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Laser Material Processing in Crystalline Silicon Photovoltaics

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Abstract**--**Lasers play a major part in the processing of the numerous materials used in engineering and manufacturing. The range of processes in which lasers are involved is ever increasing. One of the areas in which laser has recently found application is in energy systems. With the dwindling non-renewable sources of energy such as fossil fuels and increasing demand of electricity, there is increasing interest in addressing the energy problem through development of systems for renewable energy alternatives such as solar energy. Though solar energy is readily available and has no adverse effects on environment such as pollution and greenhouse effects, it has not been fully exploited due to a number of challenges. Some of these challenges include high capital cost and the low conversion efficiency. Therefore photovoltaic industry has taken advantage of the benefits inherent in laser technology, namely accuracy, cost-efficiency, and flexibility that are critical in manufacturing today. This paper presents a review of the various production and assembly methods employed in the manufacture of solar panels where laser technology plays a predominant and the types of lasers are preferred along the photovoltaic production chain from the silicon raw material to the finished laminated solar modules.

Keywords**--** In-laminate laser soldering, Laser, Metal-to-plastic joining, Monocrystalline solar cell, Photovoltaic, Solar panel assembly.

I. INTRODUCTION: LASER MATERIAL PROCESSING

OVER the last two decades laser processing has become an indispensable part of competitive manufacturing throughout the world. Whether the project involves metal, glass, plastic, silicon, rubber, or even wood, laser materials processing has proven its superiority in terms of accuracy and process efficiency. The term “laser materials processing” refers to a number of different types of processes all utilizing the unique benefits offered by laser light. These processes include welding, cutting, cladding, heat treating, machining and drilling which are easily accomplished with lasers instead of traditional manufacturing techniques, tools and machinery.

Laser processing has a number of important benefits over other available methods. One of the benefits of laser processing is its ability to work with many different types and shapes of materials. Traditional drilling methods, for example, are difficult to use on rounded materials. With laser drilling, a non contact process, geometric limitations are easily overcome with conventional or shaped holes easily processed. Additionally, cutting certain materials has always been nearly impossible for standard machinery, but with lasers, it is easy to burn, vaporize, or melt away the edges to leave a clean consistent cut. Another benefit is efficiency; for example, the use of laser in processing is faster than traditional industrial methods in say, welding, cutting, and drilling. As a result higher production rates are achievable with laser.

Moreover, since laser processing does not require direct contact between the materials and the equipment, there is no wear nor tear on the tools and there is little down-time. Of course, one of the most important benefits of laser processing is precision. Due to the fact that the positioning of laser beam is computer controlled and that there is no direct contact of the workpiece with the laser equipment much higher accuracy is achieved than for any of the conventional equipment. In conventional processes, as tools become worn they also become less precise. That never happens with laser processing – the first cut is as precise as the thousandth cut. The bottom line is that accuracy, cost-efficiency, and flexibility are critical in manufacturing today when saving money and preserving quality are the keys to staying ahead of the game. Laser processing can be the solution that provides all three of those factors [1, 2]. Laser technology can be used in processing of almost all types of materials including the hardest and most difficult to materials. Some of the meaterials that are easily cut with lasers include super alloys such as Inconel, Waspaloy, titanium and many aluminum alloys.

II. LASER TECHNOLOGY IN PHOTOVOLTAICS

When it comes to laser technology, photovoltaic industry has not been left behind and most of the numerous processes in cell manufacturing and modules assembly use in one way or another laser technology. The involvement of laser systems depends on the type of the initial material, crystalline or polycrystalline silicon or thin film solar cells, et cetera.

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Here our emphasis will be on silicon crystalline solar cells and on laser welding/soldering of solar cells in panel assembly, because contrary to well established laser processes like laser cutting and scribing of cells , laser welding/soldering is still under investigation in many photovoltaic research institutions [3]

III. TYPES OF SOLAR CELLS

Today, two PV technologies compete for market dominance, crystalline silicon (c-Si) and thin film. Currently about 80 - 85% of all PV modules are manufactured using c-Si technologies [4]

c-Si technology involves the fabrication of high purity ingots of poly- or single crystal Si material usually from natural quartz. These ingots are doped with boron. The ingots are sliced into wafers and doped on the surface with phosphor using a thermal diffusion process forming a p-n semiconductor junction. Some manufacturers grow thin ribbons of Si directly from molten Si and cut wafers from these ribbons avoiding the requirement of slicing or sawing wafers from ingots, thereby saving significant quantities of costly silicon [5].

