High power picosecond lasers enable higher efficiency solar cells.

The combination of high peak power and short wavelength of the latest industrial grade Talisker laser enables higher efficiency solar cell manufacture, while the high (500 kHz) pulse repetition rate supports increased productivity.

Introduction

The key to future growth in the market for solar power is reaching grid parity with conventional power sources. Essential strategies for achieving this include the development of solar cell architectures with higher conversion efficiency and reductions in manufacturing costs. Ultrafast laser processing is a key enabling technology for lowering production costs, particularly in the area of thin film patterning. This whitepaper presents picosecond (ps) laser processes for thin film patterning that minimize thermal damage, thereby delivering higher efficiency silicon solar cells at high throughput rates – line speeds up to 1200-3000 wafers per hour.

Reducing Costs and Increasing Efficiency

Crystalline Silicon (c-Si) designs dominate the solar cell market. Figure 1 shows the schematic of a typical finger and busbar pattern formed by metal paste screen-printed directly onto the passivation layer. The textured front surface is coated with a passivation layer, usually silicon nitride (SiN) that also acts to increase light gathering efficiency.

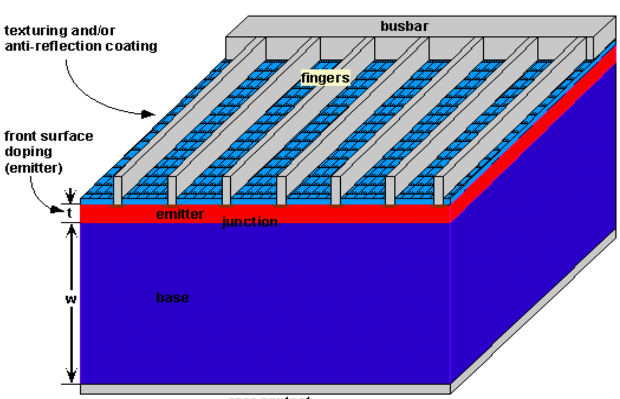

Figure 1 *Simplified schematic of a silicon solar cell with front-side finger and busbar pattern.*

Relative to conventional screen-printed solar cells, there are two main criteria for obtaining higher conversion efficiency. Firstly, the silicon substrate must be high quality with long charge carrier lifetime. Secondly, the metalized electrical contacts to the semiconductor cell need to have high quality to ensure low series resistance, thereby maximizing current flow. High quality silicon requires a low semiconductor defect concentration. Improvements in the front and backside contacts through the passivation layers are of vital importance to both lower series resistance and to eliminate surface recombination of optically generated current carriers [1-3]. In addition, moving to thinner silicon wafers of thickness ~200 µm (future target of 40 µm) allows both an improvement in material cost and wafer processing times ~3 seconds per wafer (or 1200wafer/hour).

Optimizing Selective Removal of Thin Films

A laser offers the advantage over mechanical machining of being a non-contact direct-write process. Additionally, laser machining demonstrates clear advantages over traditional lithographic processes as a hazardous chemical free process.

Short pulse picosecond lasers (~10 ps) are ideal tools for selective patterning of thin films, since the laser-material interaction time is less than typical material thermal and acoustic response time. As a result, the use of a short pulse picosecond laser eliminates any significant damage to surrounding layers [4].

In the silicon solar industry the passivation layer thickness (<100 nm) is considerably less than the optical penetration depth; as a result thin films are readily removed by laser spallation. In this process, optical pulse energy from the laser penetrates the surface transparent thin film and is strongly absorbed at the thin film/silicon interface. The thin film is then 'spallated' by a build-up of vapour pressure, trapped at the interface as indicated in Figure 2. In this case, selective removal is dependent on limiting damage to the underlying silicon, making control of the laser fluence or irradiance (energy per unit area) a critical process parameter. Finding the optimum fluence is straightforward with the stable, reliable performance of the Coherent Talisker: a short pulse picosecond laser, with models offering UV, Green or IR output wavelengths.

