

Toward Cu(In,Ga)Se₂ solar cells on textile substrates

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SUMMARY OF THE ABSTRACT

This work presents preliminary results from developing Cu(In,Ga)Se₂ (CIGS) thin-film solar cells on textile substrates. To achieve this, it is essential first to understand the properties of textiles, such as their surface roughness and thermal stability, as CIGS solar cell growth requires high temperatures and a smooth surface with good adhesion. Since textiles are not inherently heat-resistant and have a rough surface, evaluating the temperatures they can withstand and their typical surface roughness is crucial. Thus, we developed methods to enhance the thermal stability of a polyester (PES) textile by impregnating it with vermiculite. We also improved the surface roughness by applying an acrylic resin incorporated with silica nanoparticles. Results show that a vermiculite-impregnated textile can withstand a temperature of 350°C with minimal weight loss and that 3 layers of acrylic resin coating reduce the surface roughness by 43%. After these textile treatments, we deposited CIGS on glass at 200, 300, 400, and 450°C and identified a promising 'window of opportunity', for growing CIGS at 350°C, thus compatible with the vermiculite-coated textiles. We also show a complete reference CIGS device on an untreated textile fabricated at 200°C.

APPLICABLE TOPIC AND SUB-TOPIC NUMBER

TOPIC 2 Thin films and New Concepts; 2.3 Compound and Organic Semiconductors

AIM AND APPROACH

Using textile substrates offers new possibilities for developing solar cells, on clothing, tents and canopies, tarps, sails, airships, wearable devices, and potential applications for the automotive industry [1]. Several studies on textile-based flexible thin film solar cells (TFSCs) include Cu(In,Ga)Se₂ (CIGS), perovskites, and dye-sensitized [2-4]. However, research on textiles as a substrate for TFSCs is very limited and still in its early stages. The main challenges hindering the use of textile substrates for solar cells include rough surface morphology, low thermal stability, chemical vulnerability, high oxygen and water vapor permeability, low physical strength, and adhesion issues due to high thermal expansion. These obstacles must be overcome to develop textile-based TFSCs.

CIGS is a leading thin-film photovoltaic (PV) technology due to its high power conversion efficiency (PCE), simple manufacturing processes, low-cost production, and excellent long-term durability and stability. A record 23.6% PCE has been reported for CIGS solar cells on conventional glass substrate [5] at high temperatures (530°C). CIGS has also been deposited at lower temperatures (~450°C) on flexible substrates, such as polyimide, allowing portable, foldable, and lightweight PV devices [6] However, using textile substrates would unveil additional functional properties such as stretchability, wearability, and

deformability, which is interesting for applications in wearable electronics, smart textiles, and energy-harvesting fabrics.

To our knowledge, only one study has explored textile-based CIGS solar cells [2], where devices were fabricated on glass-fiber fabric at approximately 440°C, achieving a PCE of over 8%. The fabric surface topography was smoothed by applying heat-stable resin coatings. However, the resin's unevenness and particle size affected the device's efficiency, creating shunt paths in the solar cell. While glass-fiber fabrics offer high strength and heat resistance, their properties make them less suitable for clothing and everyday textiles. In contrast, polyester (PES) textiles provide greater flexibility, affordability, aesthetic appeal, and ease of use and maintenance.

PES textile offers superior mechanical flexibility, a more uniform surface for CIGS deposition, and better compatibility with roll-to-roll processing. In this work, we use two types of woven fabrics: 100% polyester (PES) (~0.3 mm-thick) and 50% PES / 50% basalt (~0.45 mm-thick). To reduce the surface roughness, we applied up to three layers of acrylic resin coating on each side of the textiles using an automatic coater. To increase their temperature resistance, we impregnated the textiles with vermiculite, followed by knife coating. The surface roughness and morphology of the textiles were characterized by an optical profilometer, optical microscopy, and scanning electron microscopy (SEM). The thermal stability of the textiles was assessed by thermogravimetric analysis (TGA).

In parallel, we fabricated CIGS solar cells using pulsed hybrid reactive magnetron sputtering [7] at different temperatures (from 200°C to 450°C). This study aimed to determine the temperature range suitable for achieving high-quality devices, allowing us to later adapt the process for textile substrates treated with vermiculite and acrylic resin. We followed the standard CIGS solar cells configuration with 500 nm Mo back contact on a soda-lime glass substrate, 2 μ m CIGS absorber, 50 nm CdS buffer layer, and 350 nm window layer (50 nm i-ZnO and 300 nm ZnO:Al). We analyzed the devices with current density-voltage (J-V) and external quantum efficiency (EQE) measurements. Additionally, we fabricated a complete CIGS solar cell on an uncoated PES substrate to evaluate the feasibility of the whole process and establish a baseline reference. In future steps, we will fabricate solar cells on the acrylic-coated and vermiculite-impregnated PES textiles.

