Coatings on Textiles for Cu(In,Ga)Se_2 Photovoltaic Cell Formation on Textile Carriers: Preparation of Cu(In,Ga)Se_2 Solar Cells on Glass-Fiber Textiles

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ABSTRACT: Results are presented on the construction of a thin-layer photovoltaic cell on glass-fiber fabric. The unevenness of the fabric was first smoothed by the application of a high-temperature stable resin before photovoltaic layer deposition. We obtained an efficiency of light-to-current conversion of more than 8%. This constitutes a remarkably high value for a photovoltaic cell on a flexible substrate. © 2009 Wiley Periodicals, Inc. J Appl Polym Sci 115: 2763–2766, 2010

Key words: fibers; high performance polymers; photochemistry; surfaces; thin films

INTRODUCTION

Photovoltaic (PV) solar cells that directly convert solar light into electrical power are widely known today. Production costs and raw material supply are severely restricting established systems, which are mainly based on silicon technology. PV applications, with an annual growth rate of about 20–25%, demand the evaluation of several methods of technology.[1–5]

Any thin-film solar cell is based on a multilayer system (with light-to-current conversion of semiconductor/current collecting layers and protection layers). Thin-film solar cells are mainly deposited on solid carriers, such as glass plates, ceramics, or special metals. PV-active semiconductor systems based on copper indium diselenide (CIS) or systems with the addition of gallium [Cu(In,Ga)Se_2 (CIGS); some micrometer layers] have been studied with increasing frequency.[4–8]

In Figure 1, the (established) layer sequence for the construction of a CIS PV cell on a solid carrier is sketched. The layer thicknesses have to be recognized, especially with regard to the topography of the carrier.

All known preparation processes of CIS (CIGS) PV layers use a high-temperature annealing step (i.e., heating to 470°C and more for some 10 min). A very smooth base material is required to obtain smooth layering of the light-absorber materials without the introduction of shunts between layers, which would inevitably decrease the light-to-current conversion efficiency.

In this article, the construction of thin-layer CIS PV cells on glass-fiber flexible fabric and their performance are described. With regard to the layer sequence and their thicknesses, as given in Figure 1, the roughness of a real textile construction has to be tackled. Figure 2 illustrates the problem. As an example, the height difference between the warp and weft on crossing points of a smooth and thin glass-fiber fabric is about 135 μm. A big challenge of roughness is related to the requirements of PV cell layers, as given in Figure 1. Therefore, strategies for smoothing the fabric surface topography had to be developed, too. This goal was achieved by the introduction of heat-stable resins as coatings of the fabric.

EXPERIMENTAL

Details of the fabric treatment, deposition, and temperature behavior of the resin formulations can be found refs. 9–12.

Carrier material

A standard glass fabric (Klevo-Glas 41-1 L, no. 101446, Klevers, Mönchengladbach; 200 g/m^2,

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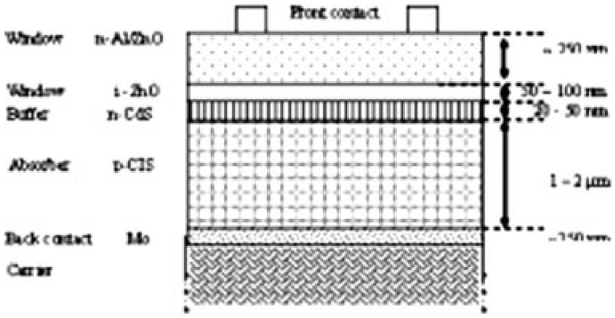

Figure 1 Principal layers of a CIS (CIGS) solar cell on a flat substrate.

0.2 mm thickness, plain weave, 400 filaments/count, 9 µm) was used.

Commercial resin preparation

Dupli-Color exhaust-pipe varnish (batch 298/03 bzw 370/04, pigmented, silicon–acrylate resin ca. 32 wt % filled with xylene as the solvent) and Dupli-Color clear varnish (pigment-free) were used.

To obtain a higher temperature stability, different inorganic fillers were applied. The fillers were applied in concentrations of 20–50 wt % in the base clear varnish. Mixtures of small, medium, and large particle fractions were used.

To prepare the particle-filled resins, a definite amount of filler was added to the base varnish precursor and homogenized with a ball mill. For application on textiles, dipping and/or a flat and roll doctor blade coating response was used. Dipping was usually applied several times until a visually homogeneous coating was reached. After air drying for the removal of low-boiling solvents, the resin-treated fabric was condensed at 200–250°C in a muffle oven. A preheating process at ambient temperature up to 400°C was done. Finally, heating and outgassing (preshrinkage) was done according to the heating program up to 490–510°C. Wet coating was in the range 200–300 g/m^2 determined after air drying and condensation at 160 to 200°C. A similar procedure was used with the pigmented varnish.

