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Full Length Article

Confinement – assisted shock-wave-induced thin-film delamination (SWIFD) of copper indium gallium diselenide (CIGS) on a flexible substrate

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ABSTRACT

The laser structuring of CIGS (copper indium gallium (di)selenide) solar cell material without influence and damaging the functionality of the active layer is a challenge for laser methods The shock-wave-induced thin-film delamination (SWIFD) process allows structuring without thermal modifications due to a spatial separation of the laser absorption from the functional layer removal process. In the present study, SWIFD structuring of CIGS solar cell stacks was investigated. The rear side of the polyimide was irradiated with a KrF-Excimer laser. The laser-induced ablation process generates a traverse shock wave, and the interaction of the shock wave with the layer-substrate interface results in a delamination process. The effect of a water confinement on the SWIFD process was studied where the rear side of the substrate was covered with a ~2 mm thick water layer. The resultant surface morphology was analysed and discussed. At a sufficient number of laser pulses N and laser fluences Φ, the CIGS layer can be selectively removed from the Mo back contact. The water confinement, as well as the increasing laser beam size A_0 and N, results in the reduction of the necessary minimal laser fluence Φ_{th}. Further, the delaminated CIGS area increased with increasing Φ, N, and A_0.

1. Introduction

Patterning processes of thermal sensitive thin-film stacks for flexible electronic or thin-film photovoltaic applications attracted increasing attention in the last decade. Especially, patterning of thin-film solar cells (TFSC) based on compound semiconductors like CIGS (copper indium gallium (di)selenide) are of great interest due to their promising potential in terms of low cost manufacturing, high effiency, and capability of using flexible substrates. In comparison to mechanical patterning of CIGS, TFSC laser patterning processes are advantageous in terms of process speed, tool wear, and flexibility. However, laser patterning of thermal sensitive materials stacks like CIGS – TFSCs is challenging due to laser induced local material modification which can induce shunts or leak currents [1,2]. By laser direct ablation of CIGS with nanosecond laser pulses, the material modifications are mainly caused by the thermal impact of the absorbed laser energy. However, also by the usage of ultrashort laser pulses, material modification like ripple formation, thermal modification of the laser irradiated surface, or the deposition of small debris can often be observed [3–5]. These laser induced material modifications influences the electrical performance of the CIGS TFSC device [6,7]. In order to overcome these limitations, several alternative approaches for laser patterning of CIGS based on laser induced thermal – mechanical processes have been reported [8–13]. For thermal – mechanical patterning of CIGS TFSC laser induce stress inside the CIGS layer or in the interface between the CIGS and the underlying material are used for the material removal process. In several studies, it could be shown that by using NIR – nanosecond laser pulses [12,13] and NIR – picosecond laser pulses [4,10], a thermal – mechanical patterning of CIGS thin films without thermal modification can be achieved. Another approach for non-thermal laser patterning of CIGS TFSCs is SWIFD (shock-wave-induced thin-film delamination) [14]. By the SWIFD patterning, a functional layer is delaminated from the substrate whereas the laser pulses absorption process is spatially separated from the delamination process [15–18]. At the SWIFD process, the non-covered rear side of the substrate is irradiated and ablated by laser by nanosecond laser pulses. This ablation process

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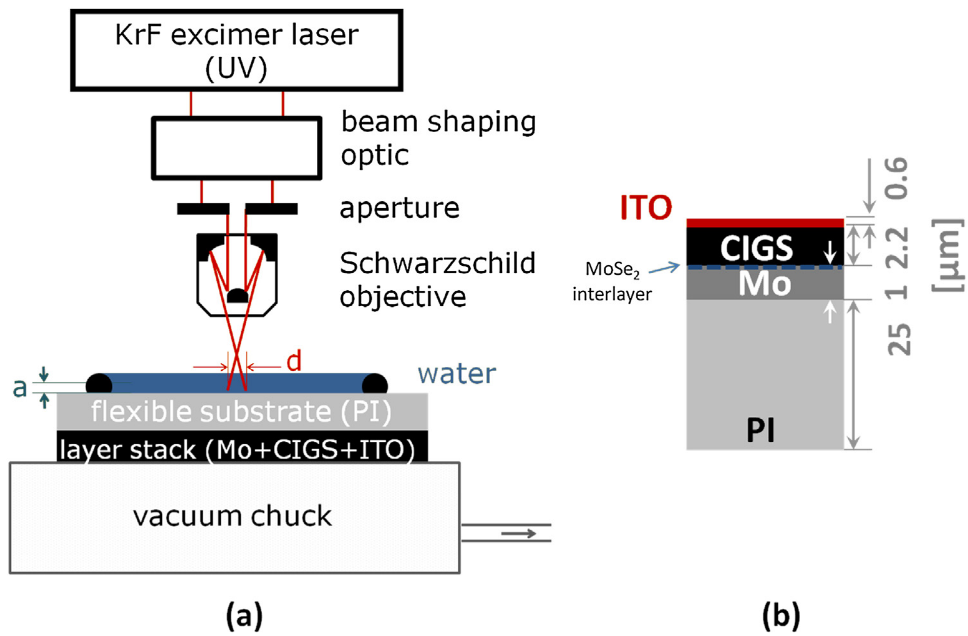

