

TEMPERATURE DEPENDENT CARRIER LIFETIME IMAGES

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ABSTRACT: Carrier Density Imaging (CDI) is a convenient tool to measure actual lifetimes in silicon with high spatial resolution. CDI is based on the detection of infrared radiation being absorbed and emitted by free carriers. Recently, a measurement mode was developed where the experimental conditions favors the emission of free carriers. This article exemplifies the advantages of emission CDI. Measurement time can be decreased to 1 s for standard multicrystalline silicon and excellent signal to noise ratios can be achieved if the temperature of the sample is increased moderately. Measuring lifetime in a wide temperature range up to 270 °C enables spatially resolved lifetime spectroscopy. First results of an intentionally contaminated molybdenum sample and a sample of multicrystalline silicon are presented.

Keywords: Experimental Methods, Recombination, Spectroscopy

1 INTRODUCTION

The measurement of spatially resolved lifetime maps is very helpful for characterization and technology. High sensitivity is needed for characterization, whereas fast measurements are required for industrial purposes. Based on the detection of infrared radiation being absorbed and emitted by free excess carriers Carrier Density Imaging (CDI) [1], a further development of Infrared Lifetime Mapping (ILM) [2], is a convenient tool to obtain lifetime images. Measurement time is reduced efficiently compared to other methods like MW-PCD [3] due to the replacement of the slow scanning principle by the use of a CCD-camera in the mid infrared. The implementation of a lock-in-system increases sensitivity to a high level and enables measurements of low-lifetime multicrystalline silicon samples.

Up to now, the absorption signal of free carriers was measured in CDI-measurements. By using high background in combination with low wafer temperatures the absorption signal is favored over the emission signal. Recently, a method to detect the emission signal has been developed [4], which uses high wafer and low background temperatures to reduce the absorption signal.

The study of the theoretical dependence of the signal height on wafer and background temperature indicates a strongly improved signal when the wafer temperature is raised to moderate values. To achieve a precise control of the wafer temperature, a setup has been developed, where samples can be heated to temperatures between 25 °C and 270 °C. The possibility of temperature control up to high temperatures enables lifetime spectroscopy in a way similar to Temperature Dependent Lifetime Spectroscopy (TDLS) [5], but contrary to this technique with high spatial resolution.

2 EXPERIMENTAL SETUP

In Fig. 1 the experimental setup for CDI measurements is shown. The sample is placed in front of a temperature controlled black background.

The sample is illuminated by a 30 W, 914 nm semiconductor laser. A CCD-camera with a detection range from 3 to 5 µm focuses on the sample. A resolution of 50 µm to 450 µm is attainable with 288² pixels.

Free carriers in the sample absorb subbandgap radiation emitted by the background. Depending on the

sample temperature they also emit IR-radiation. In emission CDI mode temperatures are chosen such that the IR-radiation emitted by the sample exceeds the background IR-radiation whereas background radiation is dominant in absorption CDI mode.

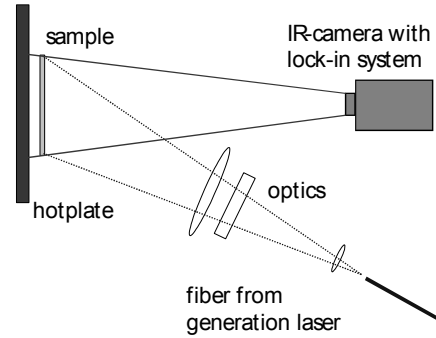


Figure 1: Setup for CDI measurements

Differences between the illuminated and the dark state are detected by application of a lock-in system. They are a measure of the optically generated minority free carrier density Δn in the sample. A lock-in frequency of only 36 Hz ensures quasi steady state conditions. The effective carrier lifetime τ_{eff} can therefore be determined from

$$\tau_{eff} = \frac{\Delta n}{G},$$

where G is the generation rate of free carriers. Note that equilibrium between generation and recombination is assumed.

