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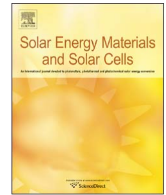

# Influence of anodic bonding on the surface passivation quality of crystalline silicon

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ABSTRACT

Developing new materials with improved thermal stability is very important as far as the passivation and processing of crystalline silicon solar cells is considered. In this work, we studied two types of hydrogenated silicon based materials (hydrogenated amorphous silicon oxide and hydrogenated microcrystalline silicon oxide) and compared them to the well-established hydrogenated amorphous silicon. We demonstrate the thermal robustness of hydrogenated silicon oxide under anodic bonding conditions (250 °C, 1000 V). The microstructural and composition evolution of passivation layers under anodic bonding was characterized by Fourier transform infrared spectroscopy, high resolution transmission electron microscopy, annular dark-field scanning transmission electron microscopy, energy-dispersive X-ray spectroscopy and secondary ion mass spectrometry. We found that oxygen can inhibit the degradation of the passivation quality under anodic bonding by suppressing the localized interfacial crystallization and re-passivating the interface. When applied to thin-film crystalline silicon solar cells, the excellent thermal robustness of hydrogenated microcrystalline silicon oxide allows to keep a good passivation to the ultrathin c-Si absorbers (1 µm).

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## 1. Introduction

An excellent surface passivation is crucial in order to achieve high efficiency crystalline silicon c-Si solar cells, whatever is the design. To passivate the surface of a c-Si wafer, various materials can be used including aluminum oxide ($AlO_x$) deposited by atomic layer deposition (ALD) [1], silicon oxide ($SiO_2$) obtained via thermal oxidation of c-Si at 1000 °C [2], silicon nitride ($SiN_x$) deposited via Plasma Enhanced Chemical Vapor Deposition (PECVD) at 300–400 °C [3], hydrogenated amorphous silicon (a-Si:H) deposited by PECVD at 200 °C [4–6] and hydrogenated amorphous silicon oxide (a-$SiO_x$:H) deposited by PECVD at 200–300 °C [7]. Among these passivation materials, a-Si:H is widely used due to its low deposition temperature and outstanding passivation quality [8,9].

Compared to the Si wafer solar cells, most ultrathin c-Si thin films require an additional process consisting of the transfer of the thin film from the parent wafer onto a foreign substrate (e.g. glass), to allow the re-utilization of the parent wafer. Two main methods can be used to transfer these c-Si thin films, namely, adhesive bonding [10,11] and anodic bonding [12,13], which is used to bond glass directly to either Si or metal. The advantage of anodic bonding is to avoid an intermediate layer which could interfere with the solar cell process [14]. However, anodic bonding can also introduce some limitations because the contamination from the alkali containing substrate and the high electric field (magnitude of up to $10^6$ V/cm [15]) and temperature required.

In this work, anodic bonding is used to transfer ultrathin c-Si thin films. During the transfer process via anodic bonding to glass (Corning 7740: Pyrex containing alkaline elements), a moderate temperature (250–400 °C) and elevated voltage (1000–2000 V) is applied to the sample. As far as the fabrication of solar cells is considered, a passivation layer was deposited on the bonding side prior to anodic bonding. Therefore, it is important to investigate and understand the influence of anodic bonding on the passivation quality, provided by a-Si:H, a-$SiO_x$:H and hydrogenated microcrystalline silicon oxide (µc-$SiO_x$:H). The passivation quality was accessed by Quasi-steady-state photoconductance (QSSPC) and Photoluminescence (PL). Fourier transform infrared (FTIR) spectroscopy was used to investigate the bonding configuration of a-Si:H and a-$SiO_x$:H. The microstructural evolution of these materials under anodic bonding was characterized by High Resolution Transmission electron microscopy (HRTEM) with the composition characterization by X-ray spectroscopy (EDS) recorded in a scanning transmission electron microscope (STEM) and Secondary Ion

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Mass Spectrometry (SIMS). Finally, we show proof-of-concept epitaxy free (epifree) c-Si thin film solar cells with the insertion of μc-$SiO_x$:H at rear side.

## 2. Passivation materials

Three types of hydrogenated materials: a-Si:H, a-$SiO_x$:H and n-μc-$SiO_x$:H deposited in a radio frequency (13.56 MHz) PECVD reactor [16] were studied. The deposition parameters are as shown in Table 1. The refractive index n and the extinction coefficient k obtained from fitting the spectroscopic ellipsometry measurements of a-Si:H, a-$SiO_x$:H and n-μc-$SiO_x$:H on c-Si wafers are presented in Fig. 1. The corresponding optical bandgaps $E_{04}$ of a-Si:H, a-$SiO_x$:H and n-μc-$SiO_x$:H are extracted to be 1.7 eV, 1.9 eV and 2.5 eV respectively based on the formula of Tauc Lorentz dispersion law [17]. With the increase of $CO_2$/$SiH_4$ ratio and plasma power, both n and k decrease significantly.