Once wafers have been diffused, the front and back metal electrical contacts are added resulting in a finished solar cell. A certain number of these cells are then connected to produce a solar panel. The advantages the c-Si technology are higher cell efficiency (up to 20%), simple and proven technology, while the drawbacks are the amount of costly Si required to produce a given amount of electricity and higher manufacturing costs.

Solar thin film technology is based on semiconductor materials such as amorphous Si, Cadmium Telluride (CdTe), and Copper Indium Gallium Di-selenide (CIGS). The thin film cells are manufactured by depositing multiple layers of these different materials on glass, metal or polymer substrates. The semiconductor junctions are formed in different ways, either as a p-i-n device in amorphous silicon, or as a hetero-junction for CdTe and CIGS. A transparent conducting oxide layer such as indium tin oxide forms the front electrical contact of the cell, and a metal layer the rear contact. The advantages of this technology include lower cost per peak electrical output Watt due to lower materials and other manufacturing costs and ease of scalability to large panels. The drawbacks are lower efficiency (up to 13%) resulting in larger panel area to produce a given amount of electricity when compared to c-Si based PV modules and complexity of the technology itself [6, 7]

There are also dye-sensitized solar cells DSSC: a modern DSSC, the Gratzel cell, is composed of a porous layer of titanium dioxide nanoparticles, covered with a molecular dye that absorbs sunlight, like the chlorophyll in green leaves. The titanium dioxide is immersed under an electrolyte solution, above which is a platinum-based catalyst. As in a conventional alkaline battery, an anode (the titanium dioxide) and a cathode (the platinum) are placed on either side of a liquid conductor (the electrolyte) [8]. Sunlight passes through the transparent electrode into the dye layer where it can excite electrons that then flow into the titanium dioxide. The electrons flow toward the transparent electrode where they are collected for powering a load. After flowing through the external circuit, they are re-introduced into the cell on a metal electrode on the back, flowing into the electrolyte. The electrolyte then transports the electrons back to the dye molecules. Dye-sensitized solar cells have not yet been developed into industrial devices as they present some inherent disadvantages. These include: the use of the liquid electrolyte, which has temperature stability problems. At low temperatures the electrolyte can freeze, ending power production and potentially leading to physical damage. Higher temperatures cause the liquid to expand, making sealing the panels a serious problem. Another disadvantage is that costly ruthenium (dye), platinum (catalyst) and conducting glass or plastic (contact) are needed to produce the Gratzel cell. A third major drawback is that the electrolyte solution contains volatile organic compounds (or VOC's), solvents which must be carefully sealed as they are hazardous to human health and the environment. This, along with the fact that the solvents permeate plastics, has precluded large-scale outdoor application and integration into flexible structure [9]

IV. APPLICATIONS OF LASER TECHNOLOGY IN C-SI BASED CELL MANUFACTURING

In the solar industry, lasers are positioned to have a very large impact on the manufacturing cost, by increasing cell efficiency, improving throughput, and providing manufacturing equipment with low cost-of-ownership. Inherently a non-contact process, lasers provide a clear advantage over competing technologies as wafer thicknesses decrease (220 to 100 microns) and wafer sizes increase (150 – 200 mm) over the next few years. Lasers have low utility requirements and provide an ideal choice for manufacturing equipment as solar production-lines themselves become more environmentally-friendly. As the manufacture of solar cells, from the sand raw material to assembled panel modules is a long and sophisticated industrial process, lasers surely have found use in many steps of the process and are indispensible tool for the success of the industry their use expand day by day. Table.1 shows the involvement of laser technology in the different steps of industrial photovoltaic manufacture process [10- 12]

Table 1. Laser utilization in industrial photovoltaic manufacturing process

Applications	Production Status		
	Widespread	Partially	R&D
Edge Isolation	√		
LGBC		√	
Dielectric Ablation		√	√
Dopant Diffusion		√	√
Drilling: Wrap-Through		√	√

