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Laser Cutting and Micromachining for Localized and Targeted Solar Cell Characterization

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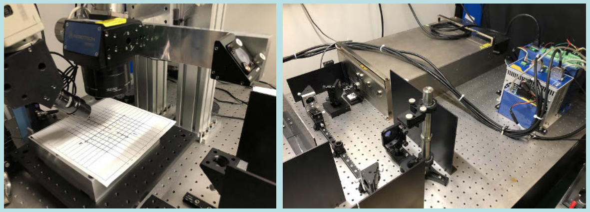
Laser cutting and micromachining can be applied to solar cell materials for processing and characterization applications. An ultrashort pulse (USP) laser with sub-picosecond pulse width can remove material with minimal thermal effects or damage, which is termed 'cold ablation'. Applications and examples include the following:

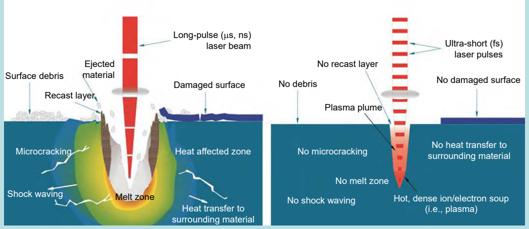
- **Small-area cutouts,**
- **Spot ablation,**
- **Defect removal,** and
- **Small-area, electrically-localized device isolation.**

Lab photos of an ultra-short pulse laser micromachining system

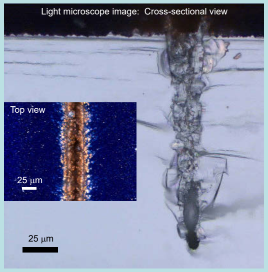


The laser micromachining system incorporates a USP laser from Advanced Optowave Corporation and a high-speed galvanometer scanner from Aerotech, Inc. The AOFemto model is a Yb-based, chirped-pulse-amplification laser with fundamental wavelength of 1030 nm. The pulse width is less than 600 fs, and the maximum power is as high as 10 W for repetition rates of 100 kHz to 1 MHz. The included doubler-crystal can optionally be used to attain up to 5 W at 515 nm. The scanner moves the 1030 nm laser beam in the desired pattern on the sample with a velocity around 1 m/s. An f-theta lens focuses the beam onto the sample with a spot size of approximately 10 μm with kerf widths ranging from 15 to 30 μm.

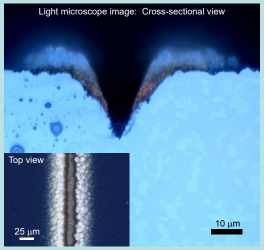
Compare long-pulse and ultra-short pulse laser micromachining



Advanced Materials & Processes, Nov.-Dec. 2014, pg. 26.

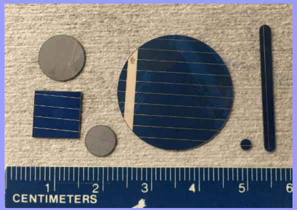


A silicon wafer with a blue silicon nitride top layer is scribed using a ns-pulse-width based laser system. The top view is shown in the inset image. The cross-sectional view shows fused and cracked silicon that indicates melt zones, microcracking, and shock waving when scribing with longer pulse lasers.



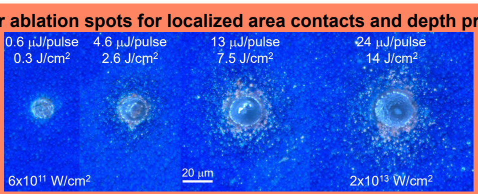
A similar sample is scribed using the USP AOFemto laser set to 17 μJ/pulse at 1030 nm. The top view is shown in the inset image, where some recast material is evident on the edges of the scribe line. No gas flow during scribing or post-laser-processing cleaning was applied. The cross-sectional view shows relatively clean surfaces at the bottom of the trench and no extensive thermally-related damage into the bulk of the silicon near the scribe area.

Laser cutouts for isolated electrical measurements, cross-sections, and small sizes suitable for microscopes and cryostats



Laser cut silicon wafer and solar cell pieces illustrate the range of various sizes and shapes that can be processed. The pieces were cut using the 1030 nm fundamental beam.

