Laser Processing of Solar Cells

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ABSTRACT

Laser processing has a long history in the manufacturing of solar cells since most thin-film photovoltaic modules have been manufactured using laser scribing for more than thirty years. Lasers have also been used by many solar cell manufacturers for a variety of applications such as edge isolation, identification marking, laser grooving for selective emitters and cutting of silicon wafers and ribbons. In addition, several laser-processing techniques are currently being investigated for the production of new types of high performance silicon solar cells. There have also been research efforts on utilizing laser melting, laser annealing and laser texturing in the fabrication of solar cells. Recently, a number of manufacturers have been developing new generations of solar cells where they use laser ablation of dielectric layers to form selective emitters or passivated rear point contacts. Others have been utilizing lasers to drill holes through the silicon wafers for emitter-wrap-through or metal-wrap-through back-contact solar cells. Scientists at Fraunhofer ISE have demonstrated high efficiency silicon solar cells (21.7%) by using laser firing to form passivated rear point contacts in p-type silicon wafers. Investigators art both the University of Stuttgart and the University of New South Wales have produced high efficiency silicon solar cells using laser doping to form selective emitters, and some companies are now developing commercial products based on both laser doping and laser firing of contacts. The use of lasers in solar cell processing appears destined to grow given the advances that are continually being made in laser technology.

Keywords: Laser processing, solar cells, laser scribing, laser doping, laser firing

1. INTRODUCTION

As shown by the large number of applications listed in Table 1, lasers have been widely used in the research, development and production of solar cells over the last few decades, and as shown in Table 2, a number of different types of lasers have been used for the various applications. Most of the laser processing has been performed using Q-switched lasers operating with pulse durations of 1 – 200 ns, but some of the processing has been done with CW (continuous wave) lasers as well as with picosecond and femtosecond pulsed lasers. This review will focus mainly on laser processes that have been used in the commercial production of solar cells, as well as those that may be commercialized in the near future.

Table 1. Various applications of laser processing in the research, development and production of solar cells

- Laser-scribed thin film PV modules
- Laser edge isolation for crystalline silicon solar cells
- Laser-grooved, buried contacts for selective emitter silicon solar cells
- Laser cutting of silicon ribbon
- Laser marking for cell or module identification
- Laser-fired base contacts and emitter contacts
- Laser-doped selective emitters and localized base contacts
- Laser-transferred doping and laser-transferred contacts
- Laser ablation of dielectric layers for localized contacts
- Laser-drilled holes for emitter-wrap-through (EWT) solar cells
- Laser-drilled holes for metal-wrap-through (MWT) solar cells
- Laser-textured antireflection surfaces
- Laser-sintered metallization
- Laser defect/shunt repair
- Laser crystallization of a-Si for thin film poly-Si solar cells

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Table 2. Lasers used in the processing of solar cells

- **Nd:YAG laser (532 nm)** – laser scribing of thin-film PV modules, laser doping
- **Nd:YAG laser (1064 nm)** – laser firing of aluminum p^+ contacts, laser drilling
- **KrF excimer laser (238 nm)** – laser scribing of TCO layers for thin-film PV modules
- **Nd:YVO_4 laser (1064 nm)** – edge isolation of silicon solar cells
- **Nd:YVO_4 laser (532 nm)** – laser-transferred contacts, edge isolation
- **Nd:YVO_4 laser (355 nm)** – ablation of dielectric layers for line and point contacts
- **Ytterbium fiber laser (532 nm)** – laser doping
- **CW Nd:YO_4 laser (532 nm)** – laser doping
- **Yb:YAG laser (1030 nm)** – laser drilling for EWT and MWT solar cells
- **Picosecond fiber laser (355 nm)** – ablation of dielectric layers for point contacts
- **Femtosecond laser (800 nm)** – laser texturing for antireflection surfaces
- **Diode-pumped disk laser (512 nm)** – laser crystallization of a-Si for thin Si solar cells
- **CW diode laser (806 nm)** – laser crystallization of a-Si for thin Si solar cells

