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Ultrathin Cu(In,Ga)Se_2 transparent photovoltaics: an alternative to conventional solar energy-harvesting windows

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A B S T R A C T

Transparent photovoltaic (TPV) devices using very thin absorbers, which are sandwiched by transparent conducting front and rear contacts, provide efficient solar energy yields and partially visible transparency. These characteristics allow such devices to be used in applications including building-integrated photovoltaics (BIPV), solar vehicles, and wearable devices. In this study, we developed the TPVs with tunable power conversion efficiencies (*PCEs*) and average visible transmittance (*AVT*) values using ultrathin Cu(In,Ga)Se_2 (CIGS) absorber layers with thicknesses ranging from 30 to 300 nm, prepared using a single-stage coevaporation process. The *PCE* and *AVT* values of these devices could be easily tuned by controlling the absorber thickness; the TPV devices exhibited respective *PCEs* ranging from 11.0% to 2.1% (front illumination) and 6.6–1.7% (rear illumination), as well as *AVTs* ranging from 9.1% to 47.8% as the absorber thickness was varied from 300 to 30 nm. The TPV device prepared with a 100 nm-thick fully depleted CIGS absorber layer exhibited an enhanced bifaciality factor close to unity owing to the field-driven charge transport and reduced recombination at the rear contact and/or in the bulk of this device. Similar *PCEs* of ~5% under front and the rear illumination at an *AVT* of ~35% were achieved. This TPV device demonstrated constant *PCEs* under low-light irradiance (10–100 mW cm^{-2}) irrespective of the illumination direction, as well as an enhanced bifacial performance as J_{SC} linearly increased from 11.4 to 19.3 mA cm^{-2} as the rear illumination intensity was increased from 0 to 60 mW cm^{-2}. It also exhibited high light-soaking stability.

1. Introduction

Photovoltaics (PV) represent an innovative and cost-effective renewable energy source that may replace conventional fossil fuels in many countries, as the energy sector transitions towards achieving carbon neutrality [1–3]. For the installation of large-scale PV, new solar power technologies, including building-integrated PV (BIPV) as well as floating, agricultural, and mobile PV systems, have been developed along with conventional utility-scale and rooftop PV. BIPV is a promising approach to meet large-scale PV demands because it utilizes the large surface areas of buildings. Additionally, it can produce electricity in urban areas which consume large amounts of energy, thus reducing electrical transmission losses, the need for storage capacity, and installation costs [4–6]. Transparent photovoltaic (TPV) devices, which provide tunable power conversion efficiencies (*PCEs*) and good average visible transmittance (*AVT*), are appealing for BIPV applications as electricity-generating façades, windows, skylights, and shelters [7,8]. Recently, TPVs with a novel configuration, wherein ultrathin absorber layers and front and rear transparent contacts are utilized, have become increasingly fabricated [9–13]. These new TPV devices have many advantages over see-through-type PV devices because of their enhanced aesthetics, high annual-energy yield due to their ability to receive incident light from both sides, and simple fabrication process as additional laser scribing (known as P4 laser scribing) to form an aperture is not required. Implementing highly efficient absorber materials is essential for increasing the light absorption in the ultrathin absorber layers, which will result in high-performance TPVs. Cu(In,Ga)Se_2 (CIGS) is a direct-bandgap absorber material with a high absorption coefficient of $\sim 10^5$ cm^{-1} [14]. High efficiencies (> 20%) have been reported for CIGS solar cells with 2–3 μm-thick absorber layers and opaque Mo rear electrodes [15–17]. Using a thinner absorber improves the industrial competitiveness of this technology and reduces costs by lowering the

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