第 36 卷　第 12 期
2009 年 12 月
中　国　激　光
CHINESE JOURNAL OF LASERS
Vol. 36, No. 12
December, 2009

文章编号： 0258-7025(2009)12-3116-09

Laser Processing in Solar Cell Production

(Invited Paper)

Shizhou Xiao　Andreas Ostendorf*
(*Laser Applications Technology, Department Mechanical Engineering,*
Ruhr-University Bochum, Bochum 44780, *Germany*)

Corresponding author: *ostendorf@ruhr-uni-bochum.de*

Received October 13, 2009

Abstract　Laser technology as one of the most important manufacturing tools in industry has entered the solar cell production processes in almost all aspects. Laser processing is extensively applied in the complete production line of major parts of high efficiency solar cells based on silicon wafer today, including laser edge isolation, grooving, drilling, soldering, etc. The thin-film solar cells which are on the threshold between development and mass production exhibit further potential in the reduction of production costs and also provide many opportunities for laser processing like laser scribing, laser edge deletion, etc.

Key words　solar cell; thin-film photovoltaic; laser processing; laser drilling

CLCN: V261.8　　**Document Code**: A　　**doi**: 10.3788/CJL20093612.3116

1　Introduction

Solar industry has grown tremendously over the last few years, driven by government subsidies and concerns over rising oil prices, increased air pollution, and global warming. The demand for solar electricity (photovoltaic (PV) power) has grown rapidly during the last decade. Global production of PV modules is believed to have reached 1.25 GWp in 2004 through a year-on-year growth rate of 67% and over a five year period from 2006～2010 is estimated at 52% CAGR, from 2000 MWp to approximately 11000 MWp[1]. Although solar industry is suffering resilience during the current economic trouble time, as shown in Fig. 1(a), the tendency of global annual PV installations with growth rates of 25%～35% per annum, is anticipated over the next 10 years[2].

However, for solar cell technology to become competitive in the long term, both an increase in energy generating efficiency and a significant reduction in production costs are required. The main goal is to decrease the costs per kWh generated electricity. Laser processing is expecting to play an inevitable role in PV industry due to its non-contact nature, possibility to offer a selective tool fine patterning with high aspect ratio features, negligible mechanical stress, and minimal thermal effect. A common feature to many of the high efficiency cells under development is the use of different lasers along the entire process chain, from the silicon wafer material to the assembly of complete solar modules, including cutting silicon wafers, grooving the wafer surface as part of the front grid electrical contact and heat treatment of thin multi-layers on the rear cell surface to form the rear contact. Lasers are also extensively used in all thin-film solar cell technologies. Figure 1(b) demonstrates the laser revenue mix in both c-Si cells and thin-film solar panels in 2008[3].

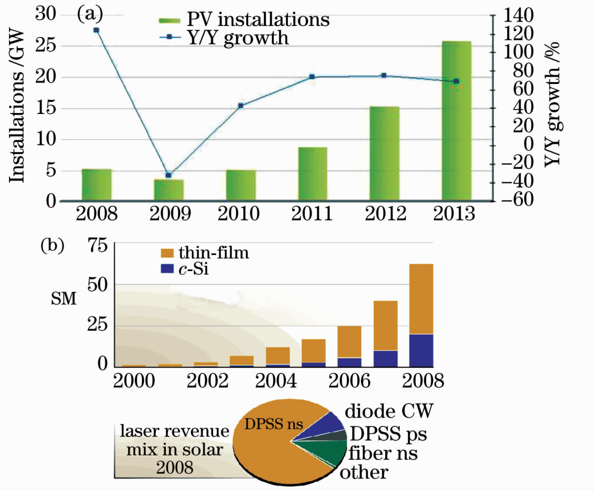

Fig. 1　(a) Global annual PV installations prediction; (b) laser revenue mix in PV of 2008[2]

The widely used silicon based solar cells take advantage of the PV effect which occurs when light is absorbed by a semiconductor. The energy of the photons is transferred to electrons in the valence band of the semiconductor, elevating them into the conduction band resulting in the formation of electron-hole pairs. To extract the energy of the photoexcited carriers as usable electricity requires the existence of a charge separating junction such as a p-n diode. The passage of the excess charge carriers, known as minority carriers (electrons in the p-region, holes in the n-region), across the junction prevents electron-hole recombination and, as a consequence, voltage is generated. In this case when external electrical contacts and load are connected, current is generated from the p-n junction, as shown in Fig.2(a). Figure 2(b) shows a typical *I*-*V* curve for a silicon solar cell. From the illustration of the figure, we can better understand the definition of fill-factor (FF), which is one of most important parameters for qualifying a solar cell. It can be calculated by the following equation:

$$\mathrm{FF} = \frac{I_{\mathrm{mpp}} \times V_{\mathrm{pp}}}{I_{\mathrm{sc}} \times V_{\mathrm{oc}}} \times 100\%, \tag{1}$$

where $I_{\mathrm{mpp}} \times V_{\mathrm{pp}}$ means the solar cell operating at maximum power point, I_{sc} and V_{oc} stands for the short-circuit current and the open-circuit voltage, respectively. Currently, the individual PV market is split into two main technological branches: modules made from wafer-based solar cells and emerging thin-film PV module.

