

## Letter

## Thin-film monocrystalline-silicon solar cells made by a seed layer approach on glass-ceramic substrates

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## ABSTRACT

Solar modules made from thin-film crystalline-silicon layers of high quality on glass substrates could lower the price of photovoltaic electricity substantially. One way to create crystalline-silicon thin films on non-silicon substrates is to use the so-called “seed layer approach”, in which a thin crystalline-silicon seed layer is first created, followed by epitaxial thickening of this seed layer.

In this paper, we present the first solar cell results obtained on 10- $\mu\text{m}$ -thick monocrystalline-silicon (mono-Si) layers obtained by a seed layer approach on transparent glass-ceramic substrates. The seed layers were made using implant-induced separation and anodic bonding. These layers were then epitaxially thickened by thermal CVD. Simple solar cell structures without integrated light trapping features showed efficiencies of up to 7.5%. Compared to polycrystalline-silicon layers made by aluminum-induced crystallization of amorphous silicon and thermal CVD, the mono-Si layers have a much higher bulk diffusion lifetime.

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## 1. Introduction

Solar modules made from thin-film crystalline-silicon layers of high quality on glass substrates could lower the price of photovoltaic electricity substantially. Almost half of the price of wafer-based silicon solar modules is currently due to the cost of the silicon wafers themselves. The use of thin crystalline-silicon films as the active material provides numerous advantages. First, compared to wafer-based cells, the silicon consumption can be minimized. Second, the high crystalline quality of the silicon layer should ensure a high cell-efficiency potential. Third, crystalline silicon has a demonstrated stable performance over time and irradiation. Finally, the knowledge about silicon wafer physics can be easily transferred and applied to crystalline-silicon thin films.

One way to create a crystalline-silicon thin film on a non-silicon substrate for solar cell applications is to use the so-called “seed layer approach”. The seed layer approach is a two-step process in which a thin crystalline-silicon seed layer is first created, followed by an epitaxial thickening of this seed layer. Recently, we made promising thin-film polycrystalline-silicon (pc-Si) solar cells by using aluminum-induced crystallization

(AIC) of amorphous silicon to obtain the seed layers and thermal chemical vapor deposition (CVD) for the epitaxial thickening [1]. Although high-temperature CVD restricts the type of substrates that can be used, it provides two main advantages compared to other techniques: it achieves the growth of high-quality epitaxial layers leading to enhanced electronic properties of the silicon absorber layers and, at the same time, it provides a deposition rate above  $1\ \mu\text{m}\ \text{min}^{-1}$ , which is an important parameter in view of achieving a high process throughput. With AIC in combination with thermal CVD, pc-Si cell efficiencies of up to 8.0% and 6.4% were reached on opaque alumina and transparent glass-ceramic substrates, respectively [1,2]. Although the AIC process enables the fabrication of pc-Si layers with large grains [3–6], the limited structural and electronic quality of the AIC seed layers was found to be one of the main cell-efficiency-limiting factors [7–9]. Higher cell efficiencies can therefore be obtained by improving the AIC seed layer quality or by using a different method to fabricate the seed layer. The use of a monocrystalline-silicon (mono-Si) seed layer instead of a polycrystalline-silicon seed layer would be of particular interest since it would enable simpler device processes, a higher process yield and a single-crystal-like efficiency due to the intrinsic higher quality of the material and the absence of grain boundaries.

In this paper, we present the first solar cell results obtained on 10- $\mu\text{m}$ -thick monocrystalline-silicon layers, which were made by a seed layer approach on transparent glass-ceramic substrates.

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Thin (001)-oriented monocrystalline-silicon seed layers were prepared on glass-ceramic substrates by Corning's proprietary process that consists of anodic bonding and an implant-induced separation [10]. These mono-Si seed layers were then epitaxially thickened at IMEC by thermal CVD and made into simple solar cell structures. The results of these first mono-Si solar cells are compared with polycrystalline-silicon solar cells on glass-ceramic substrates made by the AIC approach.

## 2. Monocrystalline-silicon seed layers on glass-ceramic substrates

In this work, monocrystalline-silicon seed layers were prepared on transparent glass-ceramic substrates. Since the thin seed layers will be epitaxially thickened by thermal CVD at temperatures above 1000 °C, the substrates used should be compatible with these high temperatures. We therefore chose to use Corning's spinel glass-ceramic (code 9664) substrates [11], which have a strain point of 910 °C and have a coefficient of thermal expansion (CTE) that matches the CTE of silicon. The fact that these substrates are transparent will allow the fabrication of thin-film solar cells in superstrate configuration, in which the light enters through the glass side of the cells. In a previous work, we already demonstrated that these spinel glass-ceramic substrates are compatible with epitaxial silicon deposition at temperatures as high as 1130 °C [2].

