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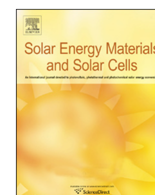

Overcoming electrical and mechanical challenges of continuous wave laser processing for Ni–Cu plated solar cells

C. Geisler *, W. Hördt, S. Kluska, A. Mondon, S. Hopman, M. Glatthaar

Fraunhofer Institute for Solar Energy Systems, Heidenhofstrasse 2, 79110 Freiburg, Germany

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ABSTRACT

Continuous wave laser processes used to create solar cells with selective emitter and plated Ni–Cu front contacts are a widely discussed topic. Particularly low adhesion of the front metal contact has been identified as a serious challenge. In this work a detailed surface characterization of laser doped and patterned front sides of solar cells shows that formation of silicon oxynitride hinders nickel silicide formation and reduces contact adhesion of Ni–Cu plated contacts. In order to overcome the observed tradeoff between metal contact adhesion and penetration of the pn-junction, this paper presents a novel process sequence based on the formation of a deep selective emitter using a green continuous waver laser and subsequent patterning of the dielectric using a nanosecond-pulsed laser.

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1. Introduction

Upgrading existing production lines based on screen-printed solar cell design with technologies that increase the performance of the emitter and front metal contact system has been a route pushed by many manufacturers in recent years [1–5]. The most conspicuous effort was made by the company Suntech Power with its Pluto technology [6]. In advanced cell concepts such as the PERL cell design recombination at the front surface accounts for more than 50% of the total recombination loss [7]. Laser patterning of the front side in combination with self-aligned Ni–Cu plating [8] proves to be a viable route to overcome these limitations. In the literature a wide range of laser systems have been investigated ranging from picosecond pulsed UV laser to ablate the dielectric without damaging the underlying emitter up to continuous wave (cw) IR lasers penetrating deep into the Si allowing incorporation of dopants to create a selective emitter structure [7,9,10]. At the time of writing ps-ablation without additional incorporation of dopants is favored due to the reduced process complexity and satisfactory electrical and adhesion results [11–13]. However a selective emitter brings additional benefits with regard to performance as well as reliability: the furnace diffused emitter can be tailored for low recombination losses below the passivated area of the device whilst the laser doped emitter can be optimized for low Si–metal contact resistance [3,14,15].

Besides electrical performance, processes for industrial production have tight constraints on processing speed, process stability, parasitic plating and long-term stability. Especially the adhesion between Si and Ni of the plated front metal contacts to has been identified as a challenge [15–18]. Poor adhesion can cause problems during automated module manufacturing, leads to detachment of contact fingers and reduces long-term module stability. The adhesion of Si and Ni can be promoted by mechanical interlocking of the metal within surface keying features [19–21]. A more commonly used approach to improve adhesion is based on the creation of a Ni silicide (Ni_xSi_y) layer jointing Si and Ni by chemical bonding [22–24]. In the latter approach plated Ni diffuses into the underlying Si wafer and forms a Ni_xSi_y layer during an annealing step at elevated temperatures ($\approx$300–450 °C). Here Si and Ni_xSi_y are bound by covalent bonding and Ni_xSi_y and Ni by metal bonding [25].

Mondon et al. [24] have demonstrated excellent contact adhesion between solar cell and front side metallization using this method. However, the growth of Ni_xSi_y into the emitter involves the risk of metal-induced shunting of the pn-junction lowering cell fill-factor and efficiency [22,9,26]. For this reason forming a deep emitter under the contacts by using a long pulse or cw-laser process seems particularly interesting. However, in this paper we will show that the laser treated surface is not suitable for Ni_xSi_y formation due to a blocking SiO_xN_y layer. By means of X-ray photoelectron spectroscopy (XPS) measurements the laser treated surface is analyzed and implications of different surface treatment's on Ni_xSi_y formation are

* Corresponding author.
E-mail addresses: christian.geisler@ise.fraunhofer.de, christian.geisler@posteo.de (C. Geisler).

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studied using scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX).

We will finally suggest a process sequence to form a selective emitter with cw-laser doping which proves to produce electrically and mechanical stable Ni–Cu plated solar cells. This process creates a 3.5 µm deep pn-junction which effectively reduces the occurrences of metal-induced shunts [9,26] shown using pseudo light IV measurements (Suns V_{oc}) measurements.

2. Experimental

2.1. Basic sample design

The samples within this work are fabricated using common industrial Si material and processes with the exception of the front contact system. 1–3 Ω cm industrial grade CZ-grown 156 × 156 mm^2 p-type Si wafers with random pyramid texture and a thickness of 200 µm were used. A 90 Ω emitter was created with $POCl_3$ diffusion in a tube furnace. After phosphosilicate glass removal and chemical edge isolation a silicon nitride (SiN_x) film with a thickness of 75 nm was deposited on the front side using a plasma-enhanced chemical vapor deposition (PECVD) system (Roth & Rau SiNA XS). Using screen printing and firing at 880 °C, an aluminum back surface field (Al-BSF) was formed on the back side.

Subsequently, the front-side was spin-coated with 30 wt% H_3PO_4 at 3000 rpm creating a 1.5 µm thick liquid phosphorous dopant layer. A 532 nm continuous wave laser (Spectra Physics Millennia Prime) guided by a galvometer scanning head (Scanlabs Intelliscan 20) was used to locally dope and pattern the sample. The laser beam was focused through an f-theta lens to a 15 µm (1/e^2 diameter) spot onto the front surface of the wafer. The 15 W laser spot was scanned across the sample at a velocity of 5 m/s. The laser power is sufficient to simultaneously ablate the SiN_x and create 12 µm wide and 3.5 µm deep highly doped lines. In order to remove the spin-on dopant (SOD) residue the wafers were cleaned in a DI-water rinser.