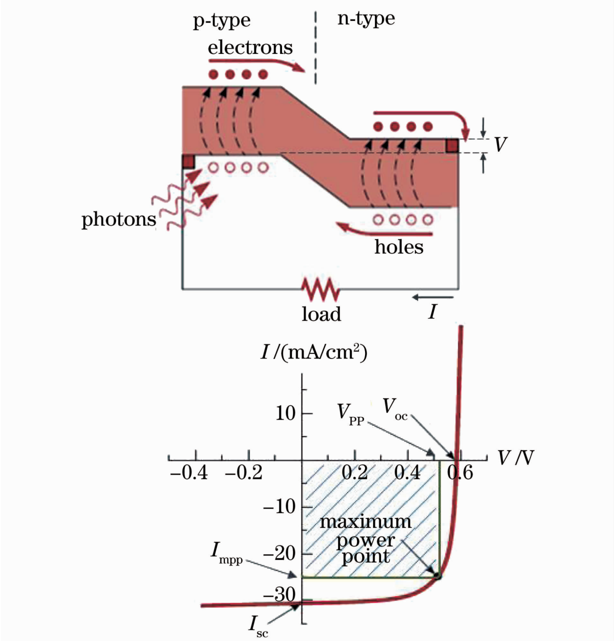

Fig.2 (a) PV effect during illumination. When an external load is connected, a current can be generated; (b) a typical *I*-*V* curve of silicon solar cells. The short-circuit current (I_{sc}), the open circuit voltage (V_{oc}), and the maximum power are illustrated to define the fill factor (FF)[4]

2 Laser Processing in High-Efficiency Wafer Based Solar Cell Manufacturing

Silicon wafer technology includes polycrystalline and single crystal silicon, and these technologies have been existed around for decades. Together they account for over 95% of solar cell production today[1]. Silicon wafer based PV solar cells start from individual silicon wafers sized five or six inch similar to those used in the semiconductor industry. The solar cell PV modules are electrically connected with each other and finally installed on a glass sheet. Such kind of crystalline silicon solar cell modules can achieve high conversion efficiencies from 13% to more than 20% depending on different architectures and processing techniques.

As the wafer thickness has become thinner over the years, currently it is around 160 μm, and they are suffering the risk of breakage due to brittle characteristics of fragile silicon during the processing. Developing laser technology, one of the most important manufacturing tools in industry, finds lots of opportunities in such silicon wafer based PV applications. Actually, laser processing technology is still the key tool in some aspects of this industry today.

2.1 Basic Interaction Phenomena in Laser Processing of Silicon

Laser removal of silicon by ablation is the result of a strong energy transfer from laser radiation to the target material. The transfer occurs in two stages: absorption and conversion. Absorption excites electrons into the conduction band and conversion occurs as the electrons return to the valence band, emitting thermal energy. This process can produce melting, vaporization, ionization, plasma, and material ejection. The interaction depends on several physical parameters of the laser source such as wavelength, pulse energy, pulse duration (τ_{p}), and the thermodynamic properties of the target material. Material removal only occurs if the laser energy imparted exceeds both the bandgap energy E_{g} and the bond dissociation energy D_0, which correlates to the applied laser wavelength. The maximum wavelengths for bandgap energy and bond dissociation energy criterion for silicon are 1106 and 612 nm, respectively. The optimal laser wavelength also depends on the material's spectrum absorption coefficient, which defines the achievable efficiency of energy transfering to the material system at different injected laser wavelengths. When only considering the absorption profile of silicon shown in Fig.3(a), the ideal wavelength is expected to be 285 nm at which silicon is most absorptive[5]. However, the optical penetration depth of silicon should be also taken into account.

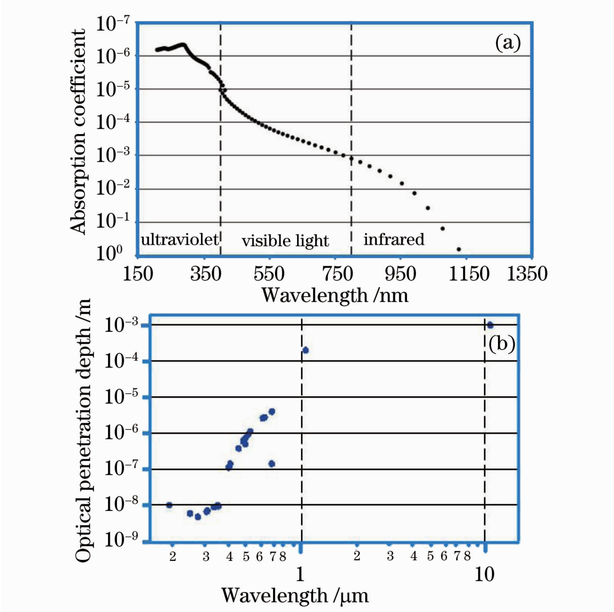

Fig.3 (a) Absorption coefficient profile of silicon at different wavelengths[5]; (b) optical penetration depth of mono c-silicon for various wavelengths at $T=300$ K[6]

Different laser wavelengths, pulse energies, and pulse durations will have specific impacts on the heat affected zone (HAZ) in the material. The thermal penetration depth of a laser pulse is given by

$$L_D = \sqrt{\kappa \cdot \tau_p}, \tag{2}$$

where κ is the material thermal diffusivity and τ_p is the laser pulse duration. In Fig.3(b) the penetration depth of c-silicon is detected as a function of the laser wavelength[6]. All of these parameters need to be optimized in different applications in laser processing solar cells.