Texturing		√	√
Laser Fired contacts		√	
Cell cutting		√	√
Module soldering		√	√
Wafer Marking	√		

A. *Edge Isolation*

One of the traditional laser applications is edge isolation. The p-doped wafers are coated with an outer layer of n-doped silicon to form a large area p-n junction. This thin (10-20 microns) layer coats the entire wafer, including the edges, and often the rear surface, creating an unacceptable recombination pathway between the front and back surfaces. This pathway can be eliminated by edge isolation, whereby a groove is continuously scribed completely through this n-type layer. In order to maximize cell active area and hence efficiency, this groove has to be as narrow and as close to the edge as possible. For this purpose the usual laser of choice is a Q-switched diode-pumped solid state (DPSS) laser with a pulse repetition rate around 30 kHz. Some manufacturers use 1064 nm lasers: however, an increasing number of manufacturers are utilizing 532 and 355 nm lasers for this application [13] due to several reasons.

First - these shorter-wavelength green / UV lasers can scribe narrower grooves. In addition, 1064 nm lasers can create microcracks that emanate from the scribed groove and which, if reaching the edge of the wafer, can compromise structural integrity - this limits how close the 1064 nm-machined trenches can be placed to the edge of the wafer. The 532 and 355 nm lasers give an additional advantage of generating less heat affected zone, HAZ, compared to IR lasers. But fibre lasers are catching in: 20 W (average output power) Q-switch ytterbium pulsed fiber laser (YLP) lasers are being be used for scribing edge isolation grooves at a high speed (2 m/sec or faster). The use of the 532-nm wavelength (frequency doubled) results in a somewhat reduced scribing speed and increased cost but yields scribes with much reduced crystal damage resulting in potential higher yield.

B. *Drilling Vias*

A simple solar cell has front and back contacts for the charge carriers and the front metal contacts cover a significant area of the cell (5-7%) and thereby reducing the cell efficiency by obscuration of the sun light. To increase the efficiency and power from each module, newer technologies such as “Metal Wrap Through” (MWT) and “Emitter Wrap Through” (EWT) are being implemented wherein the front contacts are moved to the back surface, leaving the front surface nearly free of metal obscuration. To connect the front surface of the cell with the back surface, drilling hundreds of small holes or vias in the wafer is part of the solution. A 20 W Q-switch fiber laser is used to drill 50 micro diameter holes in 250 micron thick wafers at a speed of 100-200 holes/sec. For laser drilling of the vias processing throughput can be optimized depending on the wafer thickness and the hole density. To achieve the throughputs required for this application, 1064-nm fiber lasers offer the best combination of peak power, pulse energy and higher pulse repetition rate compared to a 532-nm laser.

C. *Front Surface Contacts*

Buried electrical contacts represent one approach to minimizing the area obscured. This is called “Laser Grooved Buried Contacts”, or LGBC method. After the surface has been antireflection-coated with silicon nitride, lasers can scribe narrow surface grooves which are then plated. This results in electrodes with a high volume and collection surface, relative to their width. The grooves have a width and depth of 20-30 microns and are cut at 2-3 mm intervals along the cell. In a recent adaptation of this approach, lasers cut only through the AR coating, and the exposed semiconductor is electroplated. It remains to be seen if ‘next-generation’ front-surface contact methods will bypass LGBC into mass production within the solar industry [14,15].

D. *Laser Fired Contacts*

With thinner wafers, it can be electrically and thermo-mechanically advantageous to include a passivation layer between the rear surface aluminum electrode layer and the silicon: however, this passivation layer is non-conducting. The Laser Fired Contacts (LFC) technique, recently developed by Fraunhofer ISE, provides a means through which lasers create localized contacts. At each site, a 1064 nm laser pulse drives the aluminum through the passivation layer and several microns deep into the silicon, creating a localized Al / Si alloy. Similar to the LGBC method above, the transition from research to mass production has yet to be realized within the industry [16-18].

