Application Note

Spatially Resolved TRPL Imaging of Laser-Patterned Perovskite Solar Mini Modules

Maxim Simmonds[1], Emilio Gutierrez-Partida[2], Galaan Merga[2], Janardan Dagar[1], Eugeny Ermilov[2], Marcus Sackrow[2], Eva Unger[1], Rainer Erdmann[2]

[1]Department Solution Processing of Hybrid Materials & Devices, Helmholtz Zentrum Berlin, Hahn-Meitner-Platz 1, 14109 Berlin, Germany
[2]PicoQuant, Rudower Chaussee 29, 12489 Berlin, Germany, info@picoquant.com

Combining spatial localization, spectral analysis, and time-resolved photoluminescence to investigate carrier dynamics across laser-patterned regions.

Introduction

Perovskite solar mini-modules represent an important step between laboratory-scale solar cells and large-area modules, enabling evaluation of device performance and fabrication strategies under more application-relevant conditions. In materials science and semiconductor research, it is essential to understand how device structuring influences local photophysical properties. Steady-state emission spectra provide information about bandgap-related optical characteristics but do not reveal charge carrier dynamics. Time-resolved photoluminescence (TRPL), particularly when combined with spatially resolved imaging (TRPL Imaging), enables the direct investigation of recombination processes across structured regions and allows identifying variations that are not accessible with steady-state measurements alone.

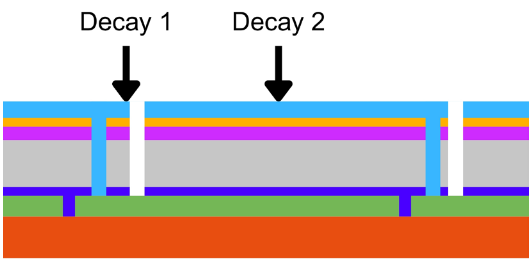

Figure 1: Simplified cross-sectional schematic of a laser-patterned perovskite solar mini module, illustrating the layered device architecture and representative measurement positions.

Methods

The photophysical characterization of structured semiconductor devices requires a combination of spatial, spectral, and temporal information. In the case of perovskite solar mini modules, laser patterning defines functional regions such as P1, P2, and P3, which can introduce local variations in morphology, interfaces, and defect densities. These variations directly influence charge carrier dynamics and recombination behavior.

A stepwise workflow was applied to identify and characterize relevant regions on the sample. Regions of interest were located using spiral scanning in combination with reflection and transmission signals, enabling reliable navigation across the structured device. Steady-state emission spectra were recorded to verify the optical response and assess the emission characteristics relative to the expected bandgap.

Time-resolved photoluminescence (TRPL) measurements were then performed using pulsed excitation with repetition rates adapted to the observed decay times in the nanosecond to microsecond range. The emitted signal was detected with single-photon sensitive detectors and recorded via time-correlated single photon counting (TCSPC) to extract charge carrier lifetimes. For spatially resolved analysis, the system was operated in scanning mode to acquire TRPL imaging data, where a full decay curve was recorded for each spatial position.

All measurements were performed using Solira, a time-resolved photoluminescence microscope designed for spatially resolved steady-state and time-resolved experiments. By combining spectral, temporal, and spatial detection within one setup, the system enables a consistent and efficient characterization workflow for structured semiconductor devices such as perovskite solar mini modules.

Figure 2: PicoQuant's Solira, a time-resolved photoluminescence microscope used for spatially resolved steady-state and time-resolved measurements in materials science applications.

Results

Sample Navigation and Region Identification

A spiral scanning approach, in which the sample is automatically traversed in an expanding spiral pattern, enabled efficient localization of structured regions on the perovskite solar mini modules. Reflection and transmission imaging modes supported rapid navigation and overview imaging of the laser-patterned area. The acquired overview images reveal the presence of multiple parallel laser-patterned lines corresponding to structuring steps.
This approach allows reliable identification of regions of interest, even in cases where the patterning is not clearly visible under standard observation conditions. The ability to rapidly navigate across the sample is essential for subsequent spectroscopic and time-resolved measurements at defined positions.

