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Metallization of Si heterojunction solar cells by nanosecond laser ablation and Ni-Cu plating

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ABSTRACT

A key step in industrialization of photovoltaics (PV) is the development of low-cost and large-area metallization processes to substitute the standard screen-printing process of silver paste. Thus Cu and Ni metallization processes enabled by laser patterning have been widely pursued in passivated-emitter rear-cell (PERC) technology. However, the undesirable opto-thermal side-effects of laser processing have so far hindered using similar processes for metallization of Si heterojunction (SHJ) solar cells due to the relatively high sensitivity of SHJ cells to thermal shocks. Here an innovative process is described, in which the laser damage to the SHJ cell is minimized by using a double-mask layer that optically and thermally isolates the device from the laser beam. As a proof of concept, Si heterojunction solar cells of 235 cm^2 surface area are metallized using this method and $>19\%$ power conversion efficiencies are achieved. This process is applicable to any temperature-sensitive electronic device with front conductive surface, such as perovskite/Si multi-junction and semi-transparent perovskite solar cells.

1. Introduction

Presently the PV market-share is dominated by Al back-surface field (Al-BSF) and passivated-emitter rear-cell (PERC) technologies [1,2]. However, the development and market share of Si heterojunction (SHJ) technology is rapidly expanding with an estimated potential of 10% market share by 2025 [1–4]. This technology has the world-record power conversion efficiency for Si photovoltaics, recently set at 25.1% in the standard configuration that requires a metallic grid front-contact [5].

In an SHJ device, the surface defects of c-Si are passivated by ultrathin intrinsic hydrogenated amorphous Si (a-Si:H) layers thus enabling open circuit voltages up to 750 mV [3,4]. These a-Si:H layers are sensitive to temperature and the device loses its functionality if they are exposed to >250–$300\,^{\circ}C$ temperatures for several minutes [6]. In a standard low-temperature metallization process, the electrical contacts are made by screen-printing of a silver paste onto a thin (70–100 nm) transparent conductive oxide (TCO) layer deposited on the a-Si:H layers. The electrical conductivity of the silver paste is significantly lower than that of bulk silver because the low-temperature silver paste used in SHJ technology is less conductive than those typically used in diffused-junction c-Si solar cells [7]. Thus, using silver paste in the typical 3–5 busbars configuration either limits the efficiency or increases the cost of SHJ solar cell because of its low electrical conductivity [3] and the high cost of silver.

Copper is a low-cost alternative to silver and has proven to be effective as electrical connection in microelectronics and in PERC technology [8,9]. As a proof of concept, Ni-Cu plating has been implemented in SHJ solar cells using patterns defined by photolithography and significant improvements have been shown in the quality of the metallization relative to silver paste screen-printing process [10] because the Cu-plated metallic lines have a conductivity close to that of bulk Cu [11]. The lithography patterning step is costly and needs to be replaced by high-throughput and low-cost alternative processes such as laser ablation or inkjet printing [12]. In fact, laser ablation has already been successfully used for patterning the SiN_x dielectric layer of Si solar cells with diffused junctions allowing subsequent Cu plating [13,14]. This process functions because in diffused junctions the depth of doped layers is several hundreds of nanometers in contrast to a few tens of nanometers in SHJ technology [15]. Therefore, for diffused homo-junctions, the opto-thermal damage induced by laser is less

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critical and in severe cases the damaged parts can be removed by chemical etching [16].

The development of laser patterning for SHJ solar cells, usually covered with a thin transparent conductive oxide (TCO) film, is more delicate because direct patterning of a dielectric on top of the TCO leads to damage in the a-Si:H ultra-thin surface passivation. In this work, we make the proof of principle of a double-layer masking strategy in which one layer functions as the mask for the plating process and the other layer acts as the mask for laser ablation process, protecting in large part the solar cell from the opto-thermal damages induced by the laser. The key challenge is to design the process such that the patterning is carried out by a single laser pulse to maximize the process throughput. This is achieved by precise design and iterative optimizations of the mask layers as well as the laser parameters. Using this laser process with subsequent Ni-Cu plating, 235 cm^2 SHJ devices are metallized and low-damage laser ablation along with PV efficiencies up to 19.18% is achieved.

2. Material and methods

2.1. Process scheme

Fig. 1 schematically shows the processing steps proposed for metallization of SHJ cells. The cell is coated by a double-layer mask, in which the first (bottom) layer, i.e. the "plating mask" is an optically transparent and electrically insulating layer that is free from pinholes. It functions as the mask for the Ni-Cu plating process. The pinhole-free quality is essential to prevent the creation of ghost patterns during the Ni-Cu plating step. Moreover, this layer needs to be electrically insulating so that, once it is patterned, the subsequent electroplating takes place only in areas patterned by the laser. The optical transparency is useful because in the later processing stages it is not necessary to remove this layer from the device. The second layer, i.e. the "laser mask" is an optically opaque layer for the laser beam to prevent interaction of the laser beam with the device layers where absorption of the laser light might damage the cell.