E. *Cutting Wafers*

Due to silicon foundry shortages and associated high material costs, manufacturers are moving towards using thinner wafers (100-200 microns). As the wafers get thinner, it is challenging to cut them with conventional mechanical tools which induce micro cracking and ultimately reducing the strength of the wafers. Lasers, offering a non-contact process, have been successfully implemented in production lines to cut wafers. The Q-switched solid-state lasers, with 50-100 ns pulse and peak power up to 20 kW, are used to cut these thin wafers in multiple passes. The Q-switch fiber lasers offer economical and the cleanest process to cut these wafers as secondary process such as chemical etching (often necessary for other competing technologies) are completely eliminated.[19-21]. Problems related to mechanical and thermal stress due to laser cutting of silicon wafers are well documented for example in [22].

F. *Wafer Marking*

To provide traceability throughout the industry-standard 20-25 year cell / module warranty period, long-term identification of the cells is essential. An emerging application for lasers involves 'soft' marking on the surface of the wafers. For this application, the ID mark should be clearly visible, while not causing any notable decrease in efficiency over the required lifetime of the cells / modules [23]

G. Laser Surface texturing

Surface texturing plays a critical role in silicon solar cell performance, affecting both reflectance and light trapping. Monocrystalline cells are typically textured using an anisotropic alkaline etch to create surface pyramids, while multicrystalline cells are textured using an isotropic acid etch resulting in a "scalloped" surface. Other methods include plasma surface texturing [24]. An alternative surface texturing technique uses ultrafast lasers that offer advantages over the standard wet etching techniques.

Laser texturing process provides an efficiency improvement and tighter efficiency binning for multicrystalline cells compared to a high quality isotexture baseline, and also maintains high efficiencies on thinner wafers due to superior light trapping. The combination of these benefits directly translates into reduced $/Wp cell manufacturing cost. Laser texturing technique using ultrafast laser [25, 26] or Q-switched Nd: YAG laser [27] also holds promise to achieve better performance and economics on monocrystalline cells than standard alkaline etches. Research shows that laser surface texturing with can be efficiently achieved on multicrystalline as well as on monocrystalline solar cells. Using an ultrafast laser processing technique it is possible to create self-assembled micro/nano structures on a silicon surface for efficient light trapping. Light reflection (including scattering) of the Si surface can be reduced to less than 3% for the entire solar spectrum [28]

II. LASER SOLDERING IN PHOTOVOLTAIC MODULE MANUFACTURING

For the production of solar modules from individual solar cells, several cells are electrically connected together in series to get the necessary nominal voltage and in parallel to get the necessary current. The tapping and stringing of the PV cells is the most time-consuming activity in the production of PV modules, as poor soldering process may damage or crack the solar cells, induce a reliability problem, and even decrease the power output and lifespan of a solar module significantly [29].

The present trend in silicon solar cell production towards thinner (< 200 μm) and therefore cheaper layers demands for gentle production methods to reduce wafer breakage during module manufacturing. Thermal and mechanical stress created during these processes leads to the formation of cracks, which is especially dangerous for thin wafers [30]. On the other hand, it is also necessary for the solder joints to exceed certain dimensions to get good electrical contact, low resistance and mechanical strength. Thus, to get a high yield it is essential to minimize the thermal and mechanical stress for the cell. Tactile methods like soldering iron are not recommendable and some researchers have even proposed to replace soldering with low temperature conductive adhesive interconnection for labour cost savings and hence a saving in production cost [31].

For different soldering methods: hot air, iron-soldering, infrared, lamp , micro flame and supersonic soldering [32,33] potential sources of damage and the link between mechanical stress induced by soldering and micro damages in silicon solar cells are well documented in literature[34-37] .

For example in [34], a finite element analysis model has been developed to simulate the bow residual stress due to soldering. According to the results of the simulation, the decreasing thickness of wafer causes the increasing residual stress and bow. Even the issues posed by the introduction of lead-free solder to replace the traditional $Sn_{60}Pb_{40}$ have been investigated [38].

Contrary to other soldering methods, the laser soldering process allows strongly localized energy deposition without heating the whole wafer. In addition the process can be controlled with a pyrometer, so that the laser power can be adapted in real-time during soldering to achieve a constant temperature even at varying material conditions. The pyrometer is integrated in the processing head and aligned in the optical path of the laser beam [39]. This allows an ideal temperature profile on the cell and a minimum of heat input.