2.2 Laser Edge Isolation

One of the main processing steps in the manufacturing chain of c-silicon is the formation of p-n junction. A phosphorous diffusion step is employed near the front-end to create a thin n-type region. However, such doping step not only creates an n-type region at the front surface but also a phosphorous silicate glass (PSG) on all exposed faces, and an undesired n-type doped layer at the sides and the rear is formed. The front-end back contact regions are at risk of electrical connection via the edges, which will result in short-circuit and requires additional process step to isolate the surface, which is the so called edge isolation. For the edge isolation step, due to the economic and environmental benefits compared with plasma and chemical etching approaches, lasers were first proposed in the mid of 1980 and are now widely adopted[7].

Figure 4(a) illustrates how laser scribing creates a thin trench through the SiN_x coating at the back-end. Indeed, research labs have compared different laser types to optimize scribe quality. Scribing trenches like grooves in silicon requires the laser operating with high peak-power pulses for effective material removal. Also, the result strongly depends on the wavelength and the pulse width. In Ref.[8] the authors proved the short absorption length with minimized impact on the bulk c-Si by green 532-nm and ultraviolet (UV) 355-nm lasers. Considered the residual surface quality, Acciarri *et al*. discussed the absorption curve with different laser wavelengths and pointed out that the ratio of absorption at 355 nm was 10^7 higher than at 1070 nm, which magnified undesired HAZ[9]. Schoonderbeek *et al*. comprehensively analyzed the laser scribing of c-Si, and provided the optical penetration depth on mono crystalline silicon for various wavelengths at $T=300$ K, as shown in Fig.3(b)[6]. Additional studies on increased lifetime ratios (decreased laser damage) when scribing lines using short wavelength 355- or 532-nm lasers can be found in Ref.[10], as shown in Fig.5(b). Sub-surface carrier lifetimes were measured before and after irradiation at laser radiation in infrared (IR) (1060 ~ 1070 nm), green (532 nm), and UV (355 nm). All

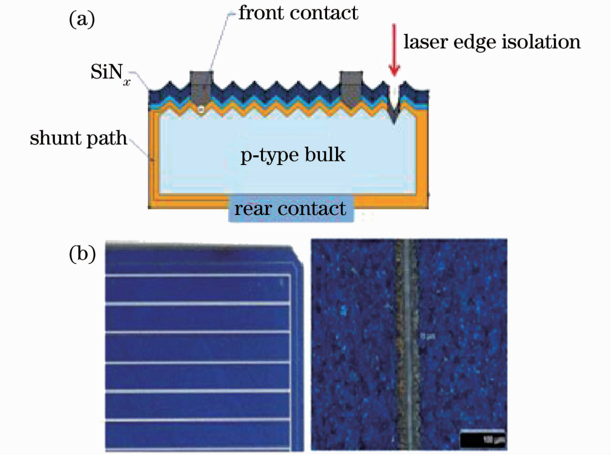

Fig.4 (a) Laser isolation scheme; (b) fine scribe isolation line from a solar cell module (source: Coherent Inc.)

laser wavelength investigations illustrate that lasers with short wavelengths are preferred for edge isolation due to less HAZ. Conventional 1060-nm IR laser are proved to create micro cracks.

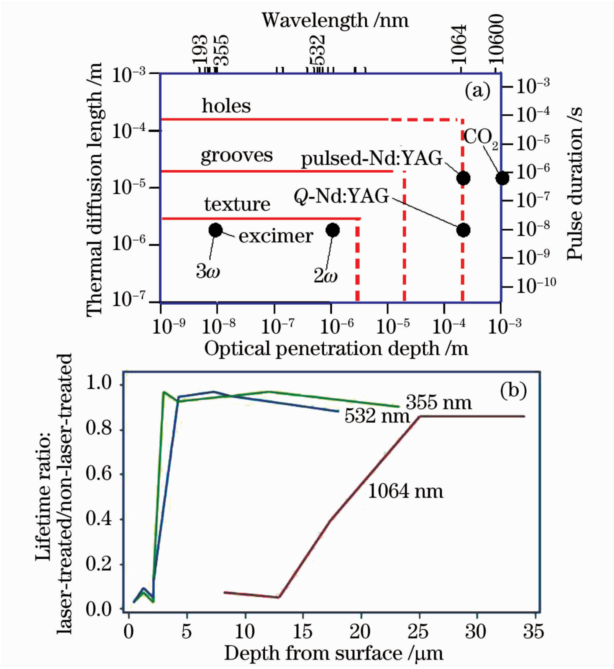

Fig.5　(a) Lasers in relation with the optical penetration depth and thermal diffusion length (mono crystalline silicon, 300 K)[6]; (b) increased lifetime ratios (decreased laser damage) are obtained when scribing lines using 355-, 532-, and 1064-nm lasers wavelengths[10]

Also laser pulse width is optimized according to experimental studies, providing that longer pulses would decrease material removal rates and increase thermal debris on the surface. Short pulses, down to picoseconds, provide cleaner ablation, but they do increase the costs. To reach the industry target scan speeds of 1 m/s, laser power levels of 100 W are needed with correspondingly high repetition rates (> 50kHz) to ensure the quality of the scribe. In Ref.[11], the findings of Emanual *et al*. provide a useful reference about the laser repetition rate and scan speed.

2.3　Laser Grooved Buried Contact

The grooved buried contacts provide an access grid from the front surface of the PV cell without heavy penalty of surface loss or shadows due to wires or metalized surfaces. Traditional mechanical saws with groove widths less than 40 μm are hard to accomplish due to the mechanical forces involved. Accordingly, the laser is quite suitable in this field by scribing trenches of every 2 to 3 mm on the front surface of the *c*-silicon, which is then selectively doped by phosphorous to create a deep contact running along the length of the surface shown in Fig. 6(a). These are called as laser-grooved-buried-contacts (LGBC).