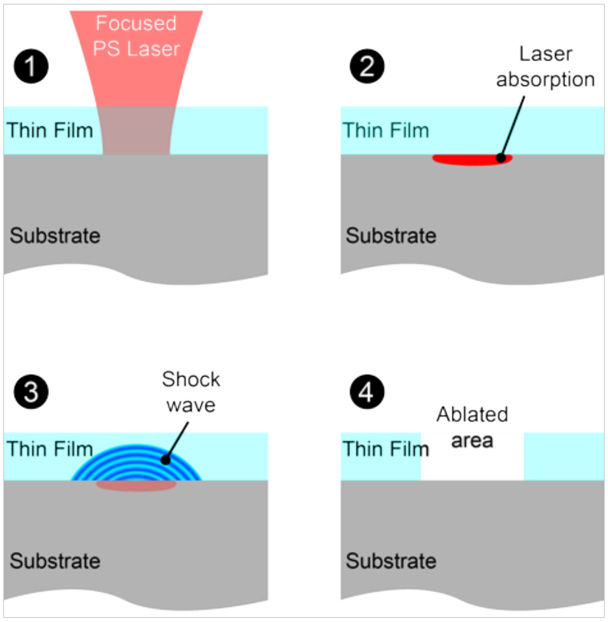

Figure 2 *Laser spallation schematic where (a) a focused laser beam is absorbed at an interface (b) heating occurs in a thin layer (c) a shock wave expands (d) the thin film layer is removed.*

This is because the Talisker laser beam has a circular Gaussian intensity profile. Consequently, increasing the laser pulse energy increases the machined hole diameter, in a controlled manner, as governed by equation (1) below. A curve fit of the laser spallated hole diameter versus the pulse energy (or fluence) is then made to find values for the laser ablation threshold fluence, F_{Th}.

$$F = F_{Th}.e^{-2r^2/w_o^2} \qquad (1)$$

where, F is the fluence, r the laser ablated diameter, w_0 the focused spot radius and the pulse energy, E, is related to fluence by $E=F/r^2$.

A curve fit of the laser spallated spot diameter versus pulse energy is shown in Figure 3 for tests with single pulse removal of 100 nm silicon dioxide (SiO_2) from silicon. From this plot an estimate of the focused spot size of $2w_0$=55 µm (the calculated value is 60 µm) is made with a threshold of F_{Th} ~ 0.09 J/cm^2. The use of a fluence close to this threshold value results in the lowest damage to the silicon. However, as can be seen in Figure 3, in this region the laser spallated spot diameter is highly sensitive to small changes in fluence, which can result from small, fluctuations in surface conditions and light coupling. Consequently, a fluence of 1.5-2*F_{Th} (indicated by the dashed lines in Figure 3) gives the optimum combination of consistent hole size and minimal damage to the underlying silicon.

The high circularity of the 355 nm Talisker laser beam is also demonstrated in Figure 3, where the laser ablated spot diameter was measured in two orthogonal directions (X and Y) and the two curve fits are superimposed almost exactly on each other.

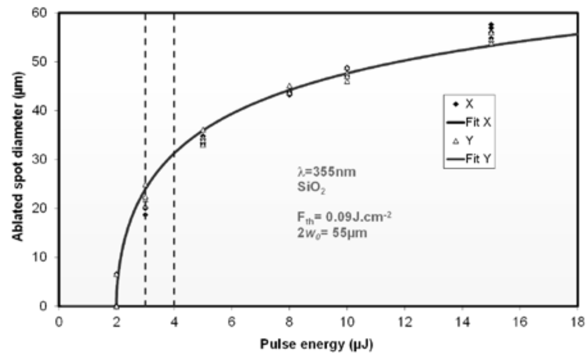

Figure 3 *Laser ablation threshold curve for a 100 nm thick SiO_2 thin film on silicon using 355 nm picosecond pulses. The dashed lines indicate the optimum removal regime.*

Laser spallation has clear benefits over laser ablation, as outlined here. Table 1 compares the laser ablation threshold obtained for removal of the same 100 nm SiO_2 film at the three wavelengths produced by the Talisker laser. In comparison, for bulk SiO_2, with a 10ps pulse duration at λ=526 nm, the laser ablation threshold fluence much higher, F_{Th}, is >1 J.cm^{-2} [6]. The reason for this large difference is that bulk silicon is conventionally ablated by a pulsed laser whereas the film is removed primarily via spallation. Note also that threshold fluence increases with wavelength due to the greater optical penetration depth at longer wavelengths. Consequently, the use of shorter wavelength, i.e., UV, enables laser spallation at lower fluence resulting in the least damage to the underlying silicon.

