO_x$:H contact layers with an effective area efficiency of 19.0% is also presented.



## 1. Introduction

During recent years, microcrystalline silicon oxide (μc-$SiO_x$:H) has established itself as a key material for functional layers in thin-film silicon solar cells and modules. It is a mixed phase material of an oxygen rich amorphous silicon oxide (a-$SiO_x$:H) phase and a doped microcrystalline silicon (μc-Si:H) phase. The tunability of its refractive index and of its optical band gap combined with a suitable conductivity as p-type and n-type doped material enables its application as a replacement for the conventional doped layers for amorphous (a-Si:H) as well as microcrystalline (μc-Si:H) cells in thin-film silicon tandem solar cells. The record of proven benefits starts with its application as an intermediate reflector (IR) between the two cells [1–6]. Due to its low refractive index $n$ a portion of the light is reflected back into the a-Si:H top cell. Microcrystalline silicon oxide has also proven its capabilities to be beneficial for the use as n-layer for the microcrystalline silicon (μc-Si:H) single solar cell [7], not just improving the optical performance of the back reflector [6,8], but also improving the electrical properties of the μc-Si:H cell [9,10]. In addition doped μc-$SiO_x$:H improves the performance when using it as window layer in amorphous silicon/microcrystalline silicon (a-Si:H/μc-Si:H) tandem solar cells on ZnO coated substrates [11,12], especially due to its adaptable refractive index between Si and ZnO yielding an improved in-coupling of the light. An additional field of application are silicon heterojunction (SHJ) solar cells where μc-$SiO_x$:H can serve as a beneficial contact layer material due to its favorable combination of electrical and optical properties. Partial implementation as emitter [13] or back contact material [14] and on both sides of the wafer as emitter and back contact [15] in SHJ solar cells has already been reported.

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For all these applications the required optical material properties are a high optical band bap ($E_{04}$) (defined as the photon energy where the absorption coefficient $\alpha$ equals $10^4$ cm$^{-1}$) to avoid parasitic absorption and adaptable refractive index, preferably $n<3$. The required electrical conductivities are above $2\times10^{-6}$ S/cm (for thicker IR $1\times10^{-5}$ S/cm) to achieve a low series resistance ($R_s$) [3,16], and below $2\times10^{-1}$ S/cm aiming a high shunt resistance ($R_{sh}$) (i) for shunt-quenching of cracks in the absorber layer [6] and (ii) for the module interconnection [17]. When interconnecting the cell stripes to a module a conductivity of the window layer above $2\times10^{-1}$ S/cm would electrically connect the front TCO of neighboring cell stripes and thus lead to a shunt. The increase in series resistance $R_s$ will be determined by the conductivity in growth direction of the µc-SiO$_x$:H and the decrease in shunt resistance $R_{sh}$ by its conductivity in lateral direction. An overview of the physical layer properties aimed for is given in Table 1. The conductivity limits are estimated as described in the device structure section. In addition, a function of µc-SiO$_x$:H as a nucleation layer for microcrystalline silicon growth might be desired [18].

The doped µc-SiO$_x$:H applications make use of the high electrical conductivity of the doped microcrystalline silicon µc-Si:H phase and the optical properties of the amorphous silicon oxide (a-SiO$_x$:H) phase [3,16,19,20]. A small fraction of highly conductive doped µc-Si:H in the a-SiO$_x$:H layer already provides a sufficient conductivity above $10^{-5}$ S/cm. This two-phase mixture allows decoupling partly the optimization task for the optical and electrical properties by adjusting the deposition parameters which deliver the appropriate mixture of the two phases and, unlike other material deposition processes for example sputtering; its in-situ deposition is fully compatible to the industrial production of thin-film silicon and SHJ solar cells.

The present study focuses on our recent developments of doped µc-SiO$_x$:H material and its successful application in thin-film silicon single junction and tandem solar cells, modules, and silicon hetero junction solar cells. Relationships between the material properties and the performance of the solar cells are discussed.

## 2. Device structures

The device structures of the a-Si:H/µc-Si:H tandem solar cells and SHJ solar cell with integrated p- and n-type doped µc-SiO$_x$:H material is shown in Figs. 1 and 2, respectively. The a-Si:H top cell's absorber layer which has typically a high optical band gap of $E_{04}=1.9$ eV is the first cell when describing the tandem cell from the light incident side. The top cell mostly absorbs the light with a short wavelength of up to 750 nm. The amount of light absorbed and consequently the generated current depends strongly on the a-Si:H i-layer thickness, carrier collection efficiency and the optical performance of the cell. The optical performance can be understood as a term for advantageous in-coupling, reduced parasitic absorption and improved trapping of the light. The µc-Si:H bottom cell absorbs the light with a longer wavelength of up to 1100 nm. Since