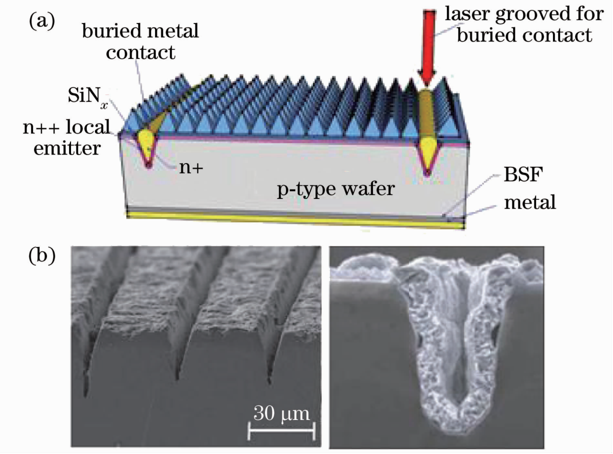

Fig.6　(a) Laser grooving p-type wafer for deep buried contact of solar cell; (b) SEM image of groove obtained by 1064-nm Nd∶YAG laser (source: 3D-Micromac AG, Germany)

Nd∶YAG or Ytterbium fiber lasers are already employed in this process. According to the research work in Ref.[10], the optimal laser wavelength for grooving of LGBC was found to be at 1064 nm where the beam penetration depth was almost the highest. The most efficient removal of silicon from the groove during laser processing was found to occur at low power levels of up to 12 W to minimize the amount of molten silicon residue and limit the laser energy losses. Also, the best groove results were obtained at a high pulse overlap ratios realized by high laser repetition rates and low scanning speeds. The laser pulse duration is not critical for this grooving process in the range of 150～200 ns. It was found that when the laser beam polarization vector was aligned to the groove axis, the groove depth increased. The optimum laser groove width and depth were found to be 20 and 35 μm, respectively, with a groove pitch of 1.5 mm. In Ref.[12], the authors presented a good result by femtosecond laser grooving silicon wafers. Using a defocused and focused method, 40-μm width and 50-μm depth trenches were obtained.

2.4　Laser Fired Contact

Thinner wafers can achieve higher efficiencies when a passivation layer between the rear surface aluminum electrode layer and the silicon is included[13]. However, this passivation layer is non-conducting SiO_2 or SiN_x. The laser fired contacts (LFC) technique is developed to solve this problem. It is proposed by Fraunhofer ISE Germany, a way for full commercial cell production by using laser shot localized contacts shown in Fig. 7(a). In LFC processes, after the deposition of a passivation layer and an aluminum layer on the rear surface of the cell, a laser is used to fire and melt the aluminum locally through the dielectric passivation to form the dot or line contact patterns. At each site, laser pulses drive the aluminum through the passivation layer and several microns deep into the silicon, creating a localized Al/Si alloy. Nd:YAG lasers emitting at 1064 nm in TEM_{00} mode are used, as shown in Fig. 7(b)[14]. LFC technology increases the solar cell's efficiency up to 21.6%, as reported in Ref.[15].

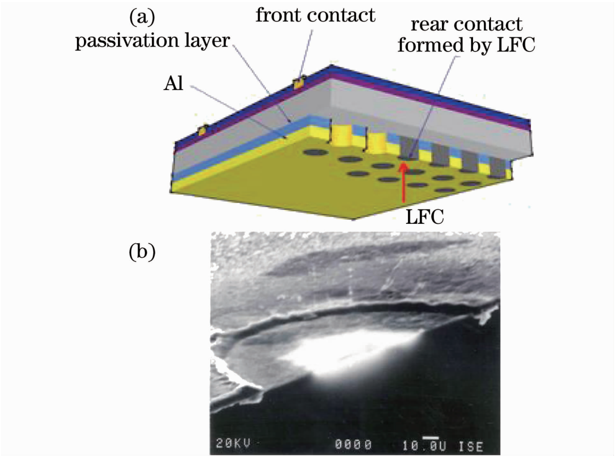

Fig.7 (a) Illustration of laser fired point contact through passivation layer for higher efficiency; (b) SEM image for cross section of laser fired contact (source: Fraunhofer Institute for Solar Energy Systems, Germany)

2.5 Laser Drilling for Emitter Wrap Through and Metal Wrap Through

Common industrial solar cells have a screen printed contact on the front side, which blocks 5% to 7% of the incoming solar light by shadowing. One possibility to increase the efficiency due to less electrical loss is to use wider metal contacts. However, shadow effects increase in parallel. To overcome this disadvantage, many new cell concepts have been developed, with the emitter contact completely or partially on the rear to avoid shading losses by the contacts. This results in higher cell efficiencies. Two designs have been developed. One is the emitter wrap through cell (EWT), where the emitter is wrapped through holes to the rear side of the cell and contacted by metallization at the rear[16,17]. The other is the front side metallization wrap through cell (MWT) where front side metallization and the emitter are wrapped through holes to the rear side, as shown in Figs.8(a) and (b)[14,18]. For these EWT or MWT cells, via holes from front to the back are necessary, for which laser drilling is the only suitable method. Furthermore, back-contacting allows mounting the solar cells close together in the solar module, which saves material cost and appears nicer.