Wavelength λ **(nm)**	***Threshold Fluence*** F_{Th} **(J/cm^2)**
1064	0.32
532	0.15
355	0.09

Table 1 *Wavelength dependence of the laser ablation threshold fluence for single pulse removal of 100 nm SiO_2 from silicon.*

1. Front-side emitter formation

Currently, the metallization on the front-side is implemented by screen printing metal paste followed by furnace firing of the metal paste through the dielectric to form electric finger contacts. However, this process typically creates a contact resistance unsuitable for high efficiency solar cells [1,5,7]. Moreover, the fingers are typically >100µm wide so significant shadowing losses occur [5], when using the optimal finger spacing of ~1 mm. A final challenge remains with firing; a high temperature process (~800°C) that is not compatible with the thinnest wafers of <0.2 mm, nor high efficiency solar cell designs [5].

Alternative metallization techniques such as inkjet printing or electroplating [7, 9] will allow good electrical contact to lightly doped silicon surfaces that have improved absorption of short wavelength sunlight [1, 5]. Photolithography is used to open contacts in these methods. However, this technique requires multiple steps and so is not considered cost effective for mass production of high efficiency solar cells [1]. Instead, selective removal of the passivation layer by a laser is a critically-enabling process making a selective emitter design possible.

Figure shows an example of complete removal of SiN on textured silicon using 355 nm picosecond pulses at a fluence level of ~1.4*F_{Th} with little visible damage to the silicon [8]. The SiN is removed with a single laser pulse and damage is minimized by maintaining the laser fluence in the range ~1.5-2*F_{Th} with minimal pulse overlap of ~10%. Extremely narrow (~10 µm width) fingers (to reduce shadowing losses) have been formed at a scan speed of 4m/s and repetition rate of 500 kHz. Wafer processing times as low as 2.5 seconds per wafer will be obtained based on a cell design with two 1 mm wide busbars and 1 mm spacing between ~30 µm wide fingers. With this approach, a 1% increase in absolute cell efficiency has been achieved compared to conventional screen-printed solar cells [8].

The diffusion constants of dopant atoms are many orders of magnitude higher in molten silicon than in solid silicon. Therefore, if the passivation layer can be removed without the silicon melting, the emitter doping profile should remain unchanged. Rana *et al.* have verified that the use of 355 nm picosecond pulses have little or no effect on the emitter dopant profile by Secondary Ion Mass Spectroscopy (SIMS) measurements after laser ablation illustrated in Figure . These authors attribute the differences in the two profiles deep inside the silicon to be a consequence of uncertainty in the depth resolution of the measurement technique.

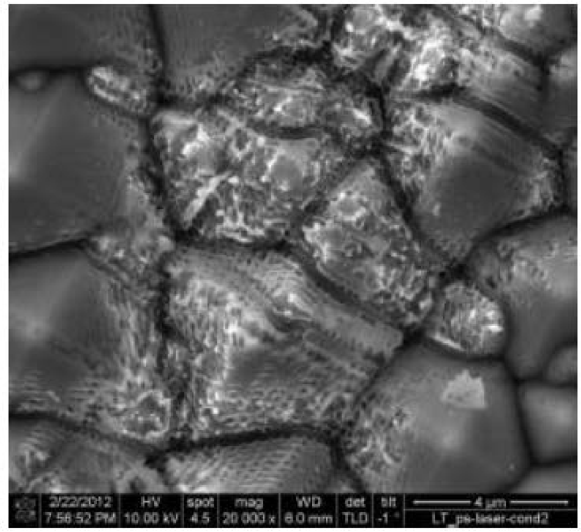

*Figure 4 SiN scribing using (~1.4*F_{Th}), 355 nm pulses at a scan speed of 4 m/s [8].*

