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# Amorphous silicon thin-film solar cells on glass fiber textiles

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ABSTRACT

In this contribution, amorphous silicon thin-film solar cells on textile glass fiber fabrics for smart textiles are prepared and the photovoltaic performance is characterized. These solar cells on fabrics delivered open circuit voltages up to 883 mV. This shows that shunt-free contacting of the solar cells was successful, even in case of non-planar fabrics. The short-circuit current densities up to 3.7 mA/cm$^2$ are limited by transmission losses in a 10 nm thin titanium layer, which was used as a semi-transparent contact. The low conductivity of this layer limits the fill factor to 43.1%. Pseudo fill factors, neglecting the series resistance, up to 70.2% were measured. Efficiencies up to 1.4% and pseudo efficiencies up to 2.1% were realized on textile fabrics. A transparent conductive oxide could further improve the efficiency to above 5%.



## 1. Introduction

Solar cells on textile substrates open new fields of application, for example, in the smart textiles sector [1]. The conversion of light into electricity in such devices permits an autonomous energy harvesting [2]. The solar cells can directly supply sensors or consumer electronics with power, or they can charge batteries. The long-term ambition of smart textiles is to integrate all necessary components for generation, transport, storage, and consumption of energy into textiles. A decentralized energy supply is essential for such isolated applications in textiles. A general overview of smart textiles is reported by Cherenack et al. [3].

A promising way for the integration of solar cells into textiles is to use fabrics or single fibers directly as substrates. Fig. 1 shows two different textile glass fiber fabrics that are used as substrates. The advantages of this glass fiber fabrics compared to conventional substrates (like glass panels, metal foils, or polymer foils) are the combination of high flexibility, light weight, temperature stability, and cost-effectiveness. These features render glass fiber fabrics perfect for substrates of thin-film solar cells and allow their integration into textiles.

On fabrics, different types of thin-film solar cells can be prepared. An overview of organic photovoltaic on single fibers [4,5] and fabrics is given in [6,7]. A fabric with interwoven metal wires and an organic solar cell on top is shown in [8,9]. Perovskite solar cells were also demonstrated on single metal fibers [10]. For textile applications in clothing, a high-quality encapsulation is needed to prevent degradation and discharge of toxic lead. Copper indium gallium diselenide solar cells were also produced on fabrics, but there the textile qualities are drastically reduced by the high-temperature stable resin required to smoothen the fabric [11]. A further alternative is to use hydrogenated amorphous silicon (a-Si:H) as photovoltaically active layer. This type of solar cells is well understood on glass substrates [12], but on fabrics, no results are reported. In the following work, we demonstrate such an a-Si:H solar cells on glass fiber fabrics. Polycrystalline silicon thin-film solar cells in single fibers [13] or on fabrics [14] are also under investigation.

The aim of this work is to prepare and characterize a-Si:H thin-film solar cells on textile glass fiber fabrics. Two different solar cell concepts are used as shown in Fig. 2. Metal wires could be interwoven through the glass fiber fabrics for current transport. A coating generates an encapsulated surface and provides local mechanical stability. On this, a transparent contact layer is deposited. A-Si:H is used as the photovoltaically active layer system. Finally, in the first concept, a reflective contact layer is deposited on top. In the second concept, the thickness of this metal layer is reduced to about 10 nm to get a semi-transparent contact. The solar cells are illuminated

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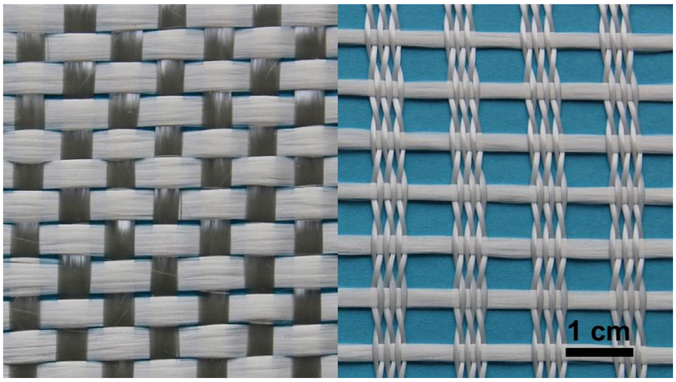


**Fig. 1.** Photographs of two different textile glass fiber fabrics used as substrates.

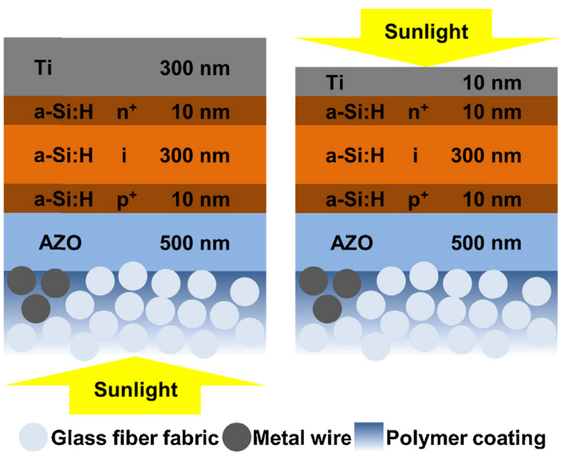


**Fig. 2.** Schemes of a-Si:H thin-film solar cells prepared on glass fiber fabrics in superstrate (left) and substrate (right) configuration.

through the glass fiber fabrics (superstrate configuration) or from the opposite side (substrate configuration).

