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Research

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Flexible CdTe Solar Cells on Polymer Films

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Lightweight and flexible CdTe/CdS solar cells on polyimide films have been developed in a 'superstrate configuration' where the light is absorbed in CdTe after passing through the polyimide substrate. The average optical transmission of the approximately 10-μm-thin spin-coated polyimide substrate layer is more than ~75% for wavelengths above 550 nm. RF magnetron sputtering was used to grow transparent conducting ZnO:Al layers on polyimide films. CdTe/CdS layers were grown by evaporation of compounds, and a $CdCl_2$ annealing treatment was applied for the recrystallization and junction activation. Solar cells of 8·6% efficiency with V_{oc} = 763 mV, I_{sc} = 20·3 mA/cm^2 and FF = 55·7% were obtained. Copyright © 2001 John Wiley & Sons, Ltd.

INTRODUCTION

Development of flexible and lightweight solar cells are interesting for many terrestrial and space applications that require a very high specific power (defined as the ratio of output electrical power to the solar module weight). Thin-film solar cells on polymer films can yield more than 2 kW/kg specific power. Additionally, they are important for the development of novel value-added products, such as portable and lightweight sources of power for emergencies and recreational use, PV integrated buildings (roofs and facades), solar boats and cars, consumer electronics (smart cards, data and telecommunication products), etc.

Polycrystalline compound semiconductor thin-film solar cells based on Cu(In,Ga)Se_2 (CIGS) and CdTe are known for high efficiency, excellent stability and their potential for low-cost generation of solar electricity for terrestrial applications.[1–4] Depending on the volume of annual production, the module cost can be as low as 0·3–0·8 Euro/W_p. These solar cells are also interesting for space applications because their tolerance to high-energy irradiation is superior to conventional Si or GaAs solar cells.[5–7] CIGS solar cells of about 10–12·8% efficiency have been developed on polymer substrates.[8,9] However, CdTe solar cells on polymer substrates have not been reported up to now, although solar cells of about 10–16% efficiency have been obtained on glass substrates by a variety of methods.[10–16] CdTe solar cells on metal foils exhibit an efficiency of ~5%.[17,18] Here, we report for the first time a development of flexible CdTe solar cells on polymer films.

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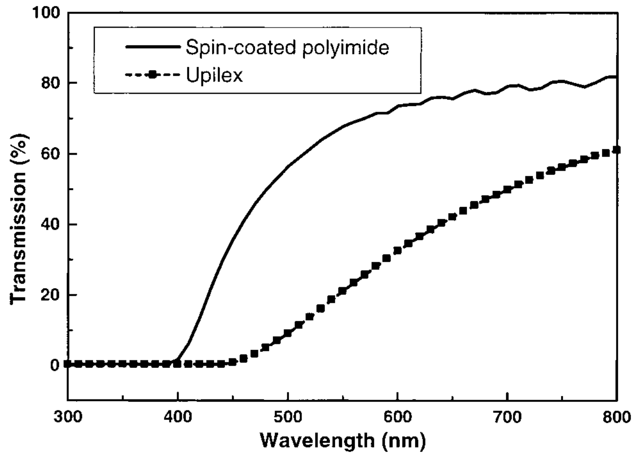

Figure 1. Transmission spectra of 50-μm-thick Upilex© and 10-μm thin spin-coated polyimide films

EXPERIMENTAL DETAILS AND RESULTS

High-efficiency CdTe solar cells are generally grown in a 'superstrate configuration' where CdTe/CdS stacks are deposited on transparent conducting oxide (TCO) coated glass substrates. The most commonly used TCO is SnO_x:F or ITO, while ZnO:Al contacts yield very-low-efficiency solar cells.[16] The choice of an appropriate substrate is crucial for flexible solar cells in the superstrate configuration because the substrate should be optically transparent and should withstand the high-temperature deposition/processing of solar cells. Most of the solar cell fabrication processes require temperatures of about 450–550°C. Transparent polymers are not stable at such high temperatures. Commercially available polyimide films such as Kapton© and UPILEX© can withstand high temperatures (~450°C), but they are dark yellow and strongly absorb visible radiation (Figure 1). Therefore, CdTe solar cells on 50–100-μm-thick polyimide films will a yield a low current, due to a large optical absorption loss in the substrate.