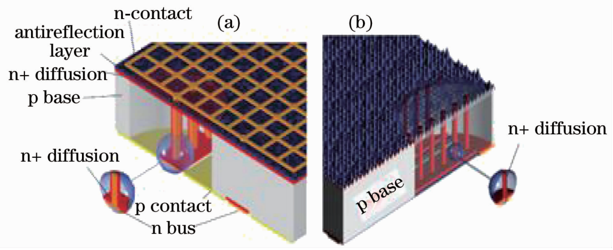

Fig.8 (a) Structure of a MWT cell; (b) structure of an EWT cell[14,18]

With MWT, it requires about 200 holes/wafer and with EWT, up to 20000 of these vias are required on each wafer. Thousands of holes per wafer required high power laser and beam splitters, which can shorten the process cycle to a few seconds. The laser of choice currently is 1064-nm lasers with tens of watts output. But again, manufacturers are already looking at 532- and 355-nm alternatives to produce smaller holes with minimized thermal damage, and both factors increase the efficiency. The MWT has been commercialized by Photovoltech. A similar cell structure called the PUM cell is developed by ECN[19]. The EWT cell design has been demonstrated to be capable of achieving high efficiencies of 21.4%[20] and suitable for industrial production as demonstrated by Advent Solar, Inc. NM, USA, resulting in cell efficiencies above higher than 15%[21].

2.6 Laser Joining of PV Modules

Currently single solar cells with dimensions of up to 156 mm × 156 mm are interconnected by stringer tapes to large modules, as shown in Fig. 9(a). Due to the decreasing thickness, less than 200 μm, laser beam soldering and laser beam micro welding are technology introduced for PV module production.

For that laser soldering is a thermal process in which a liquid phase is formed by melting an additional solder alloy or by diffusion at the interfaces,

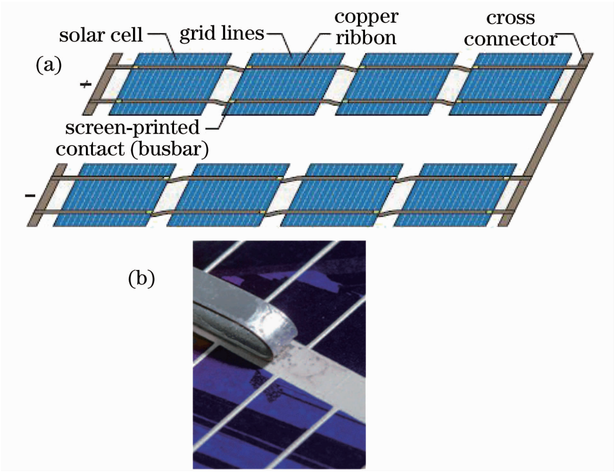

Fig. 9 (a) Schematic setup of solar strings; (b) real image of laser soldering strings on solar cell (source: Fraunhofer ILT, Germany)

laser beam soldering with its temporal and spatial selective energy input combined with the contact less operation is attractive compared with conventional soldering processes. For laser soldering in production systems, three different setups are possible: low-power direct diode lasers, high-power diode lasers with complex beam shaping, and high dynamic scanning systems with working fields up to 160 mm × 160 mm.

Laser micro welding as an alternative to conventional soldering can avoid increased scrap by breakage, because of the low and locally restricted energy input involved. Also it is very promising for future solar cells with respect to flexibility and quality since it does not require any fluxing agent. The validation of the welding process for solar cells has been performed using conventional lamp-pumped Nd:YAG lasers and diode-pumped fiber lasers. The best results with minimum damage of crystalline silicon and maximum peel forces can be achieved using a fiber laser power of 140 W and about 50-ms process duration. In Ref. [22] the author compared different laser soldering effects and pointed out that diode lasers were better for soldering, and then fiber lasers were the best choice for welding due to the small focus diameter (<50 μm).

2.7 Laser Texturing

High-efficiency silicon solar cells need a textured front surface to reduce reflectance since optical losses due to reflectance of incident solar radiation are one of the most important factors limiting their efficiency. There are three different kinds of texturization techniques for multicrystalline silicon solar cells which are currently under investigation or implementation in a production line: acid texturization[23~25], reactive ion etching[26], and mechanical texturization[27,28]. However, each of them has some advantages and drawbacks.

The technique of using lasers to texture multicrystalline silicon solar cells was first published by Zolper[29]. Initial attempts employed overlapping grooves to create an approximation of an upright pyramid texture, as shown in Fig. 10(a). Now it becomes a very promising technique for texturing multicrystalline silicon due to the contactless treatment. Moreover, texture of different patterns can easily be implemented on the treated surface without any additional masking[30~32]. Laser pulses incident on the silicon surface can create inverted cones covered in silicon based ablation by-product. The depth and shape of these cones can be controlled by the amount of energy in the pulse and the number of pulses applied. In Ref. [33] the author provided the results of effective reflectance caused by textured wafers after removal of laser induced damage layers with different thickness and conversion efficiency of corresponding solar cells by means of a 1064-nm Nd:YAG laser.