SCIENTIFIC INNOVATION AND RELEVANCE

Integrating CIGS solar cells with textile substrates has been a largely unexplored topic in photovoltaics, primarily due to the inherent challenges of textile-based substrates. The high deposition temperatures required for CIGS processing (>500 °C on glass) are incompatible with conventional textiles, and the roughness of textile surfaces hinders the formation of high-quality thin films. This work addresses these challenges through a dual approach: (i) surface smoothing via acrylic resin coatings to promote thin-film adhesion and (ii) thermal stabilization using vermiculite impregnation to improve the textile heat resistance, allowing it to keep most of its mechanical properties, such as touch feel and flexibility. These modifications could allow the CIGS deposition on textiles, an innovation that has not been systematically explored. Combining these material engineering strategies, this study takes steps toward making high-performance CIGS solar cells on textiles, which could open the door for new flexible PV applications, beyond polymer and metal foil, into a more versatile and widely used material in daily life, such as wearable energy-harvesting textiles.

RESULTS AND CONCLUSIONS

The optimal substrate roughness for CIGSe solar cells is unclear, but roughness in the tenths of micrometers likely hinders thin-film deposition. Figure 1 shows surface 2D

maps of a plain weave PES textile front side with and without acrylic resin coating, and Table 1 presents their average surface roughness. The measurements show that increasing the acrylic resin layers significantly reduced surface roughness, from 15.29 μm (uncoated) to $6.57 \pm 0.29 \mu\text{m}$ with three layers, demonstrating a clear smoothing effect.

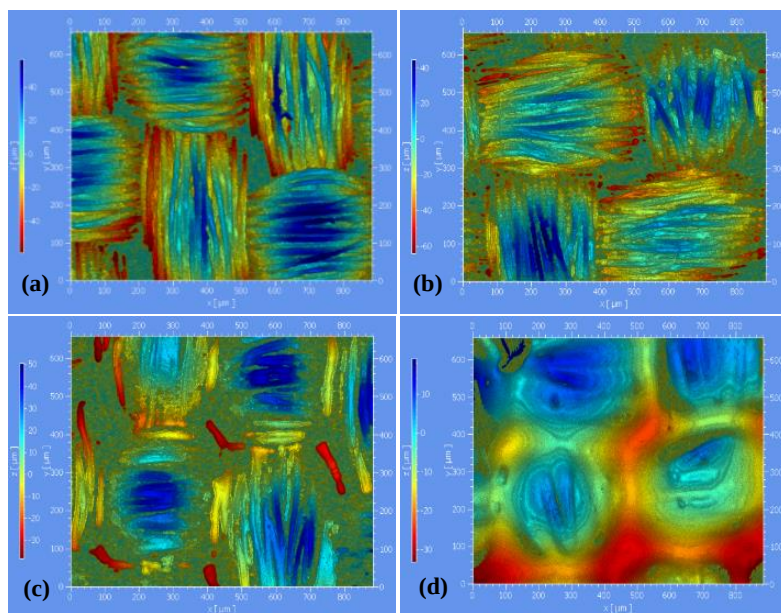


Table 1. Average surface roughness of the front side with a plain textile weave.

Front side	Avg. Roughness (μm)
Uncoated Reference	15.29
1 resin layer	12.10 ± 0.77
2 resin layers	10.42 ± 1.96
3 resin layers	6.57 ± 0.29

Figure 1. 2D maps showing surface height variations on the front side of textiles with a plain weave structure: (a) Uncoated, (b) 1 resin layer, (c) 2 resin layers, and (d) 3 resin layers coated textiles.

Thermogravimetric analysis (TGA) conducted in nitrogen atmosphere (Fig. 2) demonstrates the thermal stability of the vermiculite-coated textile compared to uncoated polyester (PES). The uncoated PES (red curve) begins to degrade around 250°C, with increasing weight loss as the temperature rises, ultimately losing about 28% after 90 minutes. In contrast, the vermiculite-coated textile (green curve) remains stable, with marginal weight loss of 0.8%. This indicates that the vermiculite coating substantially enhances the textile's thermal resistance, preventing decomposition and making it suitable for high-temperature applications.

