Photoluminescence Imaging vs. Transient Photoconductance Characterization at High Injection: Case of mc-Si

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Abstract — **Band-to-band photoluminescence (PL) imaging is one of the experimental techniques widely used to assess non-radiative recombination rates at a fixed incident light intensity. Minority carrier lifetimes in semiconductors such as mc-Si are also affected by optical injection levels. These can be measured by transient photoconductance (TPC). In this paper, PL imaging of shunts and TPC lifetime results for incident intensities of up to 50 Suns are compared for multiple samples of mc-Si.**

Keywords —Silicon, non-radiative recombination, high optical injection, transient photoconductance decay, photoluminescence imaging.

I. Introduction

Concentrator photovoltaics is a popular area of technological research. Light concentration allows reducing PV cell dimensions and PV system costs, and also capturing and converting diffusely-scattered photons. While the goal is to improve the PV conversion efficiency, in realistic semiconductors with defects and impurities, the efficiency can be adversely affected by non-radiative (NR) recombination, including Shockley-Read-Hall (at moderately high optical injection) and Auger recombination (at very high optical injection). The carrier recombination rate dependences on the incident light intensity in samples of multicrystalline silicon (mc-Si) were studied in the past ([1], [2]) using various experimental and theoretical approaches. One of the goals was to obtain realistic diffusion lengths of minority carriers in PV cells illuminated with concentrated light.

Previous experimental studies focused on the detection of iron and other transition metal point defects in Si and on assessing their effects on carrier lifetimes [3]. A more general case, considering carrier trapping and NR recombination due to metal impurities in Si was also discussed in [4]. While the PL techniques can reveal the spatial distributions of NR recombination rates and carrier diffusion, for some practical applications, such as concentrator PV, other methods could be more appropriate.

In this paper, the author compares his band-to-band IR photoluminescence (PL) maps obtained at about 1 Sun incident intensity and transient photoconductance (TPC) measurements done with pulsed intensities of up to 50 Suns. The results of the two techniques for multiple samples can help find the connections between apparent NR recombination rates from PL and directly measured carrier lifetimes from TPC. Minority carrier lifetimes can be separately measured for n- and p-type mc-Si. The fundamental question is whether the PL images taken at low excitation intensities that are widely used in detection of areas of high NR recombination rates (shunts) can be used to predict those rates at high injection. This work was supported through the NSF-RIA grant HRD-1505377.

II. Experiments and Theory

In order to obtain the band-to-band photoluminescence images, a setup including an LED light source and a highly-sensitive IR camera from Stress Photonics GFP 100 system located at UIUC Talbot Lab was used. All images of antireflection-coated samples doped with boron to 10^{16} cm^{-3} density, with dimensions of 154×154×0.2 mm from Solar World were taken in transmission. Intensities were averaged over 16 light polarizations and 10 time realizations, in order to increase the signal-to-noise ratios. The author has developed a MATLAB-based application that processes images using an adaptive 2-D Wiener filter, but in this paper, spatial averaging is applied to reduce the camera noise instead. The images of band-to-band IR PL (~1 micron wavelength) had an approximately 75×75 μm^2 pixel resolution. Since the field of view was about 30×30 mm^2, for each wafer, 25 images were taken. A reference Si wafer with a long carrier lifetime was also imaged.

The PL intensity emitted by a p-type wafer illuminated with an excitation source can be expressed as (1):

$$I_{PL} = Cpn = C(N_A + \Delta n)\Delta n, \qquad (1)$$

where p and n are the hole and electron concentrations, Δn is the excess electron concentration, C is the coefficient dependent on the electron-hole pair generation and recombination rates, I_{PL} is the PL intensity, and N_A is the acceptor doping density.

The transport of excess electrons in p-type mc-Si obeys the following equation (2):

$$\frac{\partial(\Delta n)}{\partial t} = D\nabla^2(\Delta n) + G - R, \qquad (2)$$

where D is the diffusivity of electrons in Si, G is the carrier generation rate, and R is the recombination rate that includes both radiative and non-radiative components.