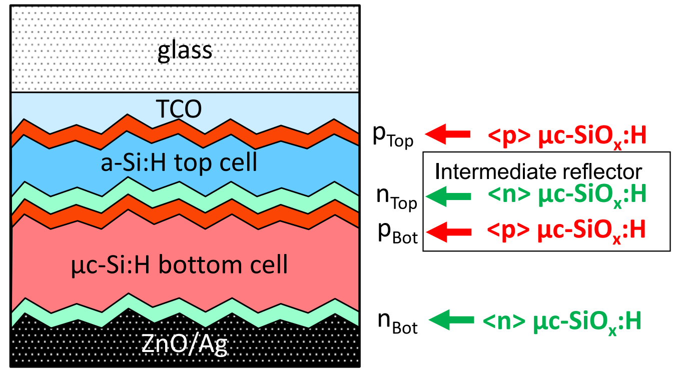


**Fig. 1.** A schematic drawing of the a-Si:H/µc-Si:H tandem solar cell. The tandem cells have a µc-SiO$_x$:H window layer ($p_{Top}$), intermediate reflector ($n_{Top}$ and/or $p_{Bot}$) and/or µc-SiO$_x$:H back contact ($n_{Bot}$). The tandem solar cells presented in the paper have doped µc-SiO$_x$:H layers within the $n/p$ junction acting as intermediate layer with a thickness of $50\pm10$ nm.

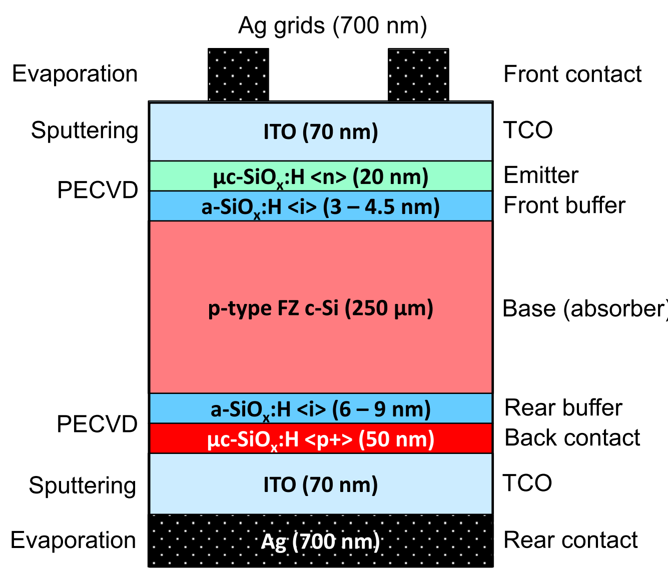


**Fig. 2.** Schematic illustration of the SHJ solar cell structure with PECVD grown emitter, back contact and buffer layers on flat p-type wafer covered with sputtered TCO and thermally evaporated silver.

**Table 1**
Targeted physical layer properties for the proposed applications in silicon solar cells. The applications of layers described in the table are sketched in Figs. 1 and 2. The limits of the conductivity were calculated as described later on. The ∗ are indicating that the upper limit of the conductivity for this layer is not known. If the conductivity for these layers is higher as for doped ZnO [45] an additional laser scribing step would be necessary.

| Applied in | as…-layer/Ref. | $E_{04}$ [eV] | $n$ | $\sigma_{\text{low limit}}$ [S/cm] growth direction | $\sigma_{\text{high limit}}$ [S/cm] lateral direction | Further issues/benefits |
|---|---|---|---|---|---|---|
| µc-Si:H single junction | Window [4,7] | $>2.2$ | $\sim2.5$ | $2\times10^{-6}$ | $2\times10^{-1}$ | TCO/window layer tunnel contact; growth compatible with TCO; nucleation layer for ⟨i⟩ µc-Si:H |
| a-Si:H/µc-Si:H tandem | $p_{Top}$ [7,11,12] | $>2.2$ | $\sim2.5$ | $2\times10^{-6}$ | $2\times10^{-1}$ | TCO/p tunnel contact; growth compatible with TCO |
| | $n_{Top}$ [2,3,6] | $>2.2$ | $<2.5$ | $1\times10^{-5}$ | ∗ | n/p tunnel contact; nucleation layer for p-layer |
| | $p_{Bot}$ [4] | $>2.2$ | $<2.5$ | $1\times10^{-5}$ | ∗ | n/p tunnel contact; nucleation layer for i-layer |
| | $n_{Bot}$ [6,8–10] | $>2.2$ | $<2.5$ | $2\times10^{-6}$ | | n/TCO tunnel contact layer |
| SHJ | $n$ window [13,15] | $>2.2$ | $\sim2.5$ | $2\times10^{-6}$ | | Tunnel contact TCO/n layer |
| | $p$ back contact [14,15] | $>2.2$ | $<2.5$ | $2\times10^{-6}$ | | |

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