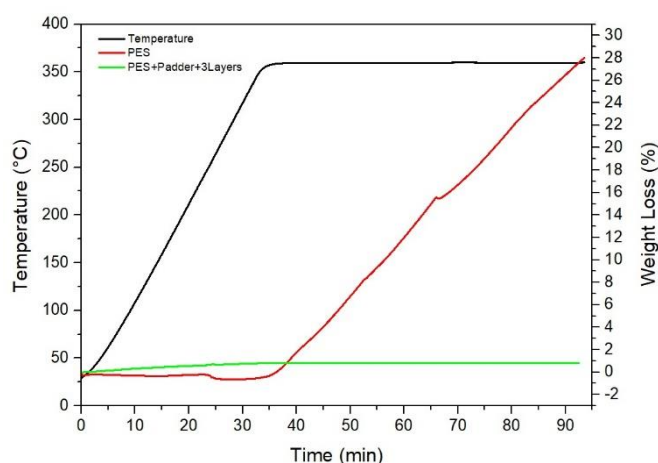


Figure. 2 The thermal properties of PES and vermiculite-coated PES (with one impregnation cycle using a padder at 3.5 bar and 3.5 m/min and three layer of knife coating of vermiculite) through thermogravimetric analysis (TGA) at a heating rate of 10 °C/min from 30 to 350°C.

Figure 3 presents the current density-voltage (J-V) characteristics and EQE spectra of the highest-performing CIGS solar cell fabricated at a nominal growth temperature of 300°C on glass. The actual substrate temperature was estimated as ~350°C. The device achieved an efficiency of 6.36%, with a short-circuit current density (J_{SC}) of 27.5 mA/cm^2 , a fill factor (FF) of 52%, and an open-circuit voltage (V_{OC}) of 0.439 V. The EQE reached approximately

41% in the visible range of the spectrum. The J_{SC} calculated from EQE integration was 24.3 mA/cm^2 , closely aligning with the value from the J-V measurements. The slight discrepancy likely stems from contact inconsistencies in the solar simulator, making the EQE-derived J_{SC} the more reliable value. Since the vermiculite impregnation treatment enhances the temperature resistance of PES textiles to approximately 350°C , it shows promise for enabling the fabrication of CIGS solar cells on these textiles in future studies.

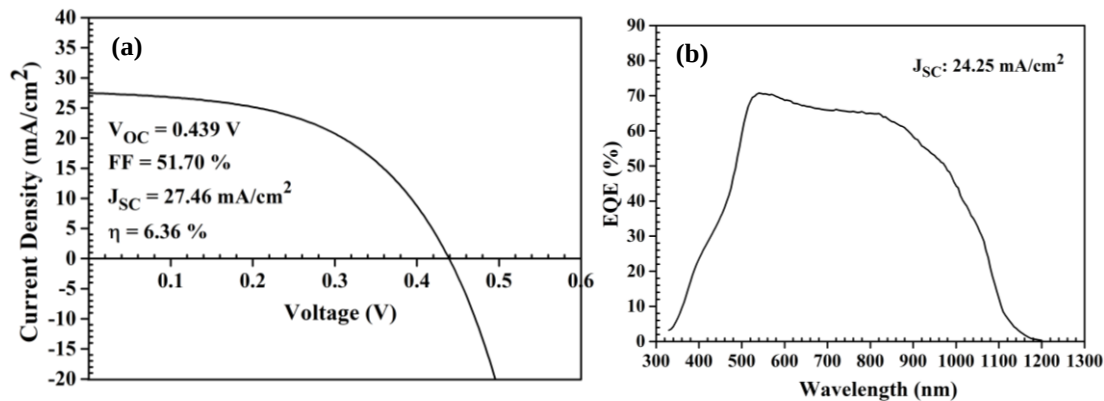


Figure 3. (a) J-V and (b) EQE spectra of the CIGS solar cells fabricated at a nominal growth temperature of $\sim 300^\circ\text{C}$ on glass.

As a first test, we fabricated a complete solar cell device on an uncoated PES textile substrate at a nominal temperature of $\sim 150^\circ\text{C}$ (actual temperature: $\sim 200^\circ\text{C}$) (Fig. 4). However, the device showed a poor photocurrent. Due to the processing, the textile substrate loses its flatness slightly, and its shape is somewhat influenced by temperature. Our goals for future studies include the fabrication of CIGS solar cells on vermiculate-impregnated and acrylic resin-coated PES textiles and the development of more heat-stable and less surface roughness PES textiles.



Figure 4. Photograph of a CIGS solar cell device fabricated on an untreated PES textile substrate at a nominal temperature of $\sim 150^\circ\text{C}$.

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