3 ABSORPTION AND EMISSION BY FREE CARRIERS

The IR radiation due to free excess carriers detected by CDI-measurements contains an absorption and an emission component. The absorption coefficient for free carriers is given by [5]:

$$\alpha_{fc} = \frac{q^3 N}{4\pi^2 \epsilon_0 c^3 nm^{*2} \mu} \lambda^2$$

where N is the free carrier density, λ the wavelength, q the elementary charge, ϵ_0 the real part of the dielectric

constant, c the speed of light, n the refractive index, m^* the effective mass and μ the mobility. This yields a linear dependence of α_{fc} on the excess free carrier density Δn . The law of detailed balance assures that the emission coefficient of the free carriers ε_{fc} is equal to the absorption coefficient α_{fc} :

Assuming a volume dV with dimensions such that thermal equilibrium is possible and the probability of reabsorption of an emitted photon in dV is zero, the emitted and absorbed radiation for each wavelength is equal. Therefore

$$\varepsilon_{fc}(\lambda, \Delta n) = \alpha_{fc}(\lambda, \Delta n) .$$

The measurable change of energy flux density between the dark and the illuminated state is proportional to the integral of Planck's radiation law:

$$E_{CDI} \propto \int_{\lambda_{min}}^{\lambda_{max}} \frac{\varepsilon_{fc}(\lambda, \Delta n)}{\lambda^5 (e^{hc/k\lambda T_w} - 1)} d\lambda - \int_{\lambda_{min}}^{\lambda_{max}} \frac{\alpha_{fc}(\lambda, \Delta n)}{\lambda^5 (e^{hc/k\lambda T_b} - 1)} d\lambda$$

where λ_{min} and λ_{max} are determined by the detection range. The CCD-camera in the setup detects photons rather than energy, so the camera signal can be described by dividing the integrand by the photon energy

$$E_{ph} = h\nu = \frac{hc}{\lambda}$$

which results by substituting α_{fc} in an expression for the camera signal (see Fig. 2):

$$S_{CDI} \propto \Delta n \cdot \int_{\lambda_{min}}^{\lambda_{max}} \left(\frac{1}{\lambda^2 (e^{hc/k\lambda T_w} - 1)} - \frac{1}{\lambda^2 (e^{hc/k\lambda T_b} - 1)} \right) d\lambda \quad (1)$$

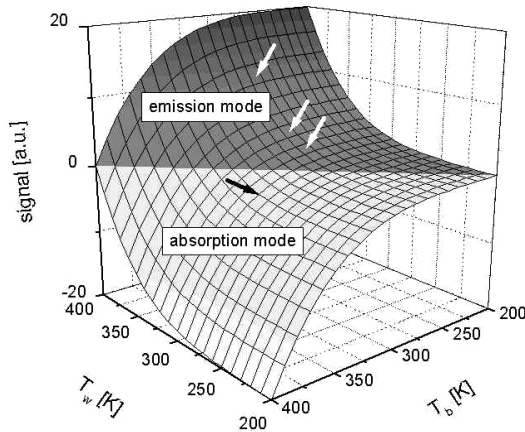


Figure 2: Dependence of the CDI-signal on background and sample temperature T_b and T_w . The black arrow marks the temperature conditions presently used for absorption CDI measurements, whereas the white arrows indicate the conditions for emission CDI of Fig. 3.

4 EXPERIMENTAL RESULTS

4.1 Emission CDI for fast measurements

Emission CDI enables measurements with drastically reduced measurement time. Fig. 2 illustrates the enhanced sensitivity for lifetime measurements at higher temperatures (cf. white arrows of Fig. 2). The image consists of measurements of a multicrystalline SiN-passivated silicon wafer at different temperatures

(from left to right): 40 °C, 59 °C, 100 °C. Measurement time was only 1 s. The average lifetime of the sample has been determined to 18 μ s.