We have minimized the absorption loss in the polyimide film and developed flexible CdTe/CdS solar cells on polyimide. The schematic diagram of the superstrate solar cell is shown in the Figure 2. These solar cells were not grown on commercially available films, but the polyimide substrates were processed in-house and a 'lift-off' method was used. A similar lift-off approach has been used earlier to develop 12·8% efficiency CIGS solar cells on polymer films.[9]

Figure 3 shows the schematics of solar cell processing. A thin buffer layer of NaCl was evaporated on a glass substrate, then a polyimide layer was spin-coated and cured at about 430°C. The thickness of the polyimide film can be controlled by the spin-coating process, we have used ~10-μm-thin polyimide films. As shown in Figure 1, the average transmission of the polyimide film is more than ~75% for wavelengths above 550 nm. There is a strong absorption of photons in the wavelength range 400–550 nm. Owing to the bandgap of ~2·4 eV, the CdS

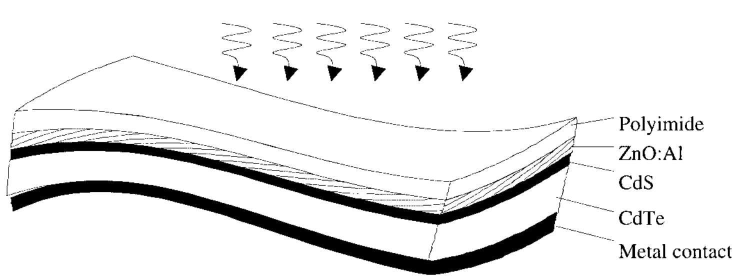

Figure 2. Schematic cross-section of the flexible CdTe solar cell on polyimide in the superstrate configuration

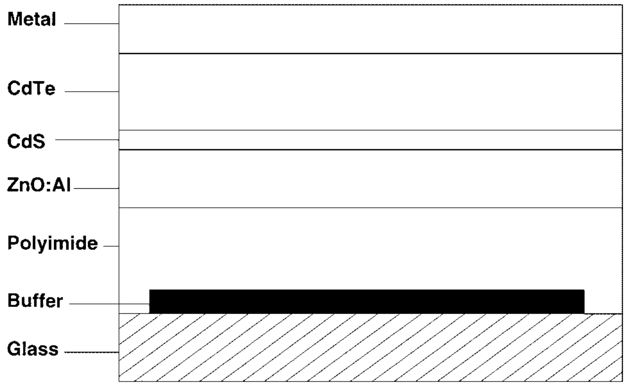

Figure 3. Schematic diagram, showing the stack of layers before the 'lift-off' process. Flexible solar cells on polyimide films are obtained by dissolving the buffer layer in water to remove the stack from the glass substrates

window layer absorbs photons of wavelength shorter than 515 nm. The transmission spectra depend on the thickness and processing of polyimide films.

For the front electrical contact with CdS, transparent and conducting ZnO:Al layers with an average transmission of about 80% and sheet resistance of 20 Ω/square were grown by RF magnetron sputtering.

CdTe/CdS solar cells were developed by a process in which all the layers were grown by evaporation methods. With this process, solar cells of ~12% efficiency have been obtained on ITO or SnO_x:F-coated glass substrates.[15,16] First, a CdS layer of ~500 nm was grown at a substrate temperature of 150°C and then annealed in vacuum at 430°C. The CdTe layer was subsequently grown in the same chamber by evaporation of CdTe source material at a substrate temperature of 300°C and a growth rate of ~4 μm/h. Typical thickness of the CdTe layer is ~3 μm. A '$CdCl_2$ annealing treatment' at 430°C was applied to the CdTe/CdS stacks. The surface of the CdTe layer was etched in a bromine–methanol solution prior to the deposition of a metal back contact on CdTe. After complete processing, the flexible CdTe/CdS/ZnO:Al/polyimide stack was removed from the glass substrate by dissolving the NaCl buffer layer in water. There are many other materials that can be used as an intermediate separation layer. For the development of flexible solar cells on polymers this lift-off approach has certain advantages, e.g., as a substrate many novel polyimides can be evaluated and their thickness can be easily controlled, surface contamination of the polyimide is minimal, and handling of the substrates during processing/deposition is easy.

