Development of recombination lifetime measurement methods for photovoltaic applications

Summary

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The continuous development of solar cells over the past decades has resulted in a dynamic year-on-year increase in their contribution to global energy production. In 2023, solar energy became the leading source of newly installed energy capacity globally. These achievements have been made possible by decades of research and development in materials science and semiconductor technology. The current record for photoelectric conversion efficiency in silicon-based single-junction solar cells is 27.3%, which approaches the recently updated theoretical efficiency limit 29.4%. Any further enhancement necessitates an even more precise determination of the relevant physical parameters. Another significant trend is the shrinking gap between record efficiencies achieved in R&D laboratories and the efficiencies of solar cells manufactured on modern production lines. Consequently, advanced and more accurate measurements are needed not only to achieve further efficiency records but also to reliably control manufacturing processes. In solar cells, a dominant factor determining the performance is the recombination rate of excess charge carriers. The bulk recombination rate within a silicon wafer, governed by the initial crystal quality and the concentration of defects and impurities, plays a central role in determining the solar cell efficiency. Additionally, surface recombination, occurring at the p-n junction and near ohmic contacts, becomes a critical factor for solar cell devices as well. To further increase energy conversion efficiency, the reduction of recombination-related energy losses is a primary goal of research projects.

Understanding and quantifying the recombination properties of silicon is essential for improving the performance of solar cells. A wide variety of measurement methods have been developed for the precise determination of charge carrier recombination lifetime. Compliance with modern manufacturing requirements demands the use of fast and non-contact technologies. Therefore, the most common measurement solutions currently rely on optical excitation and contactless detection sensitive to excess carriers. This work focuses on the development and applications of recombination lifetime measurement methods, primarily for the investigation of solar cell materials and structures, for both industrial quality control and research purposes. I believe that my work over the past four years has made a significant contribution to the photovoltaic research community and industry at three distinct levels.

At the Budapest University of Technology and Economics (BME), my research group determined the recombination properties of novel photovoltaic materials (in the perovskite family) using cryogenic carrier lifetime measurement systems, recording the recombination properties as a function of temperature. Recognizing the nonlinear behavior of the system, I developed a novel self-consistent calibration method. Beyond the development of the applied evaluation routines, I devised a method to verify the reliability of measurements over the entire investigated temperature range. Through these validation measurements, I determined the ambipolar diffusion coefficient D_{amb} of silicon at low excess charge carrier concentrations down to 120 K.

My work at Semilab Semiconductor Physics Laboratory Co. Ltd. (Semilab) has enabled the experimental determination of excess carrier lifetime in silicon samples used in different phases of solar cell manufacturing process. First, I established a new measurement method and an iterative, simulation-based evaluation algorithm to precisely determine bulk carrier lifetime of thick silicon samples. Using the developed technique, I investigated the bulk recombination processes of very high quality Si ingots which is not possible in other ways. This method is already applied in commercial carrier lifetime measurement systems, providing rapid and precise information about possible contamination in an early production phase.

I developed a unique measurement method combining, for the first time, three independent carrier lifetime measurement principles for the investigation of passivated silicon wafers. This method enabled the simultaneous determination of the density, the lifetime and the mobility of excess charge carriers in modern silicon-based solar cell structures with unprecedented accuracy. In addition to the scientific impact, based on the results an inline recombination lifetime inspection tool has been developed in Semilab for solar cell industry.