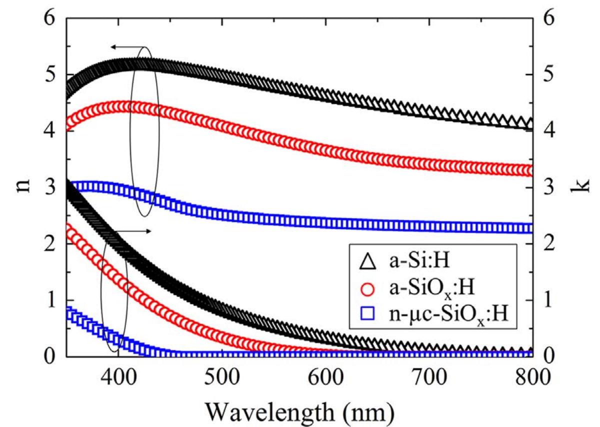


**Fig. 1.** n and k values as functions of the wavelength for a-Si:H, a-$SiO_x$:H and μc-$SiO_x$:H.

## 3. Results and discussion

### 3.1. Influence of anodic bonding on surface passivation quality

Let us first study the impact of anodic bonding on the surface passivation quality. Fig. 2 shows the evolution of the effective carrier lifetime as a function of the minority carrier density for various layers with different conditions: i) as-deposited, ii) annealed in bonder (EVG 520) at 250 °C (10 min) and iii) annealed at 250 °C under 1000 V for 10 min. Note that the values of lifetime were taken at the injection level of $1 \times 10^{15}$ $cm^{-3}$. The same type of c-Si wafers (Cz c-Si (111) n-type, 100 mm diameter, 255–305 μm, 3–5 Ω cm, polished at both sides) was used with a symmetrical deposition. In the case of a-Si:H, a bilayer stack was deposited at 200 °C with i (10 nm)/n+ (24 nm). For $SiO_x$:H, an i-a-$SiO_x$:H/n-μc-$SiO_x$:H stack was deposited with i-a-$SiO_x$:H (14 nm) at 200 °C and n-μc-$SiO_x$:H (40 nm) at 175 °C. The effective minority carrier lifetime was measured by QSSPC (Sinton). We can see from Fig. 2(a) that annealing of the a-Si:H layer stack at 250 °C (black hollow triangles in Fig. 2(a); 12.8 ms) does not affect the passivation quality as compared to the as-deposited one (black solid triangles in Fig. 2(a); 14.4 ms). However, when a 1000 V is applied at 250 °C, we observe a strong degradation of effective carrier lifetime (blue solid circles in Fig. 2(a); 3.6 ms) compared to the as-deposited state (blue hollow circles in Fig. 2(a); 20.6 ms). Interestingly, for the i-a-$SiO_x$:H/n-μc-$SiO_x$:H stack, although its initial lifetime (red hollow squares in Fig. 2(a); 6.3 ms) is not as high as in the case of a-Si:H, there is no degradation of the passivation quality after annealed at 250 °C under 1000 V (red solid squares in Fig. 2(a); 7.6 ms). Even more important, the absolute value of the effective lifetime after wafer bonding process is higher than in the case of a-Si:H passivation. A conclusion can be made that $SiO_x$:H is more tolerant to anodic bonding condition (temperature and voltage) as compared to a-Si:H. To investigate the influence of anodic bonding on the bonding configurations of a-Si:H and a-

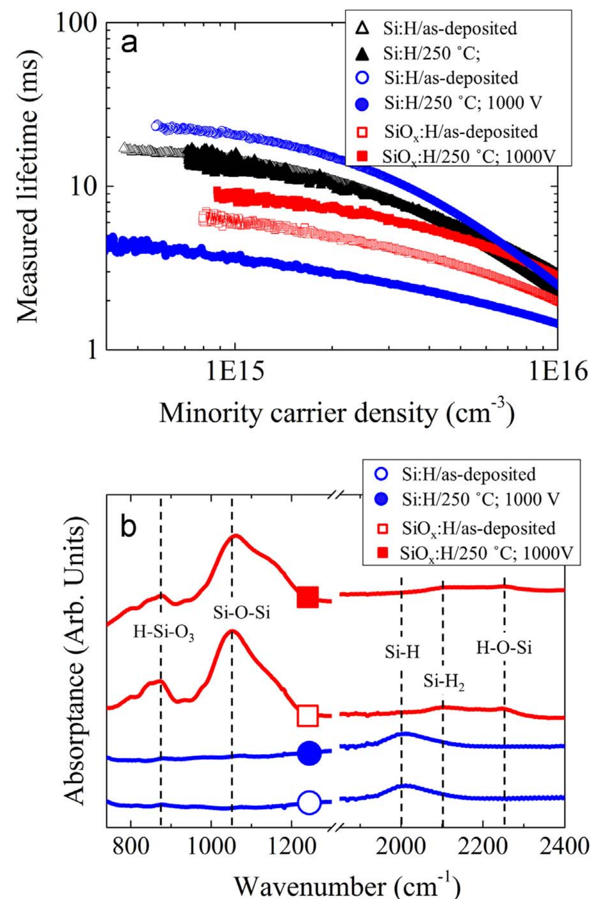


**Fig. 2.** (a) Minority carrier lifetime as a function of the minority carrier density upon anodic bonding for i/n+ a-Si:H and a-SiOx:H/n-μc-$SiO_x$:H passivated c-Si wafers. (b) FTIR spectra of i/n+ a-Si:H and a-SiOx:H/n-μc-$SiO_x$:H passivated c-Si wafers before and after anodic bonding.

**Table 1**
PECVD deposition parameters for a-Si:H, a-$SiO_x$:H and μc-$SiO_x$:H. (SCCM: Standard Cubic Centimeters per Minute). Note that n-μc-$SiO_x$:H and p-μc-$SiO_x$:H were deposited by adding 1 SCCM of $pH_3$ (1% in $H_2$) and 1 SCCM of TMB (1% in $H_2$), respectively.

| Materials | Temperature (°C) | Plasma power density ($mW/cm^2$) | Pressure (Torr) | $H_2$ (SCCM) | $SiH_4$ (SCCM) | $CO_2$ (SCCM) |
|---|---|---|---|---|---|---|
| **a-Si:H** | 200 | 5.7 | 0.05 | 0 | 50 | 0 |
| **a-$SiO_x$:H** | 200 | 5.7 | 0.07 | 0 | 40 | 10 |
| **μc-$SiO_x$:H** | 175 | 102 | 2.8 | 200 | 11 | 15 |

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