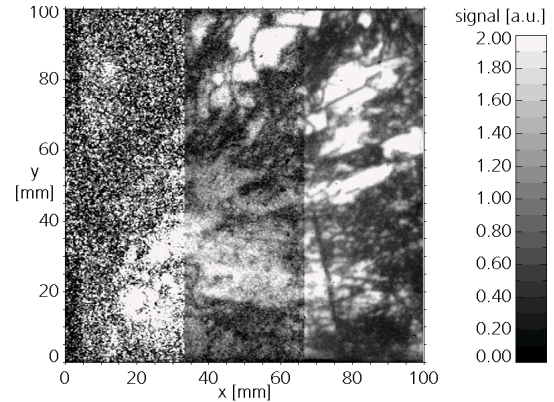


Figure 3: Carrier density measurements of a low lifetime multicrystalline silicon sample at different temperatures (from left to right): 40 °C, 59 °C, 100 °C and a measurement time of 1 s.

Care has to be taken by comparing lifetime measurements with different wafer temperatures because of the temperature dependence of the Shockley-Read-Hall-(SRH)-recombination at low level injection which is the dominant recombination process in multicrystalline silicon. Especially recombination due to shallow defect levels shows a significant dependence on temperature. However, defects with deep energy levels contribute much more to recombination. As shown in Fig. 4 the temperature dependence of deep centers is weaker.

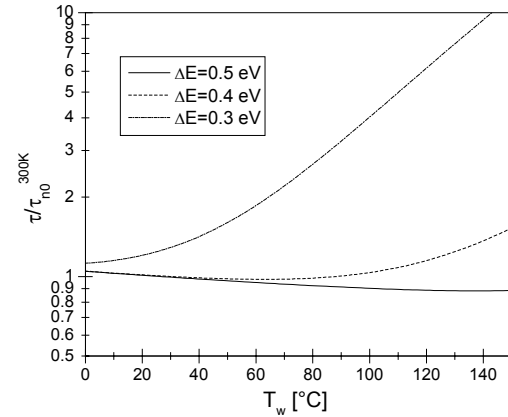


Figure 4: Dependence of the SRH-lifetime at low level injection on temperature for defects with different energy levels.

Furthermore, typical operating temperatures for solar cells are well above 25 °C. Therefore lifetime measurements at e.g. 60 °C are an appropriate means for characterization of solar cell material.

4.2 Emission CDI for high lifetime resolution

The increased sensitivity of Emission CDI measurements at higher wafer temperatures allows lifetime analysis even for unpassivated samples. In Fig. 5 lifetime measurements realized with MW-PCD (left side) and with Emission CDI at a wafer temperature of 90 °C are shown. The sample under investigation (45x45 mm²) was SiN-passivated. The mean lifetime measured with MW-PCD under high level injection was 3.5 μ s. The

image on the lower right side shows an Emission CDI measurement after mechanical removing of the surface passivation. An excellent correlation of the lifetime pattern can be observed. Measurement time of the CDI measurements were 10 min (SiN-passivated) and 20 min (without surface passivation) with effective lifetimes between 1-3 μ s.

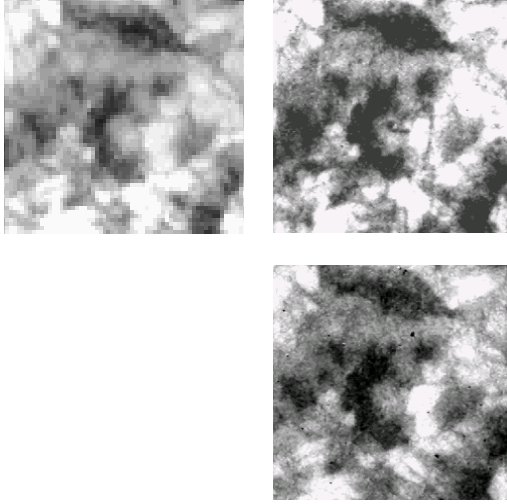


Figure 5: Carrier density measurements on a low-lifetime mc-silicon sample (45x45 mm²). On the left side a MW-PCD measurement under high level injection is shown, on the right side Emission CDI results (90 °C) are presented (upper image: SiN-passivated, lower image: with surface passivation removed). Arbitrary units on a linear gray-scale were used.