2. COMMERCIALIZED LASER PROCESSES

2.1 Laser scribing of thin film solar cells

Laser scribing of thin film solar cells was first used to fabricate monolithic PV modules by performing three laser scribes to connect amorphous silicon (a-Si:H) solar cells in series[1,2]. This process used a frequency-doubled Nd:YAG laser (532 nm) to first scribe a tin oxide coated glass substrate into a series of thin conductive strips, ~ 1 cm wide (see Figure 1). After depositing the thin film semiconductor junction (or junctions), the laser was adjusted to ablate only the semiconductor layers in a thin strip adjacent to the scribe in the tin oxide. After the rear contact metal (e.g. aluminum) was deposited, a laser scribe was performed with the light incident through the glass substrate to remove a thin strip of both the semiconductor materials and the rear metal contact completing the interconnection process.

In recent years, laser scribing and patterning has been used to fabricate CIGS PV modules[3] as well as CdTe PV modules[4].

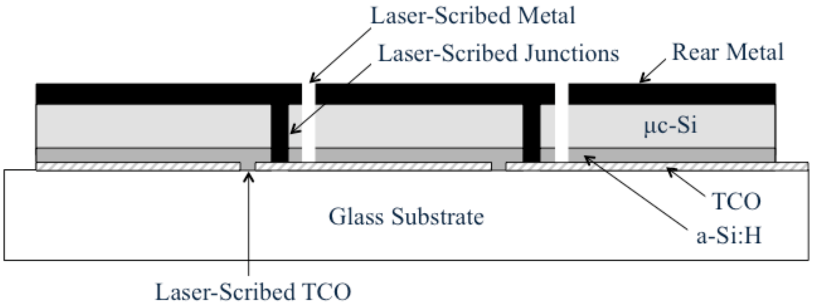

Figure 1. Schematic of a laser-scribed tandem junction (a-Si:H/μc-Si) PV module.

2.2 Laser edge isolation of crystalline silicon solar cells

The p/n junction in most crystalline silicon solar cells is formed by diffusing phosphorus into a p-type wafer at temperatures of ~ 850°C using $POCl_3$ gas as a dopant source. This process usually results in the creation of a leakage path (or shunt) from the front surface emitter to the rear surface base contact due to diffusion of phosphorus into the edges of the wafer and some wrap-around of diffused phosphorus onto the rear surface. A laser can be used to scribe an isolation groove around the outer periphery of the top or rear surface (see Figure 2), effectively removing the shunt path[5]. This is usually accomplished using a green (532 nm), Q-switched laser to scribe a narrow isolation groove near the edge of the emitter on the top surface of the wafer as shown in Figure 2(a).

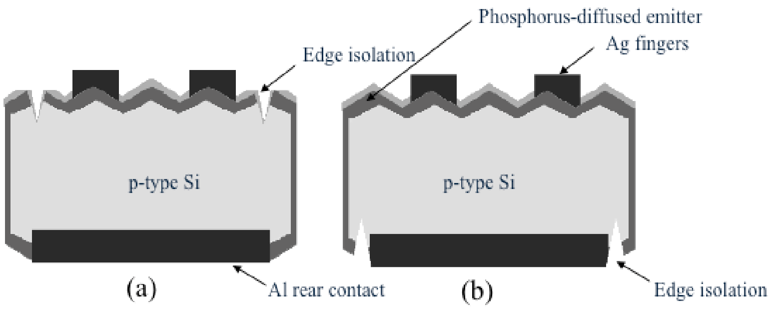

Figure 2. Schematic of silicon solar cells with laser isolation grooves on (a) the front surface and (b) on the rear surface

2.3 Laser grooved buried contact solar cells

The laser-grooved buried contact solar cell was invented by Wenham and Green[6] at the University of New South Wales and was commercialized in 1995 by BP Solar[7]. The grooves were laser scribed through both the silicon nitride antirefection layer and the shallow emitter of a textured p-type Si wafer (see Figure 3). The grooves were typically ~ 25 - 35 µm wide and ~ 30 - 40 µm deep and were formed using high-power Nd:YAG lasers or Nd:YVO_4 lasers operating at 1064 nm. After laser grooving, the wafer was etched to remove laser-induced damage, and an additional phosphorus diffusion was then used to form a heavily doped selective emitter. The grooves as well as the rear surface were then plated with Ni, Cu and Ag. Efficiency as high as 18.3% were achieved in full-size Saturn cells (147.5 cm^2) and efficiency over 20% in small area cells[8]. However, the manufacturing costs were relatively high compared to conventional screen-printed silicon solar cells, and BP Solar stopped manufacturing the Saturn solar cell in 2008.

