

# Materials Science & Engineering Doctoral Defense

## Efficiency-Limiting Recombination Mechanisms in High-Quality Crystalline Silicon for Solar Cells

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### abstract

Recent technology advancements in photovoltaics have enabled crystalline silicon (c-Si) solar cells to establish outstanding photoconversion efficiency records. Remarkable progresses in research and development have been made both on the silicon feedstock quality as well as the technology required for surface passivation, the two dominant sources of performance loss via recombination of photo-generated charge carriers within advanced solar cell architectures. As these two aspects of the solar cell framework improve, the need for a thorough analysis of their respective contribution under varying operation conditions has emerged along with challenges related to the lack of sensitivity of available characterization techniques. The main objective of my thesis work has been to establish a deep understanding of both “intrinsic” and “extrinsic” recombination processes that govern performance in high-quality silicon absorbers. By studying each recombination mechanism as a function of illumination and temperature, I strive to identify the lifetime limiting defects and propose a path to engineer the ultimate silicon solar cell. This dissertation presents a detailed description of the experimental procedure required to deconvolute surface recombination contributions from bulk recombination contributions when performing lifetime spectroscopy analysis. This work proves that temperature- and injection-dependent lifetime spectroscopy (TIDLS) sensitivity can be extended to impurities concentrations down to  $10^9 \text{ cm}^{-3}$ , orders of magnitude below any other characterization technique available today. A new method for the analysis of TIDLS data denominated Defect Parameters Contour Mapping (DPCM) is presented with the aim of providing a visual and intuitive tool to identify the lifetime limiting impurities in silicon material. Surface recombination velocity results are modelled by applying appropriate approaches from literature to our experimentally evaluated data, demonstrating for the first time their capability to interpret temperature-dependent data. In this way, several new results are obtained which solve long disputed aspects of surface passivation mechanisms. Finally, we experimentally evaluate the temperature-dependence of Auger lifetime and its impact on a theoretical intrinsically limited solar cell. These results decisively point to the need for a new Auger lifetime parameterization accounting for its temperature-dependence, which would in turn help understand the ultimate theoretical efficiency limit for a solar cell under real operation conditions.

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