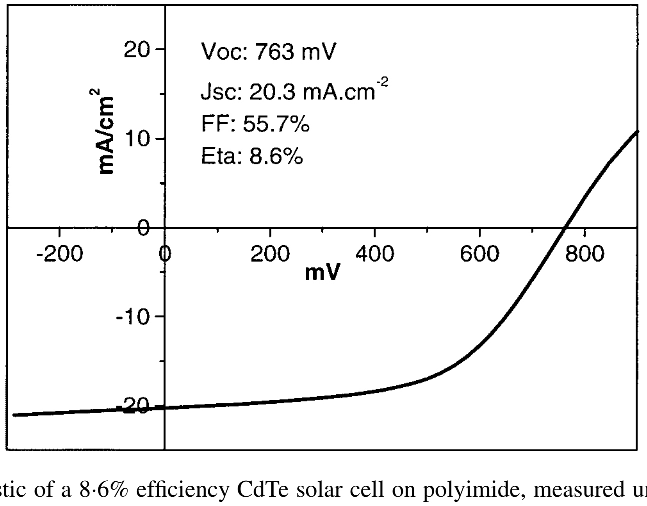

Figure 4. *I–V* characteristic of a 8·6% efficiency CdTe solar cell on polyimide, measured under AM1·5 illumination

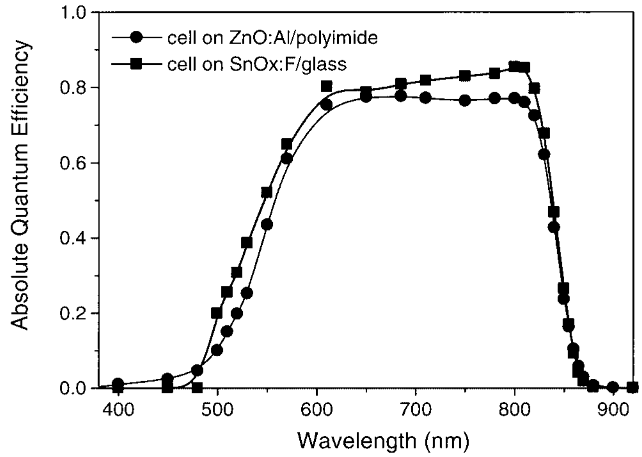

Figure 5. Comparison of the absolute quantum efficiency measurements of the 8·6% cell on polyimide with another 12% efficiency cell on SnO_x:F/glass substrate

The solar cells were grown on 3 × 3 cm substrates and scribed to smaller area for measurements. No anti-reflection coating was applied. Figure 4 shows the I–V characteristic of an 8·6% efficiency cell on a flexible polyimide film under AM1·5 illumination. For calibration we used a standard GaAs solar cell which was calibrated at ISE-FhG, Freiburg, Germany. As a secondary cross-check we have used the CdTe solar cells (on glass) and measurement data exchanged with other laboratories, the error in the efficiency measurement is within ± 5% of the measured value. The solar cell (Figure 4) has an area of 0·13 cm^2 and exhibits V_{oc} = 763 mV, I_{sc} = 20·3 mA/cm^2, FF = 55·7%. We believe that this is the highest reported efficiency of a flexible CdTe solar cell.

A comparison of the quantum efficiency measurements of a 12% efficiency cell on SnO_x:F/glass and a 8·6% efficiency cell on polyimide indicates a slight difference in the currents (Figure 5). The solar cell on polyimide has a slightly lower response in the 500–820 nm wavelength range, due to the absorption loss in the polyimide film substrate. To understand the reasons for lower efficiency of CdTe solar cells on ZnO:Al/polyimide, it is important to mention that the ZnO:Al, despite its good opto-electronic properties, does not yield efficient CdTe/CdS solar cells. Earlier we have reported[16] that solar cells on ZnO:Al-coated glass substrates exhibit about 3% efficiency because of a very low fill factor ~30%, low current density and high series resistance. However, the same process on ITO or SnO_x:F/glass yields 11–12% efficiency solar cells. In the present work we have used ZnO:Al front contact on polyimide because of the non-availability of other TCO deposition equipment in our laboratory. We believe that solar cells of more than 12% efficiency can be easily developed by replacing ZnO:Al with other TCO front contacts.

CONCLUSIONS

Lightweight and flexible CdTe/CdS solar cells in the superstrate configuration have been developed for the first time. A spin-coated polyimide layer is used as a substrate. In order to reduce the absorption loss in the substrate, the polyimide thickness is decreased from ~50 to ~10 μm. Deposition of CdTe/CdS layers and $CdCl_2$ annealing treatment were performed at temperatures below 450°C. Solar cells of 8·6% efficiency were obtained on ZnO:Al-coated polyimide with a 'lift-off' method. We believe that replacing ZnO:Al with other transparent conducting front contacts will further increase the fill factor and efficiency of solar cells. A comparison of the quantum efficiency and optical transmission measurements suggests that thinner CdS layers will increase the I_{sc}. These optimizations should yield flexible CdTe solar cells on polyimide films with efficiencies exceeding 12%.

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