Picosecond ablation of silicon nitride using 532 nm master oscillator fiber power amplifier for patterning crystalline silicon photovoltaic cells

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Fianium is based in Southampton, UK with Offices in US and Asia and has a worldwide network of representatives

- Ultrafast fiber laser portfolio is based on Master Oscillator, Power Amplifier building blocks
- Picosecond, femtosecond, and supercontinuum laser sources
- Spectral operation from 240 nm to 2500 nm
- High average power (>20W) and high energy (10 µJ) systems are available
- MHz to single-shot repetition rates

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Summit Photonics is a photonics engineering services firm based in Portland, OR

- Laser applications lab (in cooperation with Fianium)
- Photonics technology research and development

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Fianium Applications Lab

Fianium’s applications lab is run in conjunction with Summit Photonics in Portland Oregon.

- Over thirty years of combined experience over a wide base of laser processing technologies
- Focus on ultrafast materials processing
- 1064 and 532 nm processing stations

We focus on a wide range of materials and applications:

- Steel
- Aluminum
- Silicon
- Molybdenum
- CdTe
- CIG(S)
- Other metals or semiconductors
- Plastic and Urethane
- Etc.
Motivation

Silicon Nitride (SiN) thin-films are commonly used for anti-reflection (AR) and passivation coatings for crystalline-silicon solar cells.

It is preferred over other coatings due to its ability to act with the dual functionality of both passivation and antireflection, effectively eliminating a costly additional deposition step in the production process.

For certain advanced cell designs, small areas of the bulk AR/passivation layer must be removed or patterned after deposition to allow for contact areas.
Ultrafast laser ablation is a common processing mode in the industry and fits well with SiN processing.

Picosecond lasers are capable of utilizing a “cooler” ablation process to more cleanly and uniformly remove material, without the cost of femtosecond systems.

The benefits of all-fiber MOPAs:

- High $M^2$ Gaussian mode
- No optics to realign or get dusty yields robust performance
- Air cooled
- Variable repetition rate
- Good beam pointing stability
Experimental System

A Fianium HE1064/532 picosecond fiber laser generates up to 5 uJ, 30 picosecond pulses at 532 nm and 200 kHz repetition rate (variable from single pulse to 200 kHz).

The beam output from the laser is expanded by a 2-8x variable beam expander and the pulses are directed through a 100 mm fl telecentric scan lens for high-speed beam scanning over a 50 mm x 50 mm field sizes on the work surface.

The scanner is a Scanlab HurrySCAN II-14 system which is capable of over 10 m/s scan rates.

A work piece is mounted on top of stack 2D (horizontal/vertical) motorized stages used for focusing and coarse lateral adjustment.

The focused spot size is 10-50 um in diameter.

The laser output, scanner system and 2D stages are all computer controlled and synchronized.
Ablation Mechanism

SiN is optically clear to 532nm illumination, so the high energy pulses pass through the SiN layer and are absorbed in the silicon substrate.

The high energy picosecond pulse initiates an ablation microexplosion of a very thin layer of silicon which completely ejects the SiN material above.

The result is complete removal of the SiN layer above the ablation area and some minimal removal and modification to the to silicon surface.

Silicon removal depth is on the order of 10-100 nm per pulse.
A single picosecond laser pulse with energy above the ablation threshold cleanly removes the SiN thin-film layer across the entire focused spot size with minimal damage to underlying c-Si.

Small amounts of debris are left behind but can likely be removed with a subsequent wash process. No debris removal equipment was in place for this experiment.

The ablation fluence threshold for this process was determined to be \( \approx 0.1 \, \text{J/cm}^2 \).
The SiN is observed to be cleanly removed from the c-Si for fluences above 0.1 J/cm$^2$.

Pulse overlap areas consist of pushed aside silicon, which is apparent in the microscope images.

Fluence values from 0.11 J/cm$^2$ to over 0.6 J/cm$^2$ clean the c-Si surface of the SiN AR/passivation layer.

Larger fluence values create larger cleared areas, which correspond to a higher clearing rate.
Fluence Optimization

Low fluence

- Complete removal of the SiN coating
- Silicon substrate mostly undamaged
- Some melting in the pulse overlap
- Minor, submicron sized cracking of the SiN layer at the scribe edges.

High fluence

- Larger removal area
- Some retexturing/damage of the silicon surface
- Still melting in the pulse-overlap areas
- Minor, submicron sized cracking of the SiN layer at the scribe edges.
Higher pulse overlap yields straighter edges, but more Si-surface irregularity.

Higher overlap also yields a slower processing rate and removes more of the underlying Si.

The best processing rates were determined to be 2000-3000 mm/s for a 30 um spot size.

Best rate corresponds to a clearing rate of 50-75 mm²/s.
Energy–dispersive X-Ray spectroscopy (EDX) data was taken with an SEM across and along one of the cuts.

- EDX signature for nitrogen demonstrates complete removal of the SiN layer
- Small signal level inside the channel corresponds to the noise
- Measurement taken in the pulse overlap areas show no N in melt areas
- A small amount of silicon debris remains without a subsequent wash
Large areas of SiN can be quickly cleared or patterned to prepare a device for metal contacts.

• Clearing rates were approximately 50 mm²/s

• Optimization of spot size could allow for clearing rates exceeding 100 mm²/s.

• The images show complete removal of SiN over a 4 mm x 1 mm area.

• Images also demonstrate ability to pattern arbitrary shapes into the SiN layer.
Shaped Beam Processing

Steeper intensity profile edges and flat-tops make shaped beams more appropriate for nearly all processing applications than Gaussian profiles.

Diffractive shapers provide a means to flat-top, steep-edge profiles with very little loss of laser fluence.

Difficulties in proper alignment using diffractive beam shapers have hindered their application in industrial settings.
Square flat-top beams can process larger areas with less damage to the underlying silicon substrate.

Square beams require very little pulse-to-pulse overlap, which allows for 20% faster processing rates.

For our processing system we were able to double the processing area while also leaving the substrate surface more uniform.

Larger process area means faster processing speed

Superior edge quality over Gaussian beam results

Shaped Beam Results

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Conclusions

• SiN AR and passivation layer on silicon photovoltaic devices can be cleanly and rapidly removed or patterned.

• SEM data, EDX data, and microscope images show clean, complete, and uniform removal of the SiN layer from within the trench with some debris.

• Single-pass scribing speeds of 2000 mm to 3000 mm/s were found to be effective at a fluence of 0.4 J/cm². Clearing rates of 50 mm²/s were achieved with complete SiN layer removal, with over 100 mm²/s possible.

• A square flat-top beam profile was demonstrated to improve edge quality and silicon surface uniformity, while simultaneously increasing ablation area.

• Some debris material was observed around processed areas. A subsequent cleaning step could likely wash away this debris.
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The SiN edges demonstrate some sub-micron cracking, particularly in the cusps near the pulse overlaps.

The cracking is occurs at all fluence values but is slightly worse for larger fluence.

Small cracks in the SiN layer are unlikely to significantly affect device performance for most applications.

Outside the cusp regions the edges, given the appropriate processing parameters, are extremely sharp (sub-micron) and clean.
Outline

- Ultrafast laser processing of SiN motivation and background
- Experimental system for cutting/patterning SiN thin-film layers on silicon photovoltaic devices
- Single-pulse ablation threshold
- Optimal fluence, speed, and other process parameters
- Ablation quality: edge quality, residual debris, residual SiN, substrate damage, etc.
- Square, flat-top scribing beam for improved results