The use of a shorter pulse duration femtosecond (fs) laser has also been previously investigated for a similar process. For example, Neckerman *et al.* have made SIMS measurements on the phosphorus depth profile and found that after femtosecond laser irradiation a lower surface concentration is evident, suggesting removal of a thin surface layer of silicon [10]. Furthermore, recent studies definitively showed a lower laser ablation threshold (indicating lower damage to the underlying silicon) was obtained using ultra-violet (355 nm,10 ps) picosecond laser pulses, than with infrared femtosecond pulses [11,12]. These results have been verified in Figure , which shows a comparison of the laser ablation threshold for removal of a 50 nm SiN layer by femtosecond and picosecond pulses; confirming that 355 nm picosecond laser pulses remain the best choice for selective passivation layer removal.

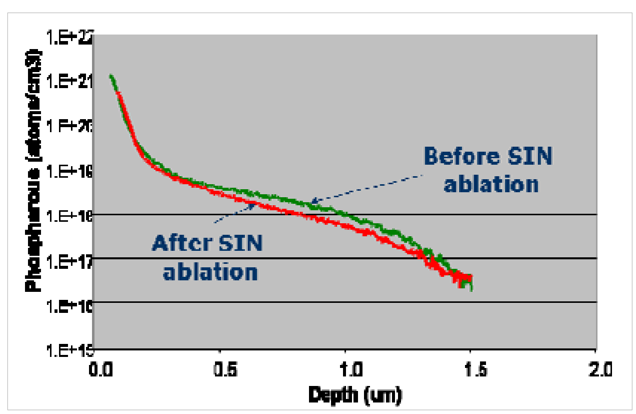

***Figure 5** Emitter dopant profile before and after laser ablation of SiN using 355 nm picosecond pulses on a textured Si wafer [9].*

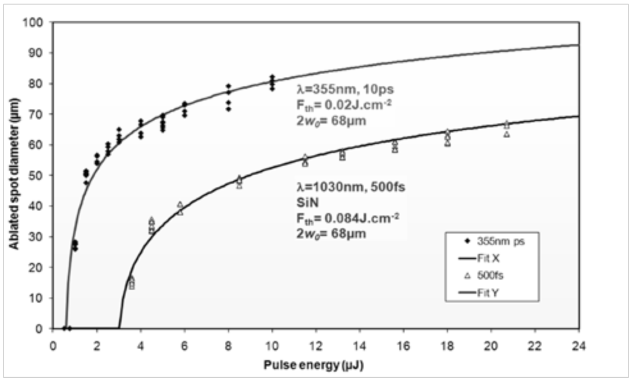

Figure 6 *Comparison of 355 nm picoseconds and 1030 nm femtosecond laser ablation thresholds for removal of thin film SiN.*

2. *Back side contact hole drilling (SiO_2)*

Current mass-produced solar cells do not have a backside passivation layer. The inclusion of this layer will reduce recombination losses, allowing higher conversion efficiency. A single step laser process offers higher throughput than a complex multiple step photolithographic procedure. Additionally the hazardous chemistry cost is eliminated. Engelhart *et al.* first demonstrated increased efficiencies based on selective removal of the rear surface passivation using picosecond laser pulses [13]. Figure7 shows an example of this process with a SEM image of a SiO_2 thin film removed from silicon using a single 355 nm pulse at an optimum fluence of ~0.11 J/cm^2 (or 1.5*F_{Th}). The high pulse-to-pulse stability of the Talisker laser (±2%) results in consistent laser drilled holes across a wafer. No molten silicon or subsurface damage is visible and so no post-process cleaning is required.