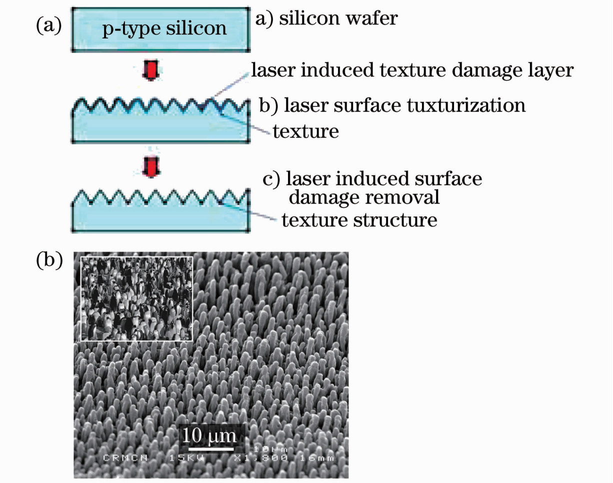

Fig. 10 (a) Laser induced surface texturing scheme; (b) SEM image for details of the laser textured solar cell surface[34]

Harvard University researchers discovered a new kind of technologies for texturing material, named black silicon after treatment from its appearance. By exposing silicon wafers to very short duration femtosecond laser pulses in the presence of sulfur hexafluoride gas, it can produce thousands of tiny cone structures on the surface and turn the silicon dark to the human eye, which means it can absorb most range of visible light, hence the name is black silicon, as shown in Fig. 10(b). Black silicon wafer could approach the theoretical limit of converting around 30%~40% of the energy falling on it into electricity[34]. The technology behind the material was licensed in an exclusive arrangement to SiO*nyx*, a Massachusetts technology startup.

3 Laser Processing of High Efficiency Thin-Film Solar Cells

Historically solar cells are manufactured utilizing silicon wafer technology. However, with the current global shortage and increasing costs associated with manufacture of silicon wafer PV cells, new thin-film on glass or even flexible solar panel alternatives are gaining popularity. Thin-film solar modules can be manufactured in an economical inline process, consuming considerably less material, thereby having the potential to compete economically with conventional energy sources. However, its lower optical-to-electrical power conversion efficiency of 5~10% makes them more suitable for applications requiring large arrays.

The typical semiconductor materials of choice for thin-film solar cells are cadmium telluride (CdTe), crystalline silicon on glass (CGS), copper-indium-gallium-diselenide (CIGS), or amorphous silicon (α-Si). Typical transparent conducting oxide (TCO) materials used are indium tin oxide (ITO), tin oxide (SnO_2), zinc oxide (ZnO), and typical metal layers are, for example, aluminum (Al), gold (Au), copper (Cu), or molybdenum (Mo). After deposition of each blanket layer of material, straight line scribes are created in the material to producing many mini-cell structures which are electrically connected in series to provide high voltage at a low current monolithic thin-film solar cell on a large glass panel. During the processes, laser manufacturing technology plays an important role for motivating such solar cells into industrial production.

3.1 P1/P2/P3 Laser Scribing of Thin-Film PV Modules

Figure 11(a) shows the typical structure of a thin-film solar cell including its electrical interconnection. The main issue is how to use the laser to selectively scribe such multilayer thin-films and forming the electrical interconnection for a larger array. These processes are often referred to by P1, P2, and P3. The P1 process separates the conductive layer such as deposited TCO or Mo contacts of the solar cell for the contact fingers. Process P2 ablates the active layer such as α-Si or CIS, through the glass substrate. Finally, the metal back electrode is removed in a process called P3. Thus, well defined electrical regions are generated for carrier separation and collection to build the most efficient thin-film solar structures. As described, scribing of such multilayer thin-film solar cells is mainly based on different transmissivities of the film materials at the used laser wavelengths, which is the so called selective scribing. Moreover, cut quality in terms of edge roughness and layer peeling is another important consideration, because solar conversion efficiency is substantially reduced by micro cracks and other types of surface and subsurface thermal damage. Therefore, it is vital to create scribes with a minimal HAZ, smooth edges, and no recast debris.

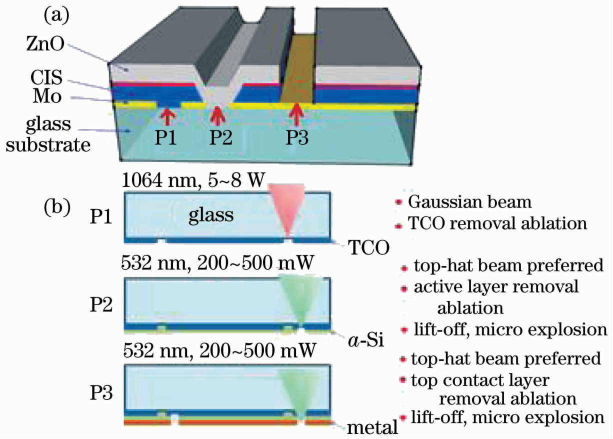

Fig. 11 (a) Schematic of the electrical interconnection structure and the different scribing steps for thin-film solar cells; (b) processing steps using laser in structuring thin film solar panel, removing the Si through a micro explosive lift-off technology

Many research works have been carried out in this area[35~37]. P1 scribing needs a laser wavelength that transmits through glass but is strongly absorbed by the TCO. It can be performed by using conventional techniques with the near-infrared 1064-nm Nd:YAG, even that several watts of laser power transmits through the glass substrate with no damage. P2 and P3 scribing involves removal of much more material than for P1, owing to the active (silicon or CIS) layer's bigger thickness. In order to avoid the use of high laser power which could damage the glass or TCO, a laser lift-off process is introduced in these steps. The lift-off process vaporizes a small amount of material at the film interface, removing the overlaying layers entirely in a micro explosive effect. This is the principal reason that these scribes are performed through the glass, as shown in Fig. 11(b)[38]. Specifically, P2 and P3 scribes are accomplished by using a fast-pulsed green 532-nm DPSS laser, which is transparent to both glass and TCO at this wavelength but strongly absorbed by Si. Additional, typically the Gaussian beam always produces a sawtooth pattern at the border of the trenches, which will increase the mechanical stress and brittleness of multi-layer solar cells. In contrast, with a square top-hat profile, smooth grooves can be generated.