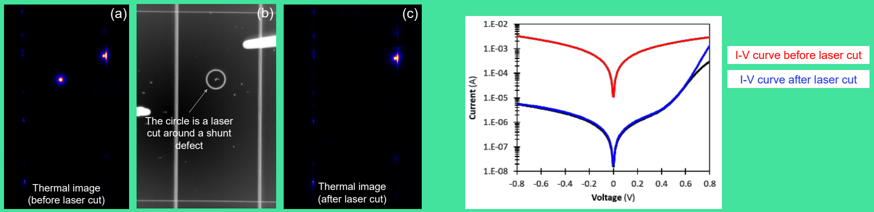
Laser ablation spots for localized area contacts and depth profiles



Light microscope images show laser ablation of silicon nitride on silicon. The laser cutting and micromachining energy can be as high as 50 μJ/pulse when using the 515 nm second harmonic. Laser ablations and scribes are typically below 20 μJ/pulse. When focused to a spot ~15 μm in diameter, the laser fluence per pulse ranges from 0.3 to 14 J/cm^2. When divided by the pulse width of ~600 fs, the laser intensity ranges from 6x10^{11} to 2x10^{13} W/cm^2. Avalanche ionization is responsible for wide-bandgap ablation when laser intensity is less than 10^{12} W/cm^2. [1] Multiphoton ionization becomes significantly strong for laser intensity above 10^{13} W/cm^2. [1]

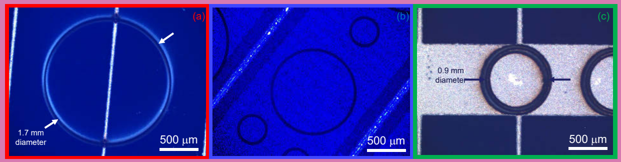
[1] L. Lucas and J. Zhang, "Femtosecond laser micromachining: A back-to-basics primer," *Industrial Lasers*, July 2012.

Determine the effect of defects and shunts by characterizing the cell before and after defect removal or isolation

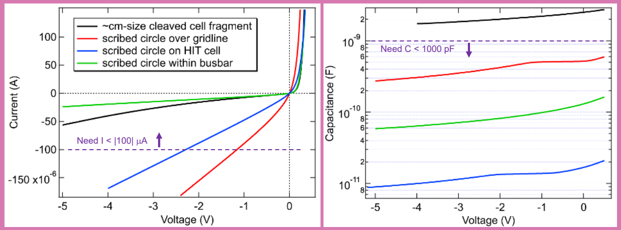


A thin-film solar cell with shunt-type defects. A thermal image is shown in (a), where two shunts are visible. In (b), the micromachining laser is used to cut the layers of the cell and isolate the shunt. After laser scribing, a thermal image (c) shows the isolated shunt is no longer electrically connected to the cell. The I-V curves show the electrical characteristics of the solar cell before and after laser scribing, where absolute value of current is plotted as a function of applied voltage.

Laser scribing to electrically isolate a smaller localized area



Silicon solar cells are laser scribed to form reduced-area samples that are suitable for Deep Level Transient Spectroscopy (DLTS) measurement. Laser scribing centered over a gridline is shown in (a), where the gridline metal provides a contact to the smaller-area device. Laser scribing a HIT cell between grid lines is shown in (b). Contact is provided by the conductive top layers of the HIT cell structure. Laser scribing a small circle confined within the width of a busbar is shown in (c).



For various samples, current-voltage (I-V) curves (left) and capacitance-voltage (C-V) curves (right) are plotted above. The black curves represent a cleaved cm-size cell piece having an area and corresponding capacitance value too large for DLTS measurement. The colored curves represent small area devices formed by laser scribing a circle centered over a gridline (red), between gridlines of a HIT cell (blue), and within a busbar (green).

Summary

- A laser micromachining system has been developed and applied to various solar cell characterization activities. USP lasers can ablate material with very minimal heating and thermal effects. Solar cell materials can be cut and scribed to form small-area test regions without significant laser-related damage or shunting. Despite the unoptimized focus and lack of gas flow to flush away vaporized material, the laser scribes successfully isolated small solar cell areas that can be used for localized electrical characterization. Laser micromachining has been used to ablate dielectric layers for localized contacts, remove shunt defect areas from larger cells, and also isolate small cell areas within larger cell pieces for restricted-area measurements, such as DLTS.

Future Work

- Add x and y stages to increase working area from 2.5 cm using only the galvanometer scan mirrors to 60 cm, which will combine both motions of the scan mirrors and the stages. This will allow laser scribing, cutting, and processing on larger substrate samples, such as standard-size Si cells and thin-film mini-modules. Other improvements will include finely-adjusted focusing and incorporating gas flow during scribing.

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

46th IEEE PVSC • Chicago, IL • June 16-21, 2019
NREL/PO-5K00-74071