Using a setup with two beam paths simultaneous soldering of the front and back contacts enables process times below three seconds per cell. For future cell concepts, laser beam welding allows a decrease of the processing times by a factor of ten compared to traditional soldering [40]. The spot size to be heated for PV soldering applications has a diameter of 1-2 mm or more. The heat needs to be delivered within a several hundreds of milliseconds. The required radiation power depends on many factors; it may range from 30-90 W. These specifications are no serious challenge for laser sources. Fiber coupled diode laser are a good choice for the application [41-44].

V. LASER-BASED SOLAR MODULE ASSEMBLY

A. In-laminate soldering

Usually when Si solar cells are interconnected to strings they get laminated into the modules. This technology requires handling for the long and fragile strings with additional equipment. Using laser the string handling can be completely avoided by soldering directly through the laminate layers. The typical sequence for these modules is glass, polymerized Ethylene Vinyl Acetate (EVA), tinned ribbons, solar cell, tinned ribbons and transparent TEDLAR® back sheet. Front and rear sides of the PV module are transparent for laser radiation. Soldering can be done either before or after lamination. This method is named In-Laminate Laser Soldering (ILLS) and there is a formidably intense research work being done at Institut für Solarenergieforschung Hameln (ISFH), Emmerthal in Germany [45, 46] and other research institutions [47]. The results show that this technological process presents many advantages over competing solutions and promise to become a mainstream technique.

B. Laser-induced damage during laser soldering

The use of laser soldering in solar panel assembly is expected to improve the quality, increase the overall yield and lower the overall cost of solar panel production. However there are reports in scientific literature on laser induced damages especially in silicon used for microelectronic production [48-52]. These reports agree among other things that the damage thresholds increase with the increasing of the laser pulse width and experimental results agree with theoretical calculations. These damages include formation of bulges, craters, cracks production and thermal stress. These damages depend on the HAZ which in turn is a function of laser beam parameters, including beam power or pulse, energy, spot size depth of focus and process parameters such as pulse repetition rate, scan speed and weld size.

The success of laser welding and soldering and monolithic module assembly will improve the quality of solar panel production if the negative effects of the laser beam on the quality of solar cells such as formation of bulges, cracks, craters, excessive thermal stress are mitigated or eliminated all together and the production process parameters are optimized.

A proposal submitted by a team of researchers from Kimathi University College of Technology, Jomo Kenyatta University of Agriculture and Technology and Moi University and funded by the National Counsel of Science and Technology (NCST) of the Ministry of Higher Education, Science and Technology (MoHEST), Republic of Kenya, addresses this problem: “Determination of the optimal laser beam parameters- that include power, spot size, mode, depth of focus and process parameters such as pulse repetition rate, scan speed, and weld size to avoid formation of bulge , cracks and other types of damages as witnesses in other operations involving silicon as well as to minimize the HAZ.

Using the results of mathematical simulation and modeling, solar panels will be assembled and their electrical and performance parameters compared with the parameters exhibited by traditionally assembled panels.

C. *Laser-assisted Metal-to-plastic joining*

The recent introduction of laser-assisted metal-to-plastic (LAMP) joining makes it possible to produce all-laser-assembled solar panels. LAMP joining is performed by melting the plastic near the joint interface and then forming bubbles in the melted plastic by utilizing a simple lap joint. The LAMP joining is applicable to join thermo-plastics, especially engineering plastics to any metal [51, 52]. The use of LAMP would eliminate the need for adhesives in the final process of laminate encapsulation. But the process is still at investigation stage and more research is needed before its widespread implementation.

VI. CONCLUSION

Laser material processing is an established technological feature in the modern manufacturing landscape including the crystalline silicon solar cell industry where it is applied almost in all steps of cell manufacturing from silicon raw material to laser soldering of complete solar cells.

Laser processes efficiently perform important steps in PV cell manufacturing. Laser systems are proven in industrial photovoltaic production with lasers used for edge isolation scribing, grooving, contact vias and emitter doping, welding and soldering of solar cells.