3.2 Edge Deletion

For thin-film devices, edge deletion is analogous to edge isolation of crystalline solar cell. Especially when the various layers are deposited on the substrate, the edges of each layer will not always terminate along the same line. This can lead to electrical short circuits and other functional problems. The films have to be removed at the edge to seal the edge with encapsulated ethylene vinyl acetate (EVA) layer. Encapsulation of the cells is needed to improve reliability and lifetime by preventing humidity and other contaminants from attacking the semiconductor film. Not removing the thin-film from the edge leads to delaminating and efficiency degradation as humidity penetrates.

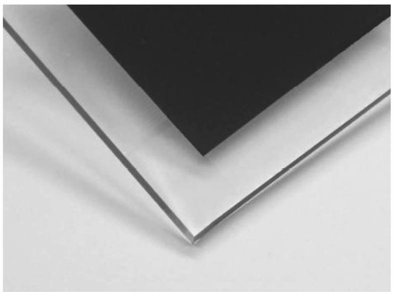

Fig. 12 Typical laser processed edge deletion sample (source: RPMC Inc., USA)

Laser scribing through all the layers down to the substrate can eliminate this problem. Standard TEM$_{00}$ lasers like Nd:Vanadate lasers used for scribing do not provide sufficient ablation rates for this application. Those diode-pumped Nd:YAG 1064-nm lasers are found that its application is this step, which can generate an average power of up to 850 W at 30 kHz, guided through a 600-μm step-index fiber, in order to produce a homogenous, flat-top intensity profile. Typical ablation widths are between 0.7 and 1.5 mm at processing speeds of up to 6000 mm/s.

4 Outlook of Laser Technology in Solar Industry

In conclusion, we summarize the key laser technologies applied in solar cell production, including wafer silicon based and thin-film solar cells. The technologies mostly used in current production lines are laser cutting, laser edge isolation, laser grooving, laser drilling, and laser scribing. Different laser sources such as Nd : YAG, DPSS, solid-state laser, etc., with wavelength of 1064, 532, and 355 nm, have all found their opportunities in different processing aspects in solar cell industry.

Also lots of novel under developing laser technologies are expected to enter this growing industry in future, like laser reactive deposition (LRD), laser processing in thin-film organic PV (OPV), etc. As the PV industry evolves with increasing laser manufacturing process steps, more PV specific laser tools will be developed for next-generation forward compatible production tools. At this point, more laser processing will move from incumbent experiment technology to that of competitive manufacturing tools in solar cell industry production.

References

1 Super sonic solar market [J]. *Photon International*, 2005, 66

2 PV Status Report-2008, http://www.jrc.ec.europa.eu. 2008

3 F. Colville. Laser in the solar industry: market size, growth rates, & trends [C]. Laser and Photonics Marketplace Seminar, 2009

4 Cengage learning, modern physics downloads, http://www.cengage.com

5 S. A. G. D. Correiaa, J. Lossena, M. Walda *et al*.. Selective laser ablation of dielectric layers [C]. *22nd European Photovoltaic Solar Energy Conference and Exhibition*, Mailand, Italien: 2007, 3~7

6 A. Ostendorf, A. Schoonderbeek. Lasers in energy device manufacturing [C]. *SPIE*, 2008, **6880**:68800B

7 M. R. Green, P. D. Morgan, M. R. Siegrist *et al*.. Isolation between amplifiers in a CO_2 laser using absorbing gases [J]. *J. Phys. D: Appl. Phys.*, 1980, **13**:1399~1404

8 F. Colville. Laser scribing tools edge in front [J]. *Global Solar Technology*, 2009, **2**(2)

9 M. Acciarria, S. Binettia, M. Bollania *et al*.. Nanocrystalline silicon film grown by LEPECVD for photovoltaic applications [J]. *Solar Energy Materials and Solar Cell*, 2005, **87**:11

10 A. Schoonderbeek, R. Kling, A. Ostendorf *et al*.. Laser technology for cost reduction in silicon solar cell production [C]. *Proceeding of 69th Laser Materials Processing Conference*, 2007. 85~90

11 G. Emanuel, E. Schneiderlöchner, J. Stollhof *et al*.. High throughput laser isolation of crystalline silicon solar cells [C]. *17th European World Conf. on PV Energy Conver- PVSEC*,

Munich: 2001

12 A. Cole, I. Baistow, L. Brown *et al.*. Technological and financial aspects of laser grooved buried contacts silicon solar cell based on concentrator system [C]. *Workshop on Concentrating Photovoltaic Power Plants*, Marburg: 2007, 11～12

13 P. H. Wu, W. C. Shen, W. J. Tsai *et al.*. Femtosecond laser grooving on silicon wafers for applications to solar cells [C]. *Proceedings of the 15th International WLT-Conference on Lasers in Manufacturing* 2009, Munich: 2009

14 S. W. Glunz, E. Schneiderlöchner, D. Kray *et al.*. Laser fired contact silicon solar cells on p- and n-substrates [C]. *19th European Photovoltaic Solar Energy Conference*, Paris, France: 2004, 7～11