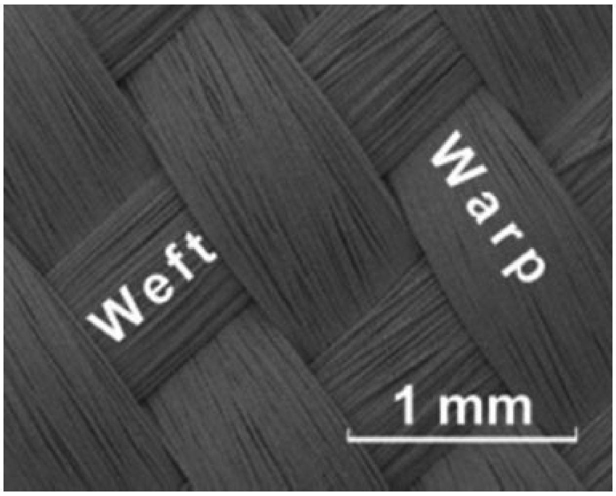

Figure 2 Details of glass-fiber fabric showing the roughness of the substrate.

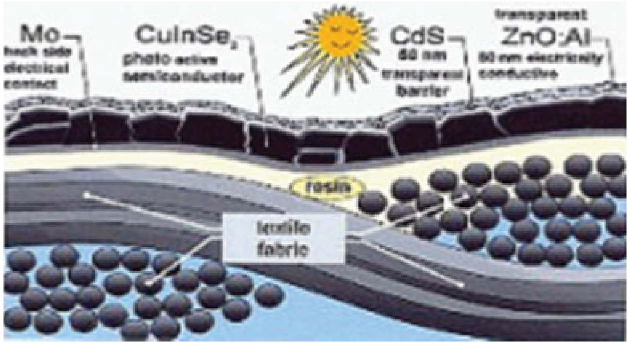

Figure 3 Strategy for smoothing the topographic unevenness of the textile construction with a lacquer or varnish coating before semiconductor deposition. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Resin-coated glass fabric samples matching crack-free conditions after preheating were processed for PV layer deposition. First, a Mo layer back contact was sputtered, followed by a layer of sodium selenide. Subsequently, coevaporation of Cu, In, Ga, and Se was done at roughly 440°C. A 50-nm layer of CdS was then deposited by chemical reaction. Then, a sputter process deposited i-ZnO about 100 nm thick and, finally, an Al-doped ZnO layer as a front contact, which was applied by a mask to obtain an electrically separate individual solar cell of varying size.

The apparatus for the formation of the PV-active layers consisted of the following:

1. A molybdenum sputter target (Ardenne Anlagentechnik) with a purity of 99.99%.
2. A ZnO sputter target (Heraeus Thin Film Materials GmbH) with a purity of 99.9%.

Figure 4 Atomic force microscopy height profile across a diagonal line on a 10 µm × 10 µm resin layer on glass-fiber fabric. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

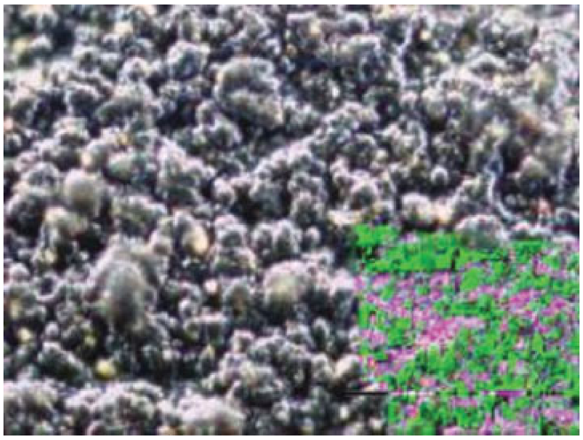

Figure 5 Final surface of a CIGS solar cell (Deutsches Textilforschungszentrum Nord-West no. 227-4 pigmented varnish; magnification = 500×). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

3. A ZnO : Al_2O_3 sputter target (Heraeus Thin Film Materials) with a purity if 99.9%.
4. Thiourea (Merck) with a purity of 99%, 25% ammonium hydroxide (Fluka), and CdS (Aldrich).
5. A selenization vacuum oven (ANTEC GmbH).
6. Heating of 10 × 10 cm^2 samples *in vacuo* up to 600°C at a maximum heating rate of 20°C/min and a cooling rate of 20°C/min.
7. An inline sputter system for use with Mo, ZnO : Al, and SnO_2 (Pfeiffer-Vakuum).
8. A system for sputtering and evaporation [MED 10 (Balzers) for Cu and In deposition].
9. Sun simulator equipment (homemade at the Institut für Solarenergieforschung).

RESULTS AND DISCUSSION

The first approach of direct deposition of the first conducting Mo layer for current collection, which might have decreased the height differences between warp and weft, did not give sufficient smoothness and only gave weak adhesion to the fabric. So another strategy for smoothing the rough textile surface was established. This strategy was based on the use of pigmented organic resins and is sketched in Figure 3.