In production, laser processes exploit the advantages of selective machining, a well defined interaction region, high precision and cost-effective processing. In order to help the solar industry to reduce the cost of electricity generation and to make it available in off-grid locations, there are increasing opportunities for laser processing to contribute to the goal of low cost of ownership in industrial manufacturing through improved module efficiencies, higher throughput and reduced process costs. These new opportunities include monolithic module assembly that may take advantage of in-laminate laser soldering and laser-assisted metal-to-plastic joining to achieve an all-laser solar cell manufacturing and module assembly. Intense fundamental research is going on to make these new laser processes mainstream in photovoltaic industry.

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REFERENCES

[1] Arcor Laser processing. Available: www.arcor.com/Laser_Processing.htm

[2] Advantages of Laser Processing. Available: www.laserdeal.com/ techninoFiles/Laser%20Advantages%202.doc

[3] R. Hendel, B. Lehner and C. Ruttimann,”Faster and reliable joining of solar cells bi-wavelength laser welding for photovoltaic module integration, “, *Laser Technik Journal*, Vol. 9. Issue 1, 2012, pp.20-23

[4] V. Kancharla and M. Varakis, “Application of fiber lasers for solar cell manufacturing”, Available: http://www.ipgphotonics.com/

[5] M.A. Green, “Crystalline Silicon Solar Cells”, Chap 4. Available: www.worldscibooks.com/etext/p.139/p/139_Chap4.pdf

[6] Thin-film amorphous Silicon Solar Cells. Avalable: www.rd.rutgers.edu/rdbirnie/Sloarclass/amorphousSi.pdf

[7] X.Wu and P. Sheldon (2000), “A Novel Manufacturing Process For Fabricating Cds/CdTe Polycrystalline Thin-Film Solar Cells” in *16th European Photovoltaics Solar Energy Conference and Exhibition*, Glasgow, Scotland, UK. May 1-5 -2000

[8] M. *Gratzel*, “Dye-sensitized solar cells, *Journal of Photochemistry and Photobiology C: Photochemistry Reviews*, 4, p.145-153, 2003

[9] Ecole Polytechnique Fédérale de Lausanne, "New Efficiency Benchmark For Dye-sensitized Solar Cells", *ScienceDaily*, 3 November 2008

[10] F. Colville, “Laser Systems and processes within Next-Generation Photovolatice Manufacturitng Equipment”, 4th *Photovltaic Manufacturing Technology Conference, Semicon*, Stuttgart, Sept. 2008

[11] F. Colville, "UV lasers in Solar Cell Manufacturing, Enabling Increased Cell Efficiency and Yields", 2009 . Available: www.coherent/Downloads/Coherent inlay_Colville OPTOmism Presentation Ver_01.pdf

[12] H. Booth, "Laser Processing in Industrial Solar Module Manufacturing", *JLMN-Journal of Laser Micro/Nanoengineering* Vol. 5, No. 3, 2010, p.183-191

[13] Spectra Physics, "Laser Edge Isolation Scribing for Crystalline Silicon Solar Cell Production". Available: http://assets.newport.com

[14] D. Kyeong, M. Gunasekaran, K. Kim, H. Kim, T. Kwon, I. Moon, Y. Kim, K. Han and Y. Yi, "Laser Edge Isolation for High-efficiency crystalline silicon solar cells", *Journal of the Korean Physical Society*, Vol. 55,.No 1. 2009, p.124-128

[15] K C Heasman, A Cole, M D Brown, S Roberts, S Devenport, I Baistow, T M Bruton, "Development of laser grooved buried contact solar cells for use At concentration factors up to 100x "in *Proc. 22nd EUPVSEC*, Issue:, p. 1511-1514, Septt 2007.

[16] S. Devenport, S Roberts, K C Heasman, A Cole, D Tregurtha and T M Bruton ,"Process optimisation for coloured laser grooved buried contact solar cells" *33rd IEEE Photovoltaic Specialists Conference* , 2008, p.1-4

[17] J. June, C. Srumpel, S. Seren, G. Halm and A. Metz, "Laser fired contact for high efficiency solar cells based on EFG material". Available: http://www.drlaser.com.cn/uploadfile/ExcelFile/2012-02/file 2012022517043756487.pdf

[18] P. Ortega, A. Orpella, I. Martín , M. Colina, G. López , C. Voz, M. I. Sánchez , C. Molpeceres, R. Alcubilla , "Laser-fired contact optimization in c-Si solar cells", *Progress in Photovoltaics: Research and Applications*, Vol.20, Issue 2, p.173-180, 2012.