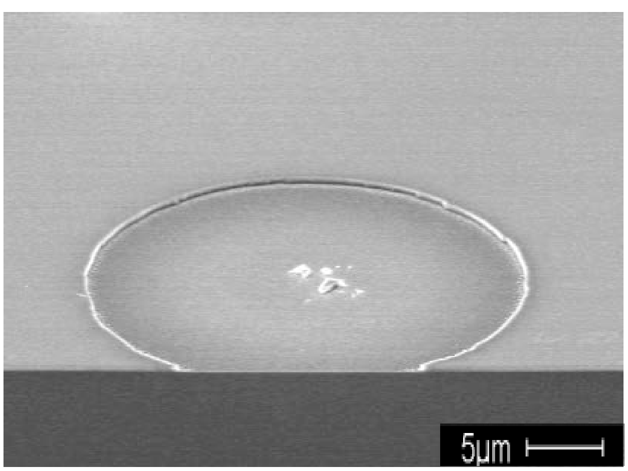

Figure7 *Removal of a SiO_2 from silicon using 355 nm picosecond pulses at an optimum fluence of ~0.11 J/cm^2 (~1.5* F_{Th}).*

3. *(Al_2O_3/SiN) passivation layers*

In recent years, alternative backside passivation stack layers containing extremely thin Al_2O_3 layers has attracted interest for high efficiency solar cells because Al_2O_3 is a negative charge dielectric that is not prone to parasitic shunts [14]. The greater selectivity of UV pulses means that 2 or 3 pulses are required to completely remove the Al_2O_3/SiN coating but with minor ablation of the silicon observed. The greater optical penetration depths possible with green (532 nm) or infrared (1064 nm) picosecond pulses allow single pulse removal of the stack layers down to the silicon. As an example, Figure shows a 65 µm diameter hole drilled using a single pulse at a fluence of ~0.24 J/cm^2 (1.6*F_{Th}) with a green 532nm laser. Some delamination of the Al_2O_3/SiN was visible, as evidenced here by the halo surrounding the laser-drilled hole. However, since the Aluminum metal layer was deposited over the passivation layer, this has no effect on the solar cell performance.

Single pulse removal is critical for high throughput. Cycle times as low as 1 second per wafer are then possible using high speed scanning or beam multiplexing techniques. Integration of this back contact drilling process has been shown to increase the solar cell efficiency by >0.5%; a significant improvement for a single step process that does not require any post-process cleaning.

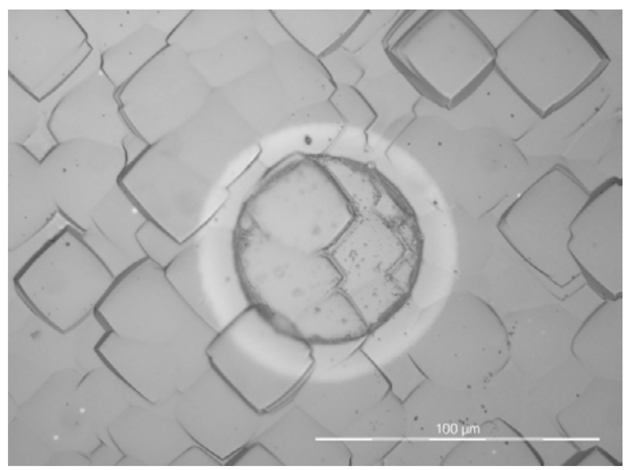

Figure 8 *Single pulse 532 nm removal of Al2O3/SiN backside passivation layer to produce 65 µm diameter contact hole.*

Conclusion

Picosecond laser processing has been shown to be a valuable tool for thin film patterning and selective material removal in the production of solar cells. In particular, the Talisker laser provides the essential combination of short pulses (10 ps), pulse energy (20 µJ) and ultraviolet (355nm) output necessary for selective removal of passivation layers without damage to surrounding areas. In addition, the Talisker UV capability offers greater selectivity than alternatives such as infrared femtosecond lasers, without the requirement of additional post-process cleaning.

The high pulse repetition rate of 500 kHz and more, together with the Talisker laser's high reliability, enables processing speeds of between 1200-3000 wafers/hour to be maintained on a volume basis, thus providing a new production tool in the quest to lower the cost of high efficiency solar cells.

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