15 A. Grohe, H. Wirth. Future market: photovoltaic industry [J]. *Laser Technik Journal*, 2009, **6**(1):30～32

16 J. M. Gee, M. E. Buck, W. K. Schubert *et al.*. Progress on the emitter wrap-through silicon solar cell [C]. *Proceedings of the 12th European Photovoltaic Solar Energy Conference*, *Amsterdam*, 1994. 743～747

17 A. Schönecker, H. H. C. de Moor, A. R. Burgers *et al.*. An industrial multi-crystalline EWT solar cell with screen printed metallization [C]. *Proceedings of the 14th European Photovoltaic Solar Energy Conference*, Barcelona: 1997. 796～799

18 S. W. Glunz. High-efficiency crystalline silicon solar cells [J]. *Advances in Opto Electronics*, 2007, **2007**:97370

19 J. H. Bultman, M. W. Brieko, A. R. Burgers *et al.*. Interconnection through vias for improved efficiency and easy module manufacturing of crystalline silicon solar cells [J]. *Solar Energy Materials and Solar Cells*, 2001, **65**(1-4):339～345

20 S. W. Glunz, J. Dicker, D. Kray. High-efficiency cell structures for medium-quality silicon [C]. *Proceedings of the 17th European Photovoltaic Solar Energy Conference*, Munich: 2001, October. 1287～1292

21 P. Hacke, J. M. Gee, M. Hilali *et al.*. Current status of technologies for industrial emitter-wrap-through solar cells [C]. *Proceedings of the 21st European Photovoltaic Solar Energy Conference*, Dresden: 2006, September. 761～764

22 F. Schmitt, A. Prießner, B. Krämer *et al.*. Laser joining processes for photovoltaic module production [C]. *Proceedings of the Fifth International WLT-Conference on Lasers in Manufacturing* 2009, Munich: 2009

23 P. Panek, M. Lipiński, J. Dutkiewicz. Texturization of multicrystalline silicon by wet chemical etching for silicon solar cells [J]. *Journal of Materials Science*, 2005, **40**(6):1459～1463

24 H. Seidel, L. Csepregi, A. Heuberger *et al.*. Anisotropic etching of crystalline silicon in alkaline solution-Orientation dependence and behavior of passivation layers [J]. *Journal of the Electrochemical Society*, 1996, **137**(11):3612～3626

25 V. Y. Yerokhov, R. Hezel, M. Lipinski *et al.*. Cost-effective methods of texturing for silicon solar cells [J]. *Solar Energy Materials and Solar Cells*, 2002, **72**:291～298

26 K. Fukui, Y. Inomata, K. Shirasawa. Surface texturing using reactive ion etching for multicrystalline silicon solar cell [C]. *Proceedings of the 26th IEEE Photovoltaic Specialists Conference*, PVSC'97. Anaheim: 1997. 47～50

27 C. Marckmann, G. Willke, E. Bucher *et al.*. Multicrystalline silicon solar cells using a new high throughput mechanical texturization technology and a roller printing metallization technique [C]. *Proceedings of the 13th European PV Solar Energy Conference*, Nice:1995. 29～32

28 C. Gerhards, C. Marckmann, R. Tolle *et al.*. Mechanically V-textured low cost multicrystalline silicon solar cells with a novel printing metallization [C]. *Proceedings of the 26th IEEE Photovoltaic Specialists Conference*, PVSC'97. Anaheim: 1997. 43～46

29 John C. Zolper, Srinivasamohan Narayanan, Stuart R. Wenham *et al.*. 16.7% efficient, laser textured, buried contact polycrystalline silicon solar cell [J]. *Appl. Phys. Lett.*, 1989, **55**(22): 2363～2365

30 L. A. Dobrzański, A. Dryga ℓa. Laser surface treatment of multi-crystalline silicon for enhancing optical properties [J]. *Journal of Materials Processing Technology*, 2008, **201**:291～296

31 L. A. Dobrzański, A. Dryga ℓa. Application of laser in silicon surface processing [J]. *Journal of Achievements in Materials and Manufacturing Engineering*, 2007, **24**(2):179～182

32 L. A. Dobrzański, A. Dryga ℓa. Processing of silicon surface by Nd:YAG laser [J]. *Journal of Achievements in Materials and Manufacturing Engineering*, 2006, **17**:321～324

33 L. A. Dobrzański, A. Dryga ℓa. Surface texturing of multicrystalline silicon solar cells [J]. *Journal of Achievement in Material and Manufacturing Engineering*, 2008, **31**(1):77～82

34 Mool C. Gupta, Barada K. Nayak, Vikram Iyengar. Ultrafast laser textured silicon solar cells [J]. *Mater. Res. Soc. Symp. Proc.*, 2009, **1123**:7～9

35 A. D. Compaan, I. Matulionis, S. Nakade. Laser scribing of polycrystalline thin films [J]. *Optics and Lasers in Engineering*, 2000, **34**(1):15～45

36 C. Molpeceres, S. Lauzurica, J. L. Ocaña *et al.*. Microprocessing of ITO and a-Si thin films using ns laser sources [J]. *Journal of Micromechanics and Microengineering*, 2005, **15**(6):1271～1278

37 H. Huber, S. Zoppel, J. Zehetner *et al.*. High repetition rate ultrafast lasers and their applications in micro machining [C]. *LAMP 2006, International Congress on Laser Advanced Materials Processing*, Kyoto: 2006

38 Corey M. Dunsky, Finlay Colville. Scribing thin-film solar panels, industry laser for manufacturing [J]. *Industrial Laser Solutions*, 2008