We created monocrystalline-silicon seed layers by transferring 300-nm-thin (001)-oriented monocrystalline-silicon layers onto glass-ceramic substrates using Corning's proprietary technology that is based on anodic bonding and implant-induced separation [10]. The transferred p- or n-type layers are then epitaxially thickened into monocrystalline-silicon absorber layers. This approach provides flexibility in the design of the device architecture. For instance, the epitaxial layer thickness and doping density can be adjusted to test various cell parameters. Fig. 1 is a schematic of this proprietary technology [12] in which a mono-Si thin film is transferred from a bulk wafer onto a glass substrate. First, the silicon wafer is implanted with hydrogen ions that penetrate the silicon substrate to a depth determined by the implant energy. After cleaning both the silicon wafer and the glass substrate, a prebond of the silicon and the glass is then achieved by bringing the surfaces into contact with each other, causing a local attraction to each other due to van-der-Waals forces. The prebonded silicon-glass then undergoes the anodic bonding procedure, which includes the simultaneous application of heat and a voltage. During the bonding process, the high electric field across the silicon and glass induces the negatively charged, non-bridging oxygen in the glass to migrate towards the silicon wafer and an anodic oxidation of the silicon takes place. At the same time, the positively charged network-modifier ions in the glass are forced away from the anode and begin to diffuse towards the cathode. These processes eventually lead to the formation of a

multi-layered structure consisting of the following: silicon, a thin layer of the electrochemically formed SiO<sub>2</sub>, a region that is devoid of mobile ions in the glass called the barrier layer, a region having a buildup of the network-modifier ions, and the remaining glass composite [10]. Moreover, the silicon exfoliates during the bonding process at a depth determined by the ion implant energy to yield a thin silicon film that is bonded onto the glass, and the remaining bulk silicon wafer. The final treatment consists of a polishing process to obtain the desired silicon surface roughness. In this paper, however, the mono-Si layers transferred to glass-ceramics were unpolished.

Corning's proprietary technology has already been successfully applied to obtain thin-film monocrystalline-Si layers on industry-standard EAGLE<sup>2000</sup>® glass for flat-panel display applications. From this Si-on-glass material, integrated CMOS devices of high quality have recently been presented [10,13]. In this paper, we show that Corning's Si-on-glass technology can also be used to obtain thin-film silicon solar cells on glass-ceramic substrates.

## 3. Experimental details

The epitaxial thickening of the mono-Si seed layers was realized in two different reactors: in a low-pressure chemical vapor deposition (LPCVD) system and in an atmospheric-pressure chemical vapor deposition (APCVD) system. The LPCVD system used is a batch-type system in which up to twenty 12.5 × 12.5 cm<sup>2</sup> wafers can be processed simultaneously. This system operates at low pressure (~1 mbar) and at a standard deposition temperature of 1000 °C. Silane (SiH<sub>4</sub>) is used as a precursor with H<sub>2</sub> as dilution gas and diborane (B<sub>2</sub>H<sub>6</sub>) as dopant gas. The silicon deposition rate is typically around 100 nm min<sup>-1</sup>. To limit the processing time, epitaxial layers with a total thickness of around 3 μm were grown in this system.

The APCVD system used is a single-wafer system that works with wafers of 8 in diameter. This system operates at atmospheric pressure and at a standard deposition temperature of 1130 °C. Trichlorosilane (HSiCl<sub>3</sub>) is used as the precursor with H<sub>2</sub> as dilution gas and diborane (B<sub>2</sub>H<sub>6</sub>) as dopant gas. The deposition rate is typically around 1.5 μm min<sup>-1</sup>. Layers with a p+/p structure were grown consisting of 2 μm p+ (~5 × 10<sup>19</sup> cm<sup>-3</sup>) and 8 μm p (10<sup>16</sup> cm<sup>-3</sup>). The p+ layers act as back surface field (BSF) and the p-type layers as absorber layers in the resulting solar cells.

Prior to introducing the mono-Si seed layers into the CVD reactors, contamination analyses were performed using total reflection X-ray fluorescence (TXRF) and secondary ion mass spectroscopy (SIMS) after annealing of the samples on top of mono-Si reference wafers at temperatures comparable to those used in the CVD reactors.

The defect density of the resulting epitaxial layers was checked by applying a Schimmel etch directly to the grown layers, after which the defects are visible by an optical or electron microscope [14].

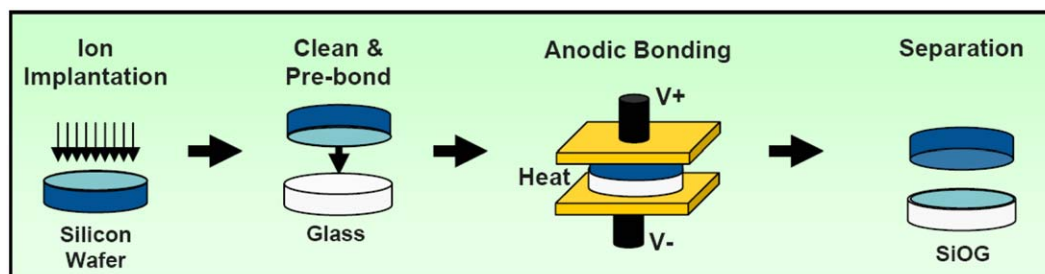


Fig. 1. Schematic drawing of Corning's Si-on-glass (SiOG) process (taken from Ref. [10]).

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