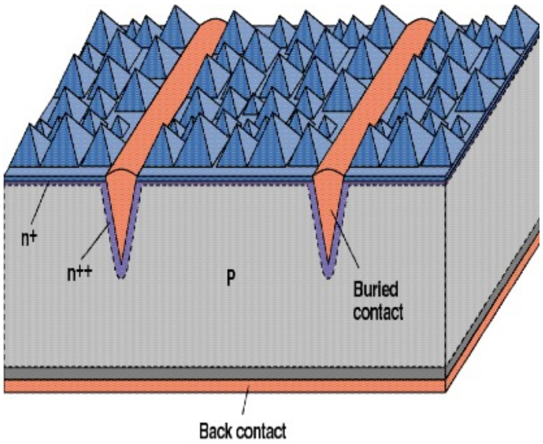

Figure 3. The Saturn solar cell utilized laser grooves to form a narrow, highly doped selective emitter.

2.4 Other commercialized laser applications

Lasers have also been used commercially to cut silicon ribbons into wafers and to mark wafers for identification. Evergreen Solar developed a process to grow silicon ribbons using string of refractory material, and they used an automated laser-cutting machine to section the ribbon into wafers for cell processing[9]. However, Evergreen Solar declared bankruptcy in 2011.

Q-Cells and other solar cell manufacturers have utilized laser marking for single wafer identification to improve quality control and to assist in process improvement[10]. Both Nd:YAG lasers (1064 nm) and Nd:YVO_4 lasers (1064 nm) have been used to create dots ~100 µm in diameter and 10-30 µm deep (using 20-50 ns pulses).

3. LASER PROCESSES UNDER DEVELOPMENT

3.1 Laser fired contacts

Scientists at Fraunhofer ISE have utilized lasers to produce localized p^+ contacts (laser fired contacts or LFCs) by laser firing an aluminum rear contact through a dielectric passivation layer[11] (see Figure 4(a)). They have demonstrated efficiencies as high as 21.7% by laser firing an evaporated Al rear contact through stacked dielectric passivation layers consisting of a-Si:H/SiOx where both layers were deposited by PECVD[12]. The cells (4 cm^2) were made using p-type float-zone (FZ) Si (0.5 Ω-cm).

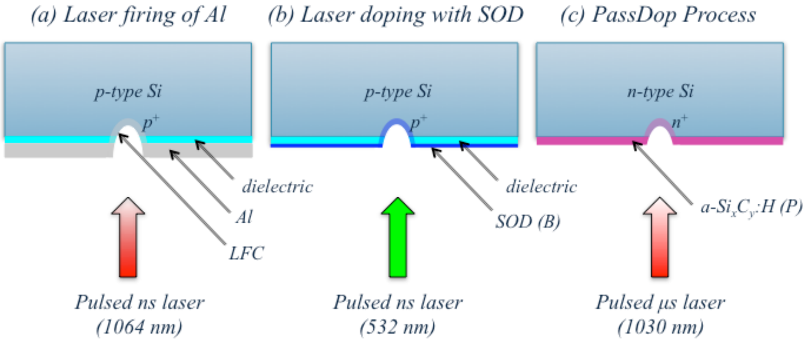

Figure 4. Lasers can be used to make localized doped contacts by (a) laser firing of Al through a dielectric, (b) laser doping of a spin-on-dopant (SOD) through a dielectric or (c) laser doping using a doped dielectric passivation layer.

They have also demonstrated solar cells with efficiencies of ~ 21% using three different types of aluminum contacts[13] – evaporated Al (2 μm thick), screen-printed Al (~ 30 μm thick) and Al foil (8 μm thick). The cells were fabricated on 1 Ω-cm p-type FZ-Si and were all 4 cm^2 in area. While a single laser pulse can produce a high quality LFC with evaporated Al, multiple pulses are usually required for screen-printed Al or Al foil. The LFCs are typically about 100 μm in diameter and form a shallow crater containing Al-doped Si in the central region of the crater (see Figure 5).