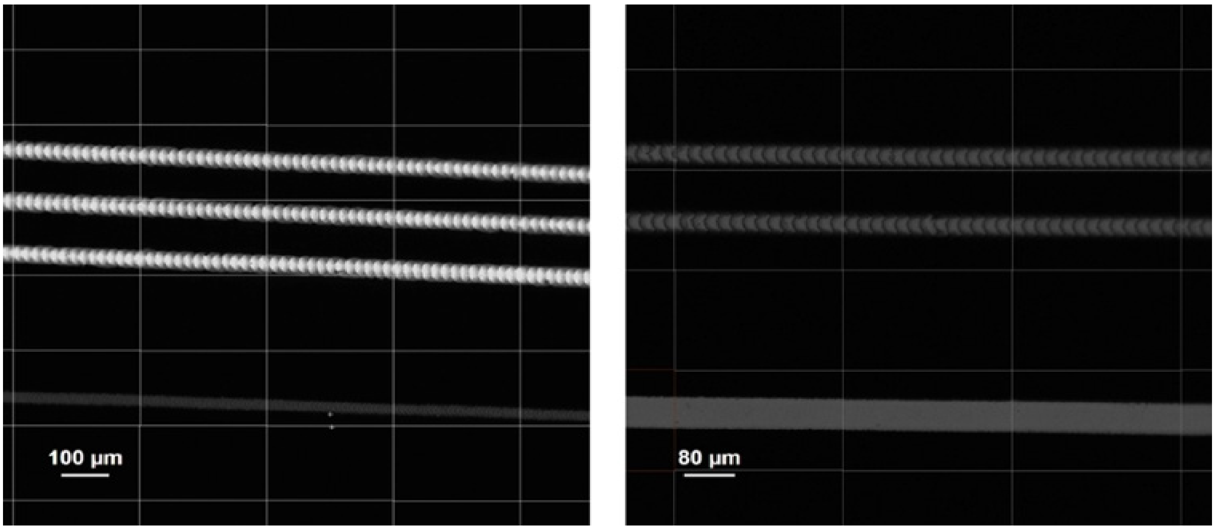

Figure 3: Overview images obtained by spiral scanning for sample A (left) and sample B (right), showing parallel laser-patterned lines identified through reflection and transmission imaging. The approach enables rapid localization of structured regions.

Spectral Characterization

Steady-state emission spectra were recorded at selected positions on the sample to verify the optical response. The measured spectrum exhibits a pronounced emission peak centered around 790 nm, corresponding to an energy bandgap of approximately 1.57–1.58 eV.
This is consistent with the expected bandgap of the perovskite material and confirms that the detected signal originates from the active layer of the device. The spectral characterization provides the basis for selecting appropriate detection conditions for subsequent time-resolved measurements.

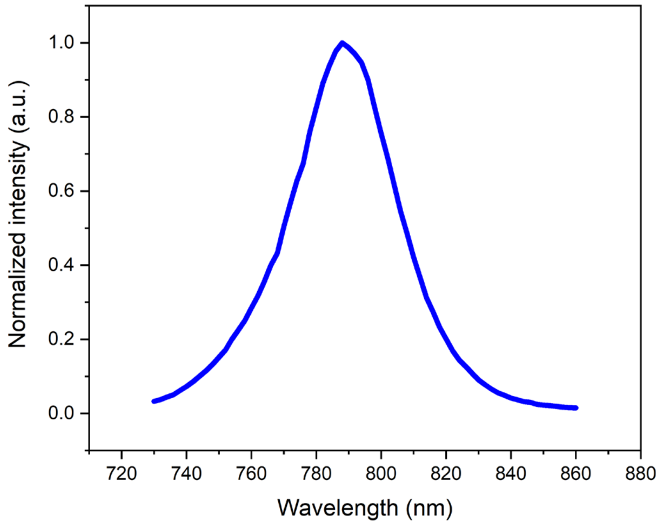

Figure 4: Steady-state emission spectrum recorded from sample A, showing a pronounced photoluminescence peak centered around 790 nm. The spectral response confirms emission from the perovskite active layer and served as the basis for subsequent time-resolved measurements.

Time-Resolved Photoluminescence (TRPL)

Time-resolved photoluminescence measurements were performed at two distinct positions on the sample, located adjacent to a laser-patterned region and in an unmodified area farther away from the structured feature. The recorded decay curves show clear differences in their temporal behavior. The decay measured close to the laser-structured region exhibits a faster decay compared to the unmodified region, where the characteristic emission at around 790 nm confirms the presence of the intact perovskite material.

The faster decay next to the structured region indicates altered charge carrier dynamics, potentially caused by faster diffusion or recombination of free charge carriers. However, based on point measurements alone, it is not possible to determine whether the material has been fully removed or only partially modified by the laser structuring.