[19] H. Booth, "Laser Processing in Industrial Solar Modules Manufacturing", *JLMN- Journal of Laser Micro/Nanoengineering*, Vol,5, No3, 2010, p.183-191

[20] Photovoltaics (Solar Cells), 2006. Available: http://www.sspi.gatech.edu /photovoltaics2006.pdf

[21] M. Naeem , "Cutting performance comparison between low power LPSS and SM fiber laser for mono and polycrystalline silicon wafers", http://www.jklasers.com/images/pdfs/

[22] "Laser cutting of silicon wafers" http://www.jklasers.com/images/pdfs/

[23] C. Leone, V. Loprestoa N. Pagano, S. Genna and I. De Iorio, "Laser cutting of silicon wafer by pulsed Nd:YAG source". Available: http://www.iproms.org/sites/default/papers/Paper_40.pdf

[24] J. Liu, J. Lu, X.Ni, G. Dai, L. Zhang1, Y. Chen, "Numerical study on thermal stress cutting of silicon wafer using two-point pulsed laser", *Optica Applicata*, Vol. XLI, No. 1, p.247-255, 2011.

[25] P.Waver, U. Vom Bauer, J. Muller and D.P. Schreiter, "Every solar cell is an original: laser marking of silicon solar cells yields new opportunites in quality control", *Photovoltaics International*, p.16-22, Nov 2010.

[26] D.S. Ruby, S.H. Zaidi, M. Roy and M. Narayan, " Plasma Texture of Silicon Solar Cells in *9th Workshop on Crystalline Solar Cell Materials and Processes*, Breckenridge, 1999

[27] C. Vineis, M. Levy-Finklshtein, J. Carey, G. Knight, E. Wefringhaus and R.Harney, "Ultrafast laser texturing for enhanced solar cell performance and lower cost" . Available: http://sionyx.com/pdf/solarcellperformance whitepaper.pdf

[28] V. V. Iyengar, B. K. Nayak and M. C. Gupta, "Optical properties of silicon light trapping structures for photovoltaics", *Solar Energy Materials and Solar Cells*, Vol.94, Issue 12, 2010, p. 2251-2257

[29] L. Dobrzanski and A. Drygala, Surface Texturing of multicrystalline silicon Solar cells, Journal of Achievements in Materials and Manufacturing Engineering, Vol. 31, Issue 1, p.77-82, 2008.

[30] B.K. Nayak, V.V. Ivegar and M.C. Gupta, "Efficient light trapping in silicon solar cells by ultrafast laser-induced self-assembled micro-nanostructures", *Progress in Photovoltaics*, Vol. 19, Issue 6, 2011, p.631-639

[31] W. Yang, H. Ay and Y.J. Ciou, "A study of optimal manufacturing parameters with lead-free solder on the c-Si photovoltaic cells by using hot-air tabbing". Avalable: http://www.istp-22.org/proceedings/proceedings/documents/162.pdf

[32] D. Nuh "An improved production process for low-wattage PV modules", ETSU S/P2/0043/ Rep, DTI/Pub URN03/532, 2003. Available: www.bis.gov.uk/iles/file16523.pdf

[33] J. Wienke , O. Tober , P. Buur and W. Brieko, "Ultrasonic welding- a connection technology for flexible thin film modules", *19th European Photovoltaic Solar Energy Conference*, pp. 3, June 2004, Paris, France,.

