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Advanced Flexible CIGS Solar Cells Enhanced by Broadband Nanostructured Antireflection Coatings

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ABSTRACT

Flexible copper indium gallium diselenide (CIGS) solar cells on lightweight substrates can deliver high specific powers. Flexible lightweight CIGS solar cells are also primary candidates for building-integrated panels. In all applications, CIGS cells can greatly benefit from the application of broadband and wide-angle AR coating technology. The AR coatings can significantly improve the transmittance of light over the entire CIGS absorption band spectrum. Increased short-circuit current has been observed after integrating AR coated films onto baseline solar panels. NREL's System Advisor Model (SAM) has predicted up to 14% higher annual power output on AR integrated vertical or building-integrated panels. The combination of lightweight flexible substrates and advanced device designs employing nanostructured optical coatings together have the potential to achieve flexible CIGS modules with enhanced efficiencies and specific power.

INTRODUCTION

Flexible and lightweight solar cells manufactured via cost-effective, reel-to-reel processes have the potential to revolutionize the utilization and applications of photovoltaic technology, in part by reducing both the hardware and non-hardware costs associated with solar energy systems. Unlike traditional rigid solar cells, flexible solar cells can be seamlessly integrated with systems of various shapes and sizes. In addition, flexible solar cells are lightweight and suitable for various terrestrial applications as well as for providing power in space, e.g., for satellites. However, solar cells fabricated on flexible substrates have historically had lower efficiencies compared to traditional rigid cells. Consequently, in recent years a major focus has been on improving the efficiency of flexible solar cells.

Among various thin-film photovoltaic devices, $Cu(In,Ga)Se_2$ (CIGS) cells exhibit the highest efficiencies. CIGS technology features high broadband light absorption characteristics and excellent light trapping capabilities. In recent years, a significant number of groups have demonstrated new record efficiencies for CIGS cells. In 2008, the National Renewable Energy Lab (NREL) demonstrated 19.9% efficient CIGS solar cells [1]. More recently, in 2011 researchers at Stuttgart's Centre for Solar Energy and Hydrogen Research (ZSW) achieved cells with 20.3% efficiency [2], and then in 2014 the same group attained 21.7% efficiency [3] with a new CIGS solar cell design. Both the NREL and ZSW cells were fabricated on rigid substrates. However, scientists at the Swiss Interdisciplinary Research and Services Institute for Material

Science and Technology (EMPA) reported record efficiency CIGS cells on flexible polyimide sheets [4].

The U.S. Photovoltaic Manufacturing Consortium (PVMC) team at the College of Nanoscale Science and Engineering, State University of New York Polytechnic Institute (SUNY Poly), which is collaborating with Magnolia, has demonstrated 17.3% efficient CIGS cells on flexible yttria stabilized zirconia (YTZ) substrates [5]. We have also demonstrated flexible CIGS photovoltaic cells with a specific power of greater than 275 W/kg on ultra-lightweight and highly durable titanium foil [6]. In this paper, we review both recent developments in flexible CIGS solar cells and a technique to further enhance their performance utilizing broadband nanostructured AR coatings.

EXPERIMENT

The quality of CIGS layers is dependent upon the deposition method utilized. Several deposition methods including coevaporation, selenization of metallic precursors, sputtering, and electrodeposition, have been developed for depositing CIGS absorption layers. The recent record efficiency CIGS solar cells [1-4] were processed using multistage coevaporation processes. Therefore, the commonly used coevaporation process can yield high quality absorption layers. As it is known that diffusion of sodium can improve solar cell efficiencies, rigid soda-lime glass has often been a preferred substrate for CIGS cells.

The U.S. PVMC team at SUNY Poly demonstrated 17.3% efficient CIGS cells on flexible YSZ substrate [5], while the Magnolia Solar and SUNY Poly team has demonstrated high specific power solar cells on ultra-lightweight and highly durable titanium foil [6]. In addition, Magnolia has developed broadband and wide-angle AR structures [7] and demonstrated them on various substrates including 6”×6” glass plates, ultraviolet (UV) stabilized polycarbonate films, and UV stabilized polyethylene terephthalate (PET) films. The optical transmittance boosting AR layer can be employed on the flexible cells to enhance the cell efficiencies.

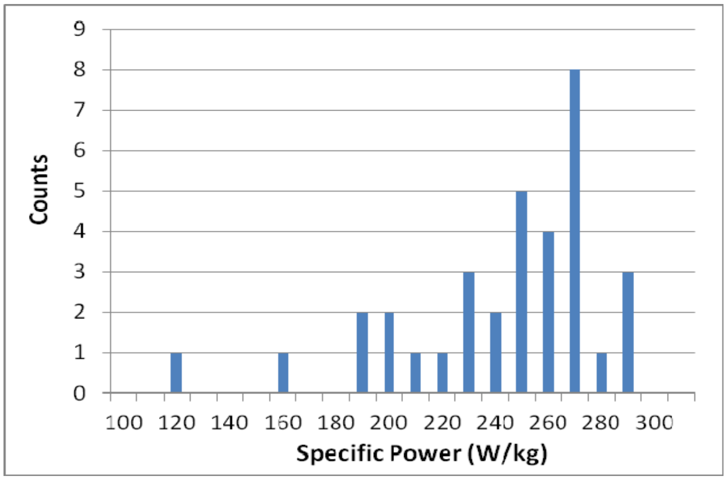

Figure 1: Histogram of flexible CIGS solar-cell-specific powers for 36 devices. The mode of the specific power distribution is 270 W/kg.

