BAPVC Annual Project Report

Project Title: Defect identification and mitigation in high-lifetime silicon materials: growth, processing, reliability
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Summary:

High lifetimes in industrial silicon materials, in some cases exceeding 1 millisecond, can often be attributed to significant reductions in impurity concentrations. Research to support further lifetime improvements in high-performance materials demands measurement techniques capable of detecting low impurity concentrations, which can be below 10^{10} cm^{-3}. The Buonassisi group proposes measuring low concentrations of impurities in high-performance crystalline silicon with temperature- and injection-dependent lifetime spectroscopy (TIDLS) implemented with free carrier absorption, which promises a small spot size and full injection range. Initial temperature-dependent lifetime measurements have been collected and compared with room temperature QSSPC, highlighting the need for measurement calibration. As a next step, calibration experiments have been performed to isolate the temperature dependence of the free carrier absorption coefficient.

Key Accomplishments:

As exemplified in Fig. 1, the researchers integrate a temperature stage from Linkam Scientific Instruments, capable of controlling sample temperatures between 77K and 690K, with a free carrier absorption (FCA) lifetime measurement FCA is a transient lifetime measurement that tracks optical interactions of pump and probe light beams with the material. A neodymium-doped yttrium aluminum garnet (Nd:YAG) laser provides a 6 ns full-width half-maximum pump pulse at a variable wavelength, while a halogen lamp equipped with a monochromator emits a continuous wave probe beam at 1550 nm through the sample to an InGaAs probe detector (5 ns rise time). This approach offers several advantages, including high spatial resolution and flexibility in terms of thickness, passivation quality, impurity type, and impurity concentration.

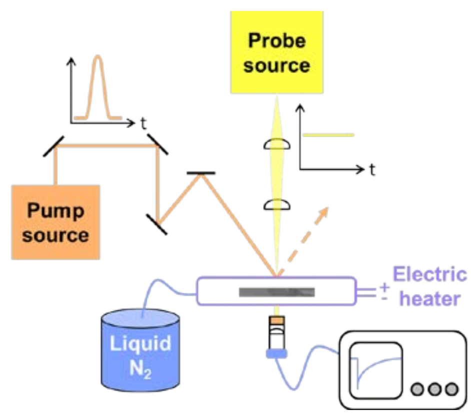

Figure 1: Schematic of free carrier absorption-based TIDLS setup, including an off-the-shelf temperature stage, a variable wavelength pump laser (1000-1300 nm), and a monochromatic probe beam (1550 nm).

Initial lifetime measurements have been made on a single-crystalline *p*-type Czochralski silicon sample. The passivation layer is 20 nm Al_2O_3 deposited by atomic layer deposition. The FCA measurements were conducted at 20°C, 75°C, and 125°C with a constant pump wavelength equal to 1050 nm.

Fig. 2 contains the measurement results, including detector voltage versus time (a), injection-dependent lifetime curves (b, c), and a photoluminescence image of the measurement sample (d). The resulting data displays a wide injection range, with the possibility to optimize the signal-to-noise ratio to achieve greater confidence in low injection (< 5×10^{14} cm^{-3}). There is agreement in the shape of the lifetime curve between QSSPC and FCA measurements; however, exact values

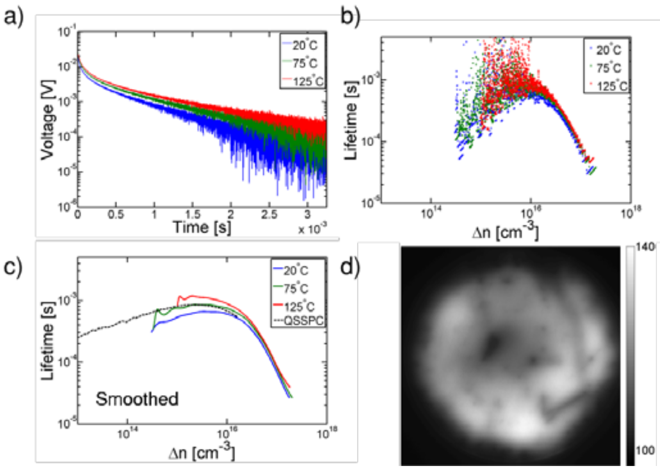

Figure 2: Free carrier absorption was used to measure the minority carrier lifetime of a *p*-type Czochralski sample between room temperature and 125°C.

are not reproduced. There are several possible explanations for this mismatch, including spatial inhomogeneity of the sample lifetime, misalignment of the pump and probe beams, and insufficient pump beam size compared to diffusion length. Calibration of the lifetime measurement as a function of temperature is required.

An important calibration step for this tool involves measurement of the temperature- and injection-dependent FCA coefficient (σ_{FCA}, units of cm^2). Previous studies have determined that σ_{FCA} is enhanced at injection levels greater than 3×10^{16} cm^{-3} and scales linearly with temperature; however, there is significant spread in the tabulated literature values (Fig. 3). Results from ongoing experiments to measure the temperature dependence of σ_{FCA} in low injection are also included in Fig. 3. To obtain these results, the injected carrier concentration is estimated using a large-area pyroelectric detector, while the detector response is determined from the voltage during the first 10 ns after the pulse (accounting for detector rise time).

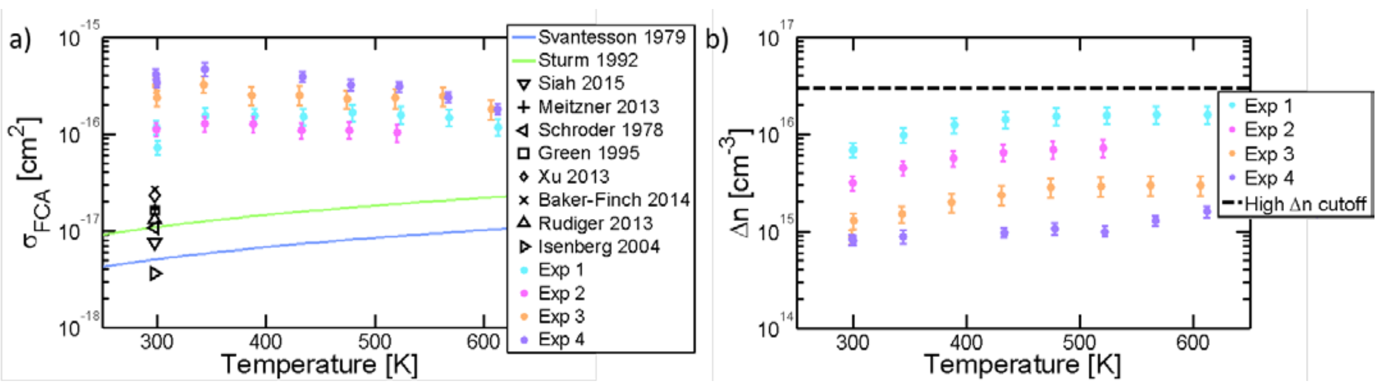

Figure 3: Reported values for the ambipolar free carrier absorption cross-section, plotted as a function of temperature.

Future Work:

To gain confidence in the lifetime measurement technique, researchers will seek to obtain agreement in lifetime measurements between QSSPC and FCA at room temperature. As part of this effort, discrepancies between measured and literature σ_{FCA} values will be investigated and resolved. TIDLS measurements will first be conducted on intentionally metal-contaminated samples. From the full temperature and injection-dependent spectra, defect parameters including defect level, ratio of capture cross-sections, and carrier capture time constant, will be extracted and compared to literature values. Finally, the technique will be applied to samples with suspected impurity contamination provided by industry collaborators.