5 THERMAL DEFECT IMAGING TDI

5.1 Temperature dependent Shockley-Read-Hall lifetime

In PV-grade silicon Shockley-Read-Hall (SRH) recombination is mostly the dominating recombination process and determines the lifetime in the bulk material. If recombination over one defect level is assumed, the measurement of the temperature dependence on lifetime allows the determination of the energy difference between defect level and band edge (valence or conduction band). This is the basic idea of Temperature Dependent Lifetime Spectroscopy TDLS [5], where the MW-PCD technique is used to measure lifetimes. Disadvantages for that method is a lack of spatial resolution and the restricted sample size.

If the inverse of temperature is plotted against the logarithmic quotient of measured lifetime and temperature, a linear dependence for high temperatures is expected (see Fig. 6). The gradient in this region depends directly on the energy level of the defect.

Thermal Defect Imaging TDI overcomes the restriction in sample size and allows a spatially resolved determination of defect levels. The technique combines the TDLS technique and Emission CDI at different temperatures. Equation (1) describes the dependence of the camera signal on the excess carrier density and on temperature. A procedure proposed by Bail et al. [2] is used to determine the scaling factor for equation (1).

At higher temperatures, filters have to be used to prevent saturation of the camera chip. An array of different polymer filters can be used for this purpose to

ensure maximal signal without saturation problems. The influence of the filters on the camera signal has to be considered in the calibration.

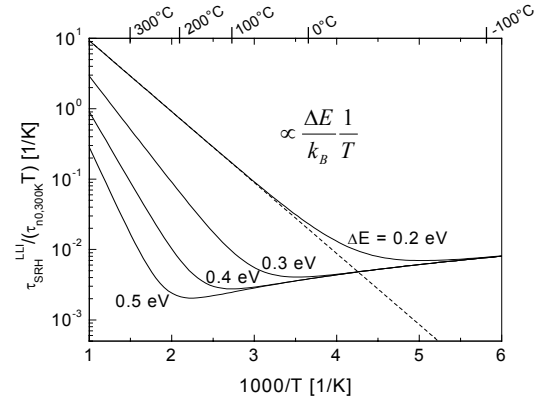


Figure 6: Calculated dependence of the SRH-lifetime at low level injection on temperature for defects with different energy levels.

5.2 Results for intentionally Mo-contaminated sample

A TDI measurement on an intentionally contaminated FZ-silicon sample has been performed in order to compare the results with TDLS measurements and to prove the functionality of TDI. Fig. 7 shows Emission CDI measurements for a temperature range from 30 °C to 270 °C. For a comparison with TDLS measurements, the mean value of carrier density over the sample is displayed.

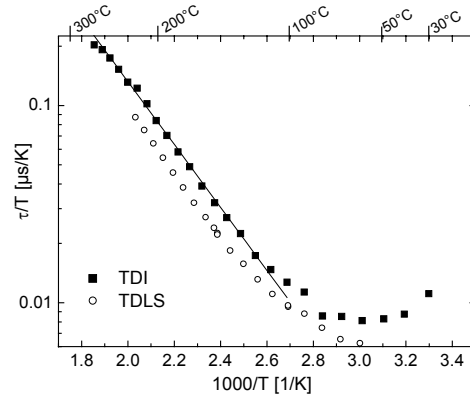


Figure 7: TDI measurement on a Mo-contaminated sample (black squares) and TDLS measurement (open circles).

From the gradient of the linear region of the TDI measurement the difference ΔE between band edge and defect level can be calculated to $\Delta E_{TDI}=316$ meV which corresponds well with $\Delta E_{TDLS}=330$ meV for the TDLS measurement. This calculation has been performed for each camera pixel, resulting in a calculated defect level for each wafer position. Excellent homogeneity has been observed over the sample.