2.2. Materials selection

In this contribution, Al_2O_3 is used as the "plating mask" because it is transparent and its refractive index is 1.77 in the visible, which is close to the geometrical mean of the refractive indices of air and the used TCO (about 2) [17]. Therefore, it functions as an additional antireflection layer. The other reason is that dense and pinhole-free Al_2O_3 layers can be deposited by atomic layer deposition (ALD) with high deposition rates (~1 nm/s) using inline ALD systems [18]. ALD provides an excellent conformal coverage, [19] which is potentially useful if there are contaminating particles on the wafer surface because through ALD they will be covered completely with the Al_2O_3 layer. Moreover, Al_2O_3 is stable in the Ni and Cu plating solutions and in many other chemicals. Therefore, it gives more freedom for choosing materials as the "laser mask" that can be removed selectively after laser patterning. Finally, it is known that Al_2O_3 is an excellent diffusion barrier and hence it blocks diffusion of Cu and moisture from the environment into the cell [9].

The a-Si:H capping layer is used as the sacrificial layer or "laser mask" in the process to prevent the laser beam from reaching the device layers and causing opto-thermal damages. The thickness of this layer needs to be chosen such that i) it is sufficiently thick to absorb the entire laser energy and ii) it is sufficiently thin to be removed along with the Al_2O_3 layer by a single laser pulse.

2.3. SHJ device preparation

In an SHJ cell, ultrathin a-Si:H layers are used on each side of the wafer to passivate surface defects of the Si wafer and create the semiconductor energy levels necessary for charge separation. SHJ devices were fabricated on n-type, 160-µm-thick, 6-in. Czochralski (CZ) wafers with nominal resistivity of 1–5 Ω cm. The wafers first received a saw-damage removal chemical step, followed by alkaline texturing and chemical cleaning. They were then dipped for 60 s into a 5% hydrofluoric acid solution to strip the remaining oxide and immediately loaded into a plasma-enhanced chemical vapor deposition (PECVD) reactor; an OctopusII cluster system from INDEOtec SA. At the front side of the device, a stack consisting of an intrinsic a-Si:H layer capped with a p-type a-Si:H layer was deposited. An intrinsic a-Si:H layer capped with an n-type a-Si:H layer was deposited at the rear side. All a-Si:H layers were deposited at 200 °C with thicknesses between 5 and 10 nm (as measured on a glass substrate). We used a gas mixture of SiH_4, H_2, PH_3 (only for n-type doping) and $B(CH_3)_3$ (only for p-type doping). The devices were eventually completed by depositing an 70 nm thick ITO (In_2O_3:Sn) layer at the front side, and an ITO/Ag stack at the rear side, using thin film sputtering.

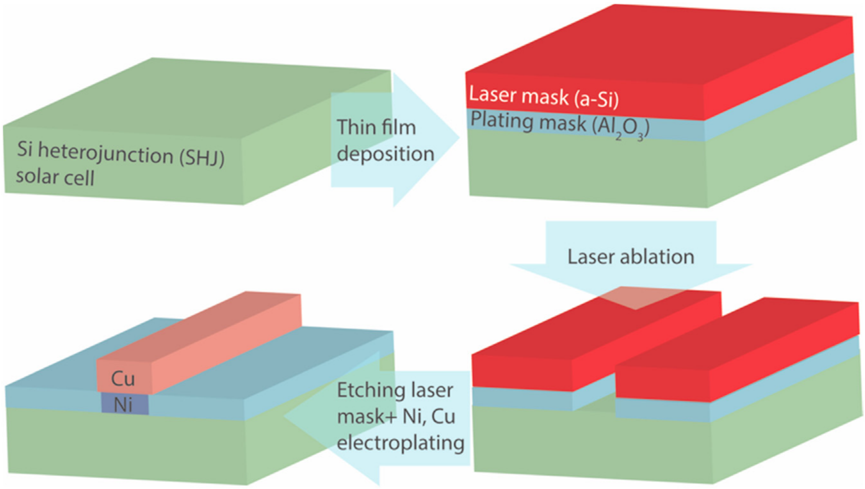

Fig. 1. Process scheme. The steps to metallize an SHJ cell by the combination of nanosecond laser ablation and Ni-Cu plating involves deposition of the mask layers, laser ablation, and etching the laser mask followed by Ni-Cu plating.