[34] C-H Chen, F-M Lin, H-T Hu, and F-Y Yeh , "Residual stress and bow analysis for silicon solar cell Induced by soldering", Available: http://140.116.36.16/paper/c38.pdf

[35] W.H. Coulter, R.C. Czyzewicz, W.E. Farneth, A. Prince and R.G. Rajendran, "Using finite element methods and 3D image correlation to model solar bowing ", *34th IEEE Conference for Photovoltaics Specialists,(PVSC)*, 2009, p.000262-000267

[36] S. Wiese, R. Meier, F. Craemer and J. Bagdahn, "Constitutive behaviour of copper ribbons used in solar cell assembly processes, *10th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Equipments in Microelectronics and Microsystems* , 2009,p.1-8

[37] J.Wendt, M. Träger, M. Mette, A. Pfennig and B. Jäckel "The link between mechanical stress induced by soldering and micro damages in Silicon solar cells " Available: http://www.q-cells.com/uploads/tx_abdow nloads/files/

[38] J.W. Morris Jr, "Lead-free Solder Issues in Microelectronics ", *15th Workshop on Crystalline Solar Cells and Modules: Materials and Processes.* Extended Abstracts and Papers, 2005, p.129-131

[39] W. Horn, "Welding and soldering with high power diode lasers" Available: http://www.dilas.com/

[40] R. Hendel, R. Lehner, "Faster and reliable joining of solar cells bi-wavelength laser welding for photovoltaic module integration", *Laser Technik Journal*, Vol. 9 Issue 1, 2012, p.20-24

[41] H. Hirth," Lasers in wafer-based PV modules", *Laser Technik Journal*, Vol 7, Issue 4, 2010, p.36-38

[41] W. Horn, "High-power diode lasers for industrial applications", *Physics'Best,* 2008, p.16-18

[43] M. Gast, M. Kontges and R. Brendel, "Lead-free on-laminate laser soldering: a new module assembling concept", *Progress in Photovoltaics: Research and Applications, Prog. Photovolt: Res. Appl*., 16, 2008 p. 151–157

[44] M. Köntges, M. Gast, R. Brendel, R. Meyer, A. Giegerich, and P. Merz, "A novel photovoltaic-module assembly system for back contact solar cells using laser soldering technique" Available: http://www.isfh.de/institut_solarforschung/files/

[45] J. M Gee, D. Meakin, S. Southimath, Martin Spath and I.Bennett "Development of commercial-scale photovoltaic modules using monolithic module assembly", *34th IEEE Photovoltaic Specialists Conference PVSC*,Vol. 87106, Publisher: IEEE, 2009, p. 002133-002137

[46] B.K.A Ngoi, K Venkatakrishnan, E.N.L Lim, B Tan and L.H.K Koh, "Effect of energy above laser-induced damage thresholds in the micromachining of silicon by femtosecond pulse laser", *Optics and Lasers in Engineering*, Vol. 35, Issue 6, 2001, p.361-369.

[47] A. P. Singh, A. Kapoor, K.N. Tripathi ,G.R. Kumar, "Laser damage studies of silicon surfaces using ultra-short laser pulses", *Optics and Laser Technology*, Vol. 34, Issue 1, 2002, p.37-43

[48] S. Baumann, D. Kray, K. Mayer, A. Eyer and G.P. Willeke, "Comparative study of laser induced damage in silicon wafers", *Photovoltaic Energy Conversion, Conference Record of the 2006 IEEE 4th World Conference on*, Vol 1,2006, p.1142-1145

[49] D. V. Tran , Y. C. Lam, H. Y. Zheng, V. M. Murukeshan, J. C. Chai and D. E. Hardt, "Femtosecond laser processing of crystalline silicon "http://dspace.mit.edu/bitstream/handle/1721.1/7449/IMST010.pdf

[50] X. Wang, Z.H. Shen, J. Lu and X.W. Ni, Laser-induced damage threshold of silicon in millisecond, nanosecond, and picosecond regimes, *Journal of Applied Physics*, Vol 108, Issue 3, p. 033103, 2010

[51] S. Katayama, "Laser joining of metal and plastic: laser provides a solution to a difficult joining process-plastic to steel, *Industrial Laser Solutions*, Dec. 2010, p.15-16

[52] A. Fortunato, G. Cuccolini, A. Ascari, L. Orazi, G. Campana and G. Tani, "Hybrid metal-plastic joining by means of laser", *Engineering International Journal of Material Forming* , Vol.3 Suppl.1, 2010, p.1131-1134., 2010