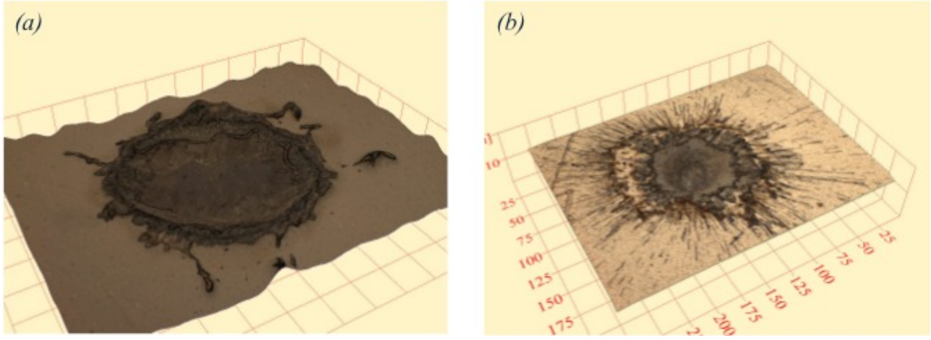

Figure 5. Images of LFCs made with ~ 1 μm of Al (a) at moderate pulse power and (b) at high pulse power.

Laser firing of Al has also be used to produce solar cells with efficiencies as high as 19.3% on n-type FZ-Si by forming an array of localized emitters on the rear surface of the wafers[14]. However, high efficiencies were only obtained on high resistivity wafers (100 Ω-cm) where the cells operated in the high injection regime. When laser-fired emitters were formed in lower resistivity wafers (1 Ω-cm), the best efficiencies were only 13.4% as the lifetime in the vicinity of the laser-fired emitters appeared to be reduced to < 1 μs due to laser-induced damage[14]. LFCs appear to be close to commercialization as Q-Cells had been using the process in a pilot plant[15], but the company has recently declared bankruptcy.

3.2 Laser doping of solar cells

Laser doping has been performed using a variety of doping sources. As shown in Figure 4 (b), one can deposit a spin-on-dopant containing either boron or phosphorus on top of a dielectric passivation layer, and then use a UV or green Q-switched ns laser to locally open the dielectric and dope the silicon wafer[16]. Another approach shown in Figure 4(c) is to use a dielectric passivation layer containing a dopant such as phosphorus-doped a-Si_xC_y:H (the *PassDop* process developed at Fraunhofer ISE[17]). Yet another approach is to form a shallow emitter using $POCl_3$ gas, and then to use a laser to drive in additional phosphorus from the residual phosphosilicate glass on the emitter surface to form more highly doped selective emitter regions[18].

Scientists at the University of Stuttgart have fabricated silicon solar cells with efficiencies as high as 18.9% using laser doping to create a full front surface emitter[19]. They sputtered a phosphorus precursor layer on a p-type FZ-Si wafer and used a pulsed Nd:YAG laser (λ = 532 nm, 65 ns) to melt the silicon surface up to a depth of about 1 μm. Since the laser-irradiated Si stays molten for ~ 100 ns, phosphorus atoms are able to rapidly diffuse into the molten Si creating a high quality emitter (ρ_{sheet} = 124 Ω/sq; J_0 = 88 fA/cm^2). They used line-shaped laser beams (typically 8 μm wide and 225 μm long) since they showed in earlier work that line-shaped beams produce less laser-induced damage than conventional circular Gaussian beams[20]. In more recent work, Dahlinger et al.[21] have fabricated 16.7% solar cells by forming a full surface laser-doped emitter by sputtering boron onto an n-type FZ-Si wafer (3 Ω-cm). The laser doping produced a high quality boron emitter as evident by a low emitter saturation current density of 47 fA/cm^2 (for a 128 Ω/sq emitter).