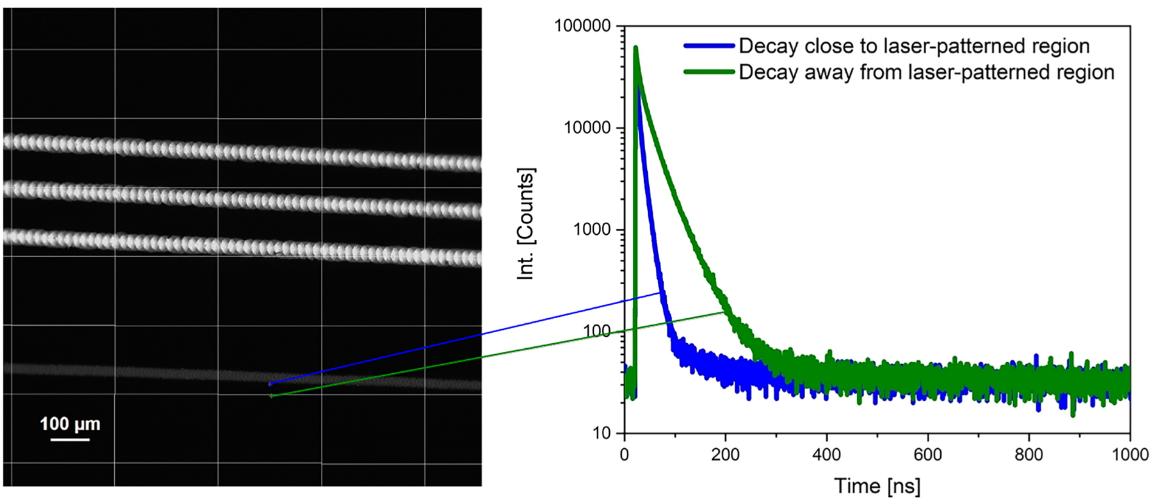

Figure 5: Time-resolved photoluminescence decay curves recorded at positions close to and away from a laser- patterned region on sample A. The decay measured adjacent to the structured line exhibits faster photoluminescence decay dynamics compared to the unmodified region farther from the laser-patterned area.

Spatially Resolved TRPL Imaging

To further investigate this behavior, spatially resolved TRPL imaging was performed. The resulting maps reveal that the laser-patterned regions still exhibit a measurable photoluminescence signal along the structured lines. This demonstrates that the emitting material is not completely removed by the laser ablation process.

Instead, the data indicate that the laser structuring modifies the local photophysical properties of the material rather than fully eliminating it. The combination of localized TRPL measurements and spatially resolved imaging thus provides a more comprehensive understanding of the effect of laser patterning on the device, highlighting the importance of spatially resolved analysis for interpreting changes in charge carrier dynamics.

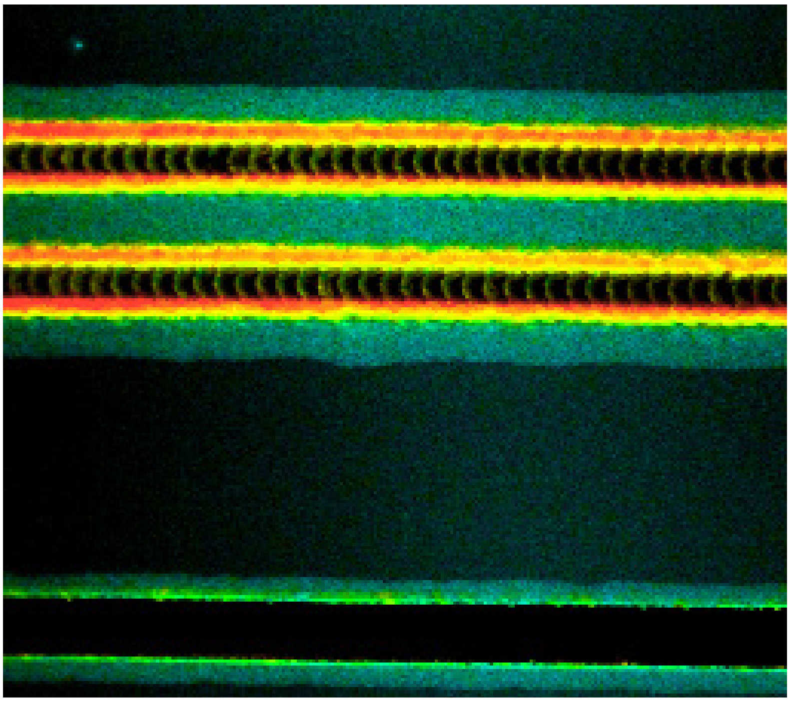

Figure 6: Spatially resolved TRPL image recorded from sample B, showing photoluminescence intensity distribution along laser-patterned lines. The structured regions remain photoluminescent, indicating that the laser process modifies local photophysical.

Conclusion

The presented results demonstrate that laser patterning in perovskite solar mini modules leads to spatial variations in photoluminescence behavior, reflecting differences in local charge carrier dynamics. Time-resolved photoluminescence measurements enable direct comparison of recombination dynamics at defined positions, while TRPL imaging extends this analysis to a spatially resolved view across the structured device.

Solira time-resolved photoluminescence microscope enables this approach by integrating spatial localization, spectral characterization, and time-resolved analysis within a single platform. This combination allows consistent measurement conditions and efficient correlation of spatial, spectral, and temporal information across the sample.

Such an integrated workflow provides a comprehensive understanding of structured semiconductor devices and is particularly relevant for materials science applications, including solar cell research and semiconductor device characterization, where local variations strongly influence performance. The ability to combine spatial, spectral, and time-resolved techniques within a single setup reduces experimental complexity and enables efficient and reliable correlation of photophysical properties, which benefits from both Solira's high sensitivity and experimental flexibility.

Acknowledgements

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PicoQuant GmbH
Rudower Chaussee 29 (IGZ)
12489 Berlin
Germany

Phone +49-(0)30-1208820-0
Email info@picoquant.com
Web www.picoquant.com