RESULTS AND DISCUSSION

Our Magnolia team, working in collaboration with the PVMC group, has developed flexible lightweight CIGS solar cells with high specific power fabricated on several 4”×4” titanium substrates. The CIGS absorber layer was synthesized by codeposition of Cu, In, Ga and Se vapor flexes on high temperature substrates. Metal grid deposition and laser scribing resulted in a series of 1.1 cm^2 size flexible devices. Current-voltage and power-voltage characteristics of the flexible devices were measured under standard test conditions [AM 1.5 spectrum, 1000 W/m^2, 25°C]. The cell level specific power was derived from the maximum power to mass ratio of the cell. Figure 1 shows a histogram of the flexible CIGS solar cell specific powers for 36 devices. The highest value of the specific power for this set of devices is 270 W/kg, with a mean of 238 W/kg. Further efforts to improve the specific powers of the devices is ongoing, including the application of advanced AR coatings.

Magnolia has developed broadband AR coatings that can significantly enhance the specific power of the flexible CIGS devices. The nanostructured AR layers were deposited using an oblique angle deposition (OAD) method and demonstrated very high, omnidirectional transmittance over the entire accessible portion of the solar spectrum and a wide range of optical incidence angles [8]. In order to evaluate the comparative flexible solar cell response, short-circuit current of the flexible devices has been measured for light transmitted through AR coated and uncoated glass sheets at various angles of light incidence on the glass.

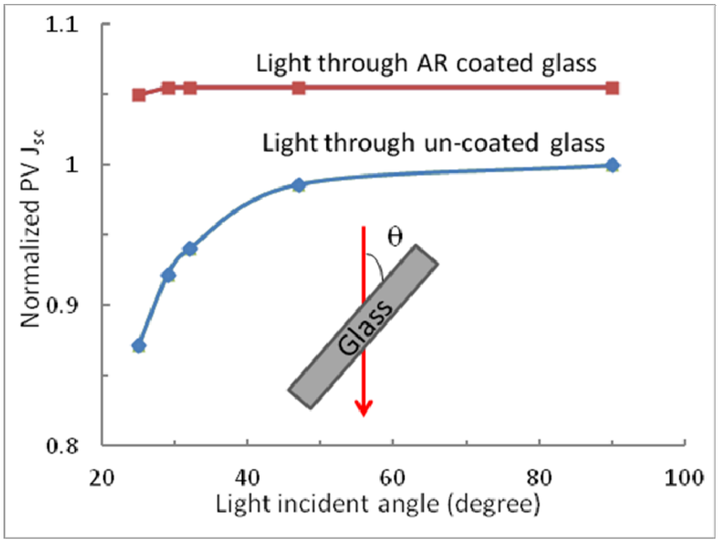

Figure 2: Comparison of normalized short-circuit current generated by a solar cell for light transmitted through AR coated and uncoated glass wafers over a range of light incident angles. At normal incidence, light transmitted through AR coated glass yields 5% more current than light transmitted through uncoated glass. At off-angles, the AR coated glass yields up to 20% more current than light transmitted through uncoated glass.

The short-circuit current analysis indicates that the light transmitted through the AR coated glass wafer yields up to 20% higher short-circuit current at off-angle light incidence compared to the light transmitted through the uncoated glass wafer. Figure 2 compares the short-circuit current observed under various illumination conditions and light incident angles. In the case of light transmitted through the uncoated glass wafer, the normalized short-circuit current varies from 1 to 0.87 as the light incident angle changes from 90° to 25°, respectively. In the case of light transmitted through the AR coated glass wafer, the short-circuit current varies from 1.06 to 1.05 for the same light incident angles. The AR coating on glass wafers thus significantly improves the short-circuit current of the flexible solar cells.

This significant improvement in short-circuit current is due to enhancement of light absorption over the entire CIGS absorption band spectrum. Light incident on a glass panel undergoes Fresnel reflection due to the difference in the refractive index between air and glass. The AR coating on glass panels minimizes the Fresnel reflection, resulting in greater light transmittance through the glass panels. This multilayer AR coating creates a step-graded index profile at the glass/air interface yielding the very high transmittance for a broad spectrum of light and wider angles of light incidence [7,8]. The transmittance enhancement maximizes the number of incident photons that arrive and are absorbed in the energy converting layers and thereby allows more charge carriers to be generated. Due in particular to their notable enhancement in the transmission of off-angle incident light, these nanostructured AR coatings have the potential to transmit sunlight into flexible CIGS solar cells with enhanced efficiencies from dawn to dusk.