In other work at the University of Stuttgart, Hoffmann et al.[22] used laser-induced transfer of antimony to laser dope and form a self-aligned selective emitter in p-type Czochralski Si. They used a pulsed laser beam (532 nm) to transfer antimony from a glass support through the dielectric passivation layer of a crystalline silicon solar cell. The antimony rapidly diffuses ($D_{Sb} \approx 1.5 \times 10^{-4}$ cm^2/s) into the molten Si creating a highly doped localized emitter. Using this process, they fabricated selective emitter solar cells with conversion efficiencies as high as 17.5%. Ferre et al.[23] have used laser-transfer doping from phosphorus-doped a-Si:H on glass to fabricate solar cells with efficiencies as high as 19.4%. These cells were made on n-type FZ-Si (2 Ω-cm) with a boron-diffused rear junction, and they used laser-transfer doping to produce selective front surface n^+ regions that were directly contacted with an Al grid.

Laser doping of solar cells has also been achieved at Fraunhofer ISE using a process called Laser Chemical Processing (LCP), which is based on the water-jet-guided laser developed by Synova and uses a dopant carrier liquid such as H_3PO_4 in the water jet[24]. LCP has been used to fabricate selective emitter solar cells with efficiencies of 20.4%.

3.3 Laser Ablation of Dielectric Layers for forming Localized Contacts

Several organizations have used lasers to ablate either a front surface antireflection coating or a rear surface dielectric passivation layer to form openings for either localized emitter or base contacts. Das et al.[25] used a UV (355 nm) Nd-YVO_4 laser (ns pulse width) to ablate 80 nm of silicon nitride on a textured Si surface with a 60 Ω/sq emitter to form both point and line electroplated Ti/Cu contacts. They demonstrated conversion efficiencies as high as 18.55% using line contact ablation on full-size solar cells. Hernández et al.[26] used a similar process to form contacts on the front surface of cells made on p-type CZ-Si wafers and also used a UV ns laser to ablate openings in a rear surface oxide/nitride dielectric stack. They formed localize base contacts by depositing aluminum and firing and obtained efficiencies as high as 19.4%.

3.4 Laser Transferred Contacts

Röder et al.[27] used laser pulses to transfer nickel from a glass support through a silicon nitride antireflection layer to contact the n^+ emitter of a solar cell. The laser transfer process creates nickel lines that are ~ 7 μm wide, and after electroplating additional nickel followed by copper, the finger widths increased to ~ 21 μm. The contacts exhibited a resistivity of 1.8×10^{-6} Ω-cm as well as a contact resistivity < 1 mΩ-cm^2. With this process, they demonstrated conversion efficiencies of 17.4% for a selective emitter solar cell (4 cm^2).

3.5 Laser Drilled Holes for MWT and EWT Solar Cells

Lasers are also being used to drill small holes through silicon wafers in the fabrication of metal-wrap-through (MWT) and emitter-wrap-through (MWT) solar cells. Lamers et al.[28] demonstrated efficiencies as high as 17.9% in full-size MWT solar cells fabricated on p-type multicrystalline Si wafers and an aperture area efficiency of 17.0% in a 36-cell module. They drilled 16 holes in each wafer for the metal-wrap-through connections that carried photocurrent from the fine grid pattern contacting the emitter on the front surface to the busbars on the rear surface. The final processing step involved using a laser to isolate the edge of the cell and around each hole. Hermann et al.[29] fabricated EWT cells (92 cm^2) on float-zone Si with efficiencies as high as 21.4%. EWT cells generally utilize a relatively large number of laser-drilled holes (~ 15,000 – 25,000 holes per wafer) to carry the photocurrent collected by a front surface emitter to the rear surface contacts[30]. In the EWT structure an emitter is formed by diffusion from $POCl_3$ gas not only on the front surface, but also on a portion of the rear surface and on the walls of each laser-drilled hole.

3.6 Laser Textured Antirefelection Surfaces

Nayak et al.[31] have used ultrafast (fs) pulses lasers to texture silicon surfaces by forming self-assembled micro/nano structures (see Figure 6), which efficiently trap incident light. The texture reduces the reflection to less than 3% for the entire solar spectrum, and the material appears completely black to the naked eye. They fabricated solar cells (1 cm^2) with efficiencies as high as 14.2% by laser texturing the front surface of the wafer and using a chemical etch to remove the laser redeposited material. They formed an emitter on the textured surface by applying a spin-on-dopant containing phosphorus and then diffusing the phosphorus into the structured Si by heating the wafer for 15 minutes at 925°C.