5.3 Results for multicrystalline silicon

Fig. 8 shows an Emission CDI measurement of a 100x100 mm² multicrystalline silicon wafer. The wafer has been vertically cut from a block-cast silicon ingot. The cap region of the ingot (top of the image) shows very low lifetimes whereas in the lower part high lifetime

grains can be seen. On the right side the influence of the crucible reduces lifetime. Three different regions have been selected for closer examination (arrows in Fig. 8):

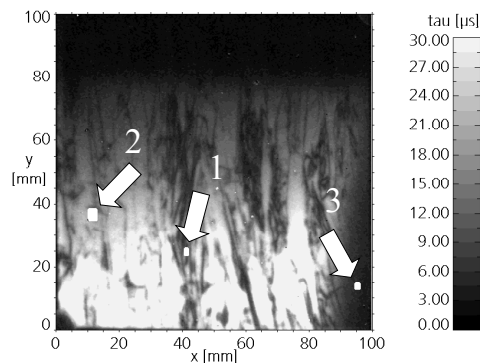


Figure 8: Lifetime measurement of an industrial mc-sample.

A region with high crystal lattice distortion (1), a region with fair lifetime (2) and a low-lifetime region at the right side (3) were chosen. The respective temperature dependence of lifetime is shown in Fig. 9.

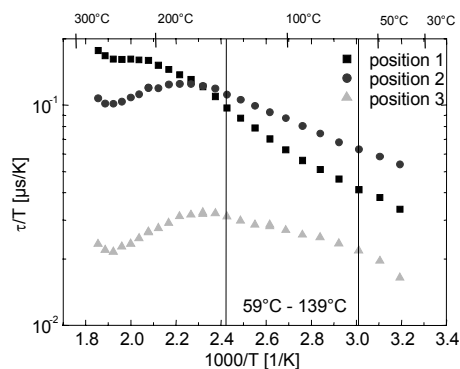


Figure 9: Temperature dependence of lifetime for three selected positions on the wafer of Fig. 8.

A linear region between 59 °C and 139 °C can be determined for all regions whereby the gradient differs for the three positions. The temperature dependence for high lifetimes appear to deviate from SRH theory. Further investigations are required.

The observed linear region has been used to determine a gradient for each camera pixel. For the case of a single and discrete dominating defect level the gradient should result in the energy difference ΔE between band edge and defect level. Fig. 10 shows the calculated spatially resolved gradients that are a measure for an “effective” energy level which may represent a more complex distribution of defect levels. The defect levels detected at grain boundaries are shallower than within the grains. Although the lifetime gradient from the bottom to the top of the image is significant, the defect level distribution does not show a clear correlation with lifetime level. At $y > 80$ mm in Fig. 10 the detection limit has been reached resulting in a vanishing gradient. How to extract more defect-specific information from TDI measurements is presently under investigation.

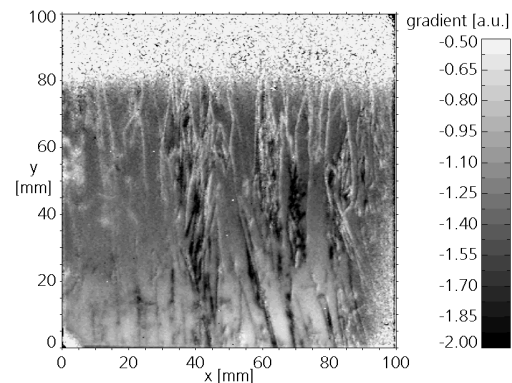


Figure 10: Image of the gradient of TDI analysis of the sample of Fig. 8.

6 CONCLUSION

Emission CDI has been proven and demonstrated to be a powerful tool for lifetime measurement. Especially at enhanced temperatures very high sensitivity is achieved, which results in significant decrease of measurement time and allows even the measurement for very low-lifetime wafers without surface passivation. Emission CDI can also be used for lifetime spectroscopy similar to TDLS measurements, but with high spatial resolution. Thermal Defect Imaging TDI has been introduced and it was demonstrated that the energy difference between bandedge and defect level may be determined. A comparison of measurements by TDLS and TDI on a Molybdenum contaminated sample shows good correlation. A TDI measurement on a 100x100 mm² multicrystalline sample has been performed. First examinations of the influence of different regions, grain boundaries and edges on the defect distribution have been presented.

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