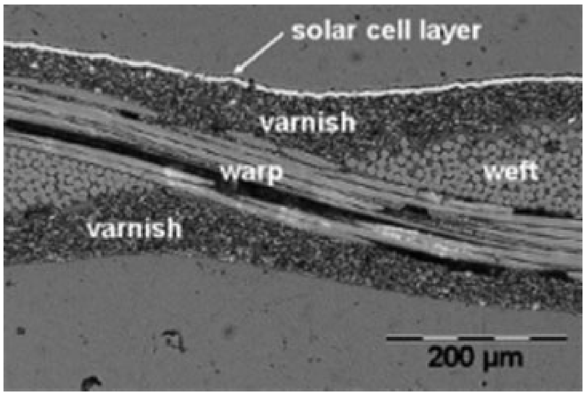

Figure 6 Cross section of a completely processed CIGS PV cell on glass fabric.

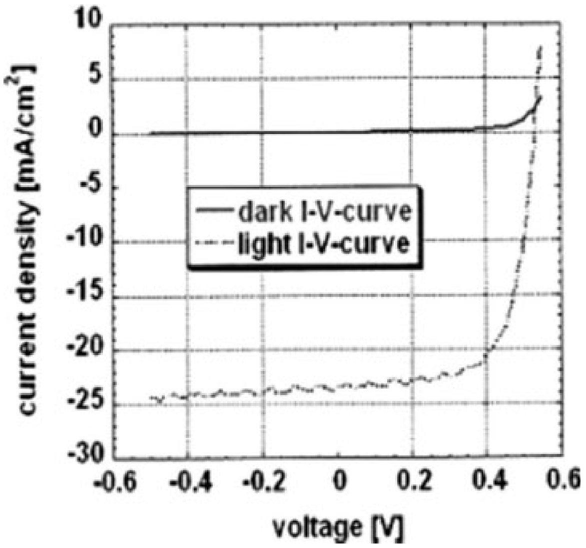

Figure 7 Current–voltage (I–V) curves of a CIGS solar cell on fabric under dark and standard illumination conditions.

Therefore, several resin formulations, stable to about 500°C annealing, were tried on the bases of silicones and polyimides for good adhesion for the Mo layer. The best results were obtained when we used a commercial exhaust-pipe varnish and/or inorganic fillers.

The varnish-covered glass fabrics containing selected particle combinations were heated *in vacuo* to 510°C for 7–10 min without the formation of cracks. This means that, for the production of thin-layer solar cells on nonmetallic flexible surfaces, this was the highest and, thus, most promising processing temperature for the selenization and annealing of the PV-active semiconductor layers obtained to this point.[9]

TABLE I
Parameters of Solar Cells 3 (DTNW No. 302-1) and 18 (DTNW No. 226-7)

Parameter	Cell 3	Cell 18
Area (mm^2)	16	100
Open-circuit voltage (mV)	541.0	538.5
Short-circuit current density (mA/cm^2)	27.9	21.6
Filling factor (%)	58.3	39.6
Efficiency (%)	8.8	4.6

DTNW = Deutsches Textilforschungszentrum Nord-West.

Figure 8 Illustration of the flexibility of PV cells on glass-fiber fabric. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Figure 4 gives a detailed height profile analysis of a varnish-coated glass textile after degassing at 500°C as used for PV cell deposition. Figure 5 shows the surface of a finally processed CIGS PV cell on fabric.

The preparation of such varnish layers on textiles for the further deposition of PV-active layers was performed. Figure 6 shows a cross section of a PV solar cell on resin-treated glass fabric (the solar cell layer consisted of several different layers, all in the micrometer to nanometer range).

The current–voltage characteristics, which describe the cell efficiency, of such a PV cell under standard illumination conditions are shown in Figure 7, and the efficiency parameters, depending on the PV cell size, are collected in Table I.

A dark current of about 28 mA was reached with an open voltage of 541 mV (area = 16 mm^2). The resulting light-to-electricity efficiency was higher than 8%, which is remarkably high for a flexible thin-layer solar cell constructed with relatively cheap components.

As an illustration for the bendability of the PV cell achieved on this glass-fiber fabric, Figure 8 shows an impression of the bending radius obtained on a small scale.

CONCLUSIONS

We showed that PV cells of the CIS family with high flexibility were applied to textile constructions after the roughness of the textile construction was smoothed by the application of high-temperature-stable varnish formulations to the glass fabric. A heat-stable (pigmented) varnish formulation was found, which withstood an annealing temperature of 500°C, for the PV semiconductor for about 10 min, which was sufficient for further processing of the PV cell.

With regard to the materials we evaluated, rather inexpensive materials were involved, as is inherently necessary for large-scale production in CIS (CIGS) thin-layer PV cells as compared to established silicon technology.

The fact that cell efficiency on the glass fabric with larger areas decreased was attributed the fiber ends (the use of a commercial simple glass weave), the unevenness of the resin layer, or the too-big particles of the resin fillers used, which caused shunts between the submicrometer layers of the PV system.

Targets for future work include

- The even development of more heat-stable varnishes.
- More homogeneous, smooth varnish surfaces to minimize shunts.
- Modular interconnection and finish with top coating and the testing of long-term stability.
- Larger areas and simplified processing steps.

The approach of the maximum value obtainable (ca. 18% solar-energy-to-electricity conversion) with CIS (CIGS) PV cells seems possible in the future for textile flexible carriers and constitutes a real challenge for research and development work.

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