Fig. 1. (a) Schematic illustration of the experimental set-up. (b) Set-up of the CIGS solar cell stack (front contact: indium tin oxide (ITO), active layer: copper indium gallium diselenide (CIGS), back contact: molybdenum (Mo), flexible substrate: polyimide (PI)).

induces a transverse shock wave, which propagates through the substrate. The interaction of the transverse shock wave with the substrate – functional layer interface can causes a delamination of the functional layer. In application of SWIFD, various materials of functional layers and substrates were combined in order to obtain more detailed information about the process. CIGS, indium tin oxide (ITO), epoxy-based negative photoresist (SU 8) and polyimide (PI), polyethylene terephthalate (PET), and stainless steel were studied as materials for functional layers and substrates accordingly [15–18]. Shadowgraphy measurement were used to investigate and directly depict the dynamics of the SWIFD treatment [15,18]. Furthermore, attraction (adhesion) of the functional layer to the substrate surface can also be studied by using the SWIFD technique [19].

In the present investigation, the SWIFD process on CIGS TFSC with and without water confinement on the rear side of the substrate was studied. The influence of the laser parameter: fluence Φ, the number of laser pulses N, and laser spot size A_0 with and without an additional water confinement on the SWIFD process were analysed and discussed.

2. Experimental set-up

The experimental set-up is schematically illustrated in Fig. 1(a). During the delamination process, the sample was fixed on a vacuum chuck, and the laser beam was focused on the rear side of the substrate where a Schwarzschild lens projected a rectangular aperture. The computer-controlled aperture size can be variated, where the projected rectangular top hat beam on the rear side was variated from $10 \times 10\,\mu m^2$ to $200 \times 200\,\mu m^2$. The top hat beam profile was produced by a beam shaping and homogenizing optics with an energy deviation in the mask plane of below 5% rms. As a laser, a KrF excimer laser with a wavelength of $\lambda = 248$ nm, a pulse duration of $\Delta t_p = 25$ ns, and a repetition rate of f = 1–100 Hz was used.

The SWIFD process was studied on a CIGS solar cell, which consists of an indium tin oxide (ITO) front contact (thickness ~0.2 µm), a copper indium gallium diselenide (CIGS) active layer (thickness ~2 µm) and a molybdenum (Mo) back contact (thickness ~1 µm) on a 25 µm thick flexible polyimide (PI) substrate (see Fig. 1(b)). The aim of the SWIFD process is the selective delaminating of the CIGS layer including the ITO front contact without damaging the Mo back contact. Therefore, the rear side of the substrate was irradiated, and the laser-induced ablation process initiated a transverse shock wave where the interaction of the shock wave with the substrate-layer stack interface cause a delamination process. At first, the SWIFD process was studied without an additional confinement at different laser spot sizes A_0, laser fluences Φ, and numbers of laser pulses N.

Further, the effect of an additional confinement on the SWIFD process was studied; therefore, the rear side was covered with a (2 ± 0.1) mm thick deionised water film (see Fig. 1(b)).The water was changed after every laser pulse to exclude absorption effects in the liquid, which can be induced by the laser-ablated material in the water.

The resultant structures on the layer stack on the front side of the flexible substrate were analysed by optical and scanning electron microscopy (SEM). Further, the atomic composition of the delaminated area was measured by energy-dispersive X-ray spectroscopy (EDX).

3. Results

The SWIFD process was studied on a CIGS solar cell at different laser parameters (laser fluence Φ, number of laser pulses N, and spot size $A_0 = d^2$) without (Section 3.1) and with an additional water (Section 3.2) confinement.

3.1. SWIFD without water confinement

In Fig. 2, the effects on the front side of the CIGS solar cell induced by the rear side irradiation are summarized dependent on the laser parameters N, Φ, and A_0 (blue: no effect, red: delamination of CIGS, green delamination: Mo, black: full penetration).

$N_{th}{}^{CIGS,Mo,Pen.}(\Phi, A_0)$ is the minimal number of necessary laser pulses N for a successful delamination of the CIGS layer, of the molybdenum back contact $(^{Mo})$ and the full penetration of the sample $(^{Pen.})$, respectively, where N_{th} is dependent on Φ and A_0.