## 2. Materials and methods

The schematic of the process flow is shown in Fig. 3. Glass fiber fabrics (Vitrulan Technical Textiles GmbH) are used as substrates as shown in Fig. 1. The fabrics consist of 400–800 single glass fibers with a diameter of 9 μm and 14 μm. Flat borosilicate float glass (Schott Borofloat 33) of $25 \times 25 \times 3.3\,mm^3$ in size is used as a substrate for comparison. In some cases, copper–tin metal wires with 70 μm diameter are interwoven into the glass fiber fabrics. The polymer coating consisting of butadiene styrene methacrylate is applied by dip coating. Then, a transparent contact layer of a 500 nm thick aluminum-doped zinc-oxide (AZO) is deposited by atomic layer deposition. The photovoltaically active layer system

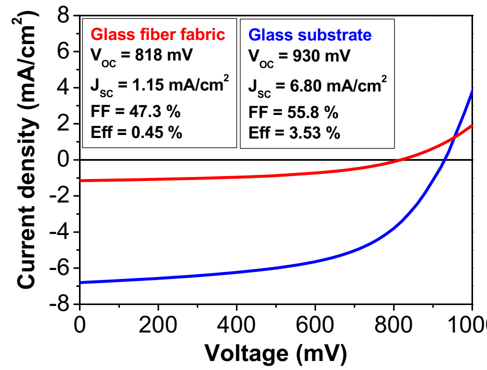


**Fig. 4.** *I–V* curves of solar cells on glass fiber fabrics and glass substrates in superstrate configuration.

of a-Si:H is deposited by plasma-enhanced chemical vapor deposition. The deposition rate is 10.7 nm/min and the heater temperature is 225 °C. Initially, a 10 nm a–Si:H ($p^+$-doped with 1.9% diborane in silane) is deposited. Then, a 300 nm a-Si:H without an intentional doping is deposited. Finally, another 10 nm a-Si:H ($n^+$-doped with 1.9% phosphine in silane) is deposited. In the first case, a 300 nm thick titanium reflective contact layer is deposited by electron beam evaporation. In this concept, the illumination is carried out through the glass fiber fabric (superstrate configuration) as shown in Fig. 2. In the second concept, the thickness of this layer is reduced to about 10 nm to realize a semi-transparent contact. So, it is possible to illuminate from the opposite side (substrate configuration) as shown in Fig. 2. The upper contact layer can be structured either already during metal deposition through a shadow mask or afterwards by laser ablation. The reported results were realized with the open fabric of Fig. 1 (right). The solar cells were prepared on the weft (horizontal) between the warp. The active areas of the solar cells are in the range of 1–10 $mm^2$ and they were measured by an optical microscope. The solar cells were electrically connected with the integrated metal wires. For the current–voltage (*I–V*) measurements, the solar cells were illuminated by a solar simulator (PET SS-80A) at air mass 1.5 and 1000 $W/m^2$. The pseudo *I–V* curve is calculated from the data of a suns-$V_{oc}$ measurement (Sinton Suns-Voc-150). For the optical characterization, a spectrometer (Perkin-Elmer Lambda 900) with an integrating sphere was used.

## 3. Results and discussion

### 3.1. *Superstrate configuration*

The conventional layer system of a-Si:H solar cells were successfully transferred from glass substrates onto glass fiber fabrics. Fig. 4 shows the *I–V* curve of such a solar cell. For comparison, solar cells on glass substrates were prepared under the same conditions of deposition and treatment. The *I–V* parameters of the solar cells

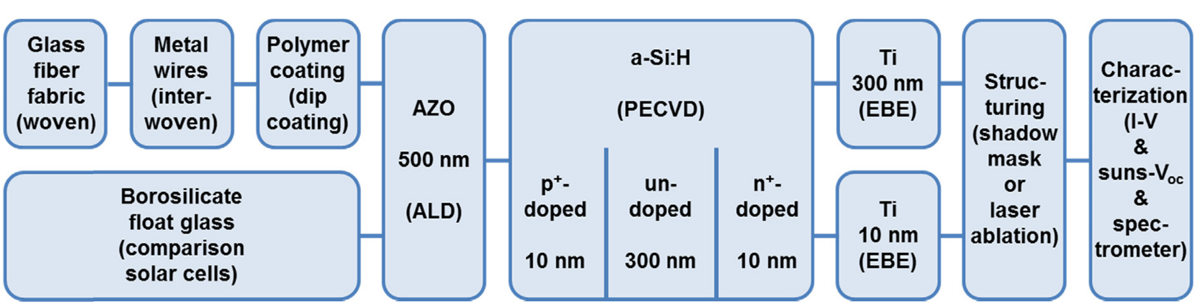


**Fig. 3.** Schematic of the process flow.