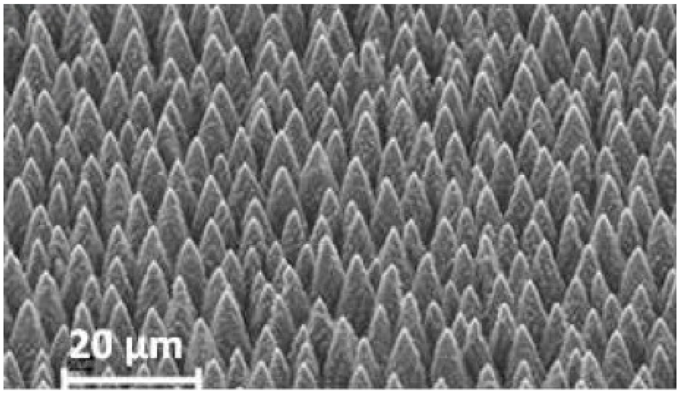

Figure 6. SEM image of a laser-textured surface where each region of the surface was exposed to ~ 300 pulses of a fs laser[31]

Abbott and Cotter[32] used a Q-switched Nd-YAG laser (1064 nm) to ablated pits that produced a textured front surface of monocrystalline and multicrystalline silicon solar cells. They used this type of laser texturing to fabricate double-sided, buried contact solar cells with efficiencies of 18.4% on 1 Ω-cm, p-type float-zone Si wafers.

3.7 Other Laser Processes for Solar Cells

Alemán et al.[33] used lasers to produce front side electrical contacts for silicon solar cells by sintering metal powders (such as silver, molybdenum and tungsten). The metal powder was spread on top of the silicon wafer, and a laser beam was used to sinter the powder forming thin electrical contacts in a finger pattern to the silicon wafer. The non-sintered powder was removed, and silver was electroplated to increase the conductivity of the contacts. They were able to form electroplated finger that were 40 µm wide and 18 µm thick, and they demonstrated efficiencies of about 14.5% in small p-type Si solar cells (1 cm^2) by laser sintering tunsten to a 50 Ω/sq emitter.

Abbott et al.[34] used a Nd-YAG laser (1064 nm, 200 ns pulses) to ablate grooves to locally isolate shunted regions in industrial silicon solar cells. Using this technique, they were able to show that a shunted 9.6% efficient industrial screen-printed solar cell could be recovered to 13.3%.

Lasers have also been used to crystallize thin amorphous silicon films on glass to form a seed layer for epitaxial growth of thicker Si films (> 10 µm) for thin crystalline Si solar cells. CW Nd:YAG lasers have been used to grown relatively large crystals (tens of µm wide and > 100 µm long)[35], but the scanning speed are not adequate for commercialization. Other work[36, 37] has focused on using CW diode lasers operating at about 806 nm, and by heating the a-Si coated borosilicate glass to 600°C, the scanning rate of a line focus (30 mm x 0.1 mm) laser was increased to several cm/s[37].

More recently, Andrä et al.[38] used both a CW diode laser and a diode-pumped disk laser (512 nm, pulse duration 250 to 600 ns) to crystallize thin boron-doped a-Si films (60 – 400 nm thick) at 600°C on borosilicate glass coated with silicon nitride. After thickening the thin silicon films using epitaxy, they fabricated solar cells with open-circuit voltages over 500 mV and short-circuit current densities as high as 20 mA/cm^2.

4. CONCLUSIONS

As discussed in the previous sections, lasers have been used in the research, development and production of solar cells by many organizations using a variety of different processes. Moreover, as laser technology continues to develop, laser are being used in a growing number of applications in many industries. The laser industry continues to make significant investments in laser technology, and worldwide laser revenues increased from $5.56 billion in 2006 to $7.46 billion in 2011. Laser technology will certainly continue to advance in the near future with the development of new types of lasers, higher power lasers, and laser systems with special features and capabilities. Thus, it is highly likely that lasers will find increasing use in the processing of solar cells, and in the next several years, laser processing should allow PV companies to produce higher performance solar cells, PV modules and PV systems at lower costs.

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