2.2. Front contact formation

In order to study the influence of the surface condition at the laser-treated region regarding silicide formation, electrical properties and metal contact adhesion 48 × 48 mm^2 test cells were produced with a finger spacing of 1.5 mm and a single 1.5 mm wide busbar. This batch was divided into three groups (20 samples each) following different processing sequences to alter the surface condition of the laser-treated areas. The different process sequences are outlined in Fig. 1.In the first group the laser doping takes place after the SiN_x deposition. Here the ablation of the SiN_x and the local dopant diffusion occurs at the same time during the passage of the laser spot. This sequence is denoted as "SiN_x→open+dope" and has proven to produce Al-BSF cells exceeding efficiencies above 19% [27,28]. In the second group the Si wafer is immersed in BHF 10:1 for 60 s after the laser doping in order to remove SiN_x residues or phosphor silicate glass. This extended sequence will be denoted "SiN_x→open+dope→BHF". It is expected that the increased etch rate of the BHF leads to an increased amount of etched pinholes in the passivation layer resulting in parasitic Ni plating. To address this limitation the third group employs two laser processing steps. The laser doping takes place directly after the furnace diffusion. This also allows us to compare the surface condition of the laser doped lines with and without the presence of a SiN_x layer during lasering. The SOD is spun onto the phosphorus silicate glass (PSG). The laser doping was performed using the same parameters (15 W, 5 m/s) as in the "SiN_x→open+dope" and "SiN_x→open+dope→ BHF" cases, which leads to similar doping depths. After the subsequent PSG etching and SiN_x deposition the dielectric patterning is performed with a ns-pulse laser (Innolas Nanio) at 532 nm. The laser doped area needs to be wider than the 14 µm ns-laser ablation width due to imperfect alignment of the two laser systems. The doping width was set to 150 µm using overlapping laser lines. Fig. 1 illustrates this sequence denoted as "dope→ SiN_x→open". As a reference two test cells have been produced without laser doping and SiN_x patterning by ns-laser pulses ("SiN_x→open").

A 1 µm thin layer of Ni was deposited on the laser pattern using light induced plating (LIP) in a Watts type Ni electrolyte after a 30 s deglaze in HF 50:1 using a RENA inline plating tool. A subsequent rather harsh annealing step at 450 °C for 5 min in forming gas atmosphere was employed to create a Ni_xSi_y silicide layer and to provoke shunting. The process sequence "dope→ SiN_x→open" proved to be electrically stable to annealing so that a prolonged time of 10 min was chosen to test this sequence in even harsher conditions.

In order to characterize the electrical properties of the fabricated solar cells a Sinton Instruments Suns-V_{oc} stage was used to determine the pseudo light IV curves. Silicidation-induced shunting was characterized using the pseudo fill factor (*pFF*) calculated from the these curves measured after annealing [9,26]. Piranha etchant [29] was used to etch off unreacted Ni from the front side of the solar cell. Using SEM and EDX the Ni_xSi_y coverage of the laser doped lines was measured. Reverse biased electroluminescence (ReBEL) studies were performed with a PIXIS 1024 camera

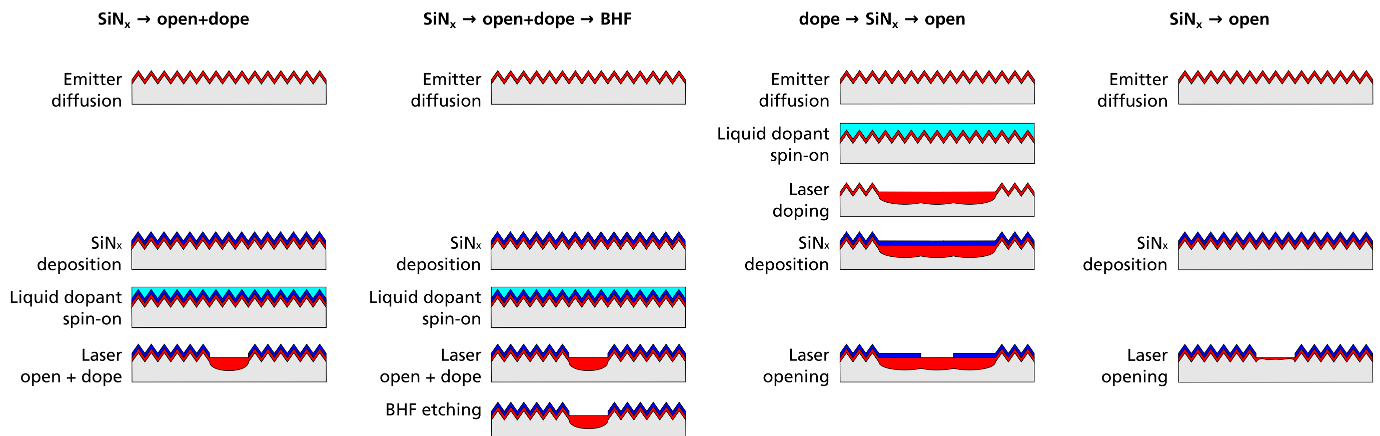

Fig. 1. Schematic of the process sequences used in this work to create selective emitter structures with a cw-laser doping process. The "SiN_x→open+dope" sequence is a straight forward approach where the local dopant diffusion and SiN_x ablation is combined into one step. Using an additional BHF treatment in the "SiN_x→open+dope→BHF" sequence alters the surface condition of the laser doped lines. The "dope→SiN_x→open" sequence splits the dopant diffusion and SiN_x ablation into separate processing steps. The "SiN_x→open" sequence creates a structure without a selective emitter where the contact openings are created using a ns-laser process.

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