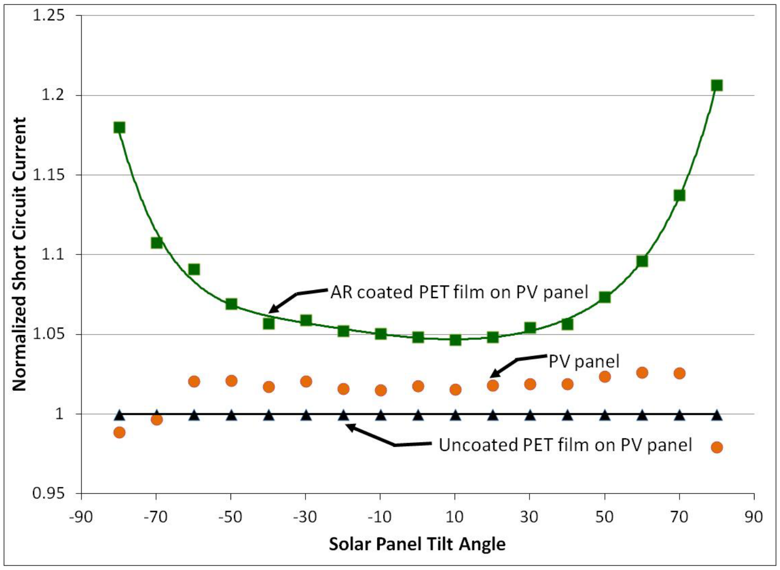

Figure 3: Normalized short-circuit current vs. solar panel tilt angles for a test PV panel, after integrating both uncoated PET film and AR coated PET film. The uncoated and AR coated films were attached using index-matching fluid between the panel and the film. The AR coating yields 5% and 20% greater short-circuit current for normal and off-angle light incidence, respectively.

To better understand the potential impact of the AR coating on annual solar energy output, single cell test panels have been fabricated by glass to glass lamination of mono-crystalline 6” square cells using ethylene-vinyl-acetate (EVA) as an encapsulant. The performance of the test panels was evaluated after integrating uncoated PET film and AR coated PET film on the test panels. In this case, the AR coating yields 5% more short-circuit current at normal light incidence and 20% more current at off-angle light incidence. Figure 3 shows short-circuit current of a test panel measured before and after integrating uncoated and AR coated PET film on its frontsheet. The same test panel was used in each case in this experiment to eliminate cell-to-cell performance variations. Integration of uncoated PET film lowers the short-circuit current due to optical absorption in the PET. The AR coated PET film integrated test panel provided more short-circuit current compared to the uncoated PET film integrated test panel. The test results indicate that the AR coating yields 5% more short-circuit current at 0° tilt and approximately 20% at 80° tilt. These results confirm the performance of AR coating on solar panels. AR-coated PET films with a step-grade profile greatly reduce the front surface reflection loss for a broad spectrum of light over a wide angular range of light incidence. These results demonstrate that the AR coating can significantly enhance light transmission through glass and PET, particularly for off-angle light incidence.

We utilized NREL's System Advisor Model (SAM) tool to predict the enhancement in annual power output of AR film integrated solar panels. SAM simulations predicted that the AR coating can yield greater than a 6.5% increase in annual power output for a given solar panel. For flat panel installation, the AR coating can provide 7.5% more current for panel location in Tucson, AZ and 8.5% more current for panel location in Albany, NY. Furthermore, for vertical mount panels, i.e., 90° solar panel tilt angle, the increase of annual power output is significantly higher.

Table 1: AR coating enhancement of annual power output for vertical panels.

Annual Power Output	Albany, NY	Tucson, AZ	Honolulu, HI
Percent Enhancement	10.6	11.2	13.9

Table 1 compares the predicted effect of AR coatings on vertically mounted solar panels for representative locations in Albany, Tucson, and Honolulu. The AR coating can provide greater than 10% enhancement in power output compared to a panel without AR coating. Therefore, our AR coatings can significantly influence the performance of vertically-mounted panels and building-integrated panels. Use of these AR coatings, which can greatly improve performance of the flexible solar cell modules, thus enhances the viability of flexible CIGS solar cells as candidates for building-integrated panels.

CONCLUSIONS

Flexible lightweight CIGS solar cells with high specific power have been demonstrated on very lightweight and highly durable titanium foil. The high specific power cells can be seamlessly integrated with systems of various shapes and sizes, potentially enabling an array of new terrestrial and space power applications. In addition, broadband and wide-angle AR coatings have been developed and demonstrated on various rigid and flexible substrates. The AR coatings increase short-circuit current of solar panels by greatly reducing reflection loss at the front surface for a broad spectrum of light over a wide range of light incident angles. Simulations utilizing NREL's SAM indicated that AR coatings can increase annual power output by up to 14% for the case of vertical mount panels. Thus, integration of the high performance broadband and wide-angle AR coatings on lightweight flexible solar cells can offer significant advancements for building integrated panels. Lightweight flexible substrates combined with an advanced device design employing nanostructured optical coatings together have the potential to achieve highly efficient flexible CIGS modules with greater specific powers.

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