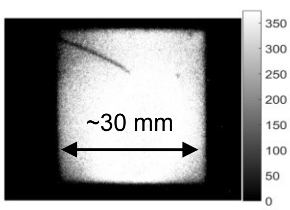
The effective minority carrier lifetime can be found, in the single-rate approximation as:

$$\tau_{eff}(\Delta n) = \frac{\Delta n}{R(\Delta n)} \qquad (3)$$

To explore recombination rate dependences on carrier concentration that could be attributed to multiple non-radiative recombination pathways, the transient photoconductance method (TPC) was used. The TPC measurements were carried out using a Sinton WTC-120 lifetime tester working in the QSSPC mode with the maximum flash intensity of about 50 Suns. One of the parameters extracted from the measurements was the minority carrier lifetime as a function of optically injected carrier concentration.

III. Analysis of Results

Typical band-to-band IR PL intensity images coming from a reference monocrystalline Si wafer and from a mc-Si sample are shown in Figure 1.



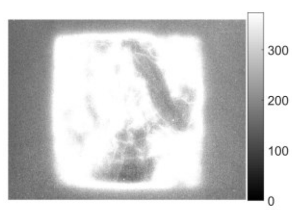


Fig. 1. Examples of band-to-band PL intensity (a.u.) images: a) from a reference n-type monocrystalline wafer, b) from p-type multicrystalline sample SB 8.

The reference n-type Si wafer (Fig. 1a) has a minority carrier lifetime of about 2×10^{-4} s. Five characteristic mc-Si samples, labeled SB 2, SB 3, SB 8, SB 9, and SB 10 were selected and compared in terms of low-injection (around 1 Sun intensity, $\Delta n \approx 1.5 \times 10^{13}$ cm^{-3}) minority carrier lifetimes. The p-type multicrystalline Si samples show areas of reduced PL intensity (Fig. 1b). Their position-averaged minority lifetimes were found to be in the 3…6 × 10^{-6} s range. As PL images reveal, most reduction in the IR PL intensity likely comes from distributed point defects (such as transition metal impurities), rather than from grain boundaries. PL intensity was spatially averaged over the central 1/25th of the sample area, roughly matching the illumination spot produced by the lifetime tester. In Figure 2 the spatially-averaged low-injection carrier lifetimes are plotted against the PL intensity for the five mc-Si samples.

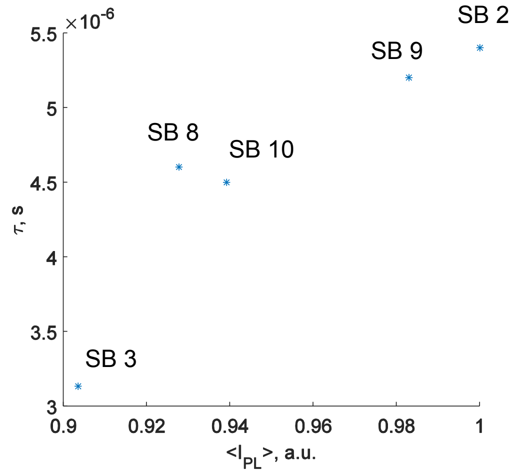


Fig. 2. Spatially averaged minority carrier lifetimes and IR PL intensities at low injection.

As one can see from Figure 2, measured minority carrier lifetimes are reasonably well correlated with the photoluminescence intensities (correlation coefficient is around +0.91 for the central 1/25th and +0.88 for the whole wafer). The result is expected, since a higher band-to-band IR PL intensity corresponds to less NR recombination, therefore, a higher lifetime. The PL intensity dependence on the carrier lifetime is also fit well with a quadratic equation (R^2=0.96), which is consistent with equations (1) and (3). While the method is useful in assessing minority carrier lifetimes, it was noticed that even upon averaging the PL images had significant levels of instrument noise. A substantial variability in averaged PL intensity from various areas of the same wafer was also observed. The ratio of the standard deviation to mean PL intensity in 25 tile images taken from the same wafer ranges from 0.088 to 0.143.

Moreover, all static IR PL measurements were carried out at low injection, while the TPC ones were at higher illumination intensities. The latter results indicate that when the optically-injected carrier concentration is above 2×10^{14} cm^{-3}, the lifetimes in relation to the excess carrier concentration can be described by a variety of functions, depending on sample-specific carrier recombination processes.

Figure 3 displays the minority carrier lifetimes extracted from TPC measurements for four other mc-Si samples that were not selected for the analysis shown in Figure 2. Sample S4 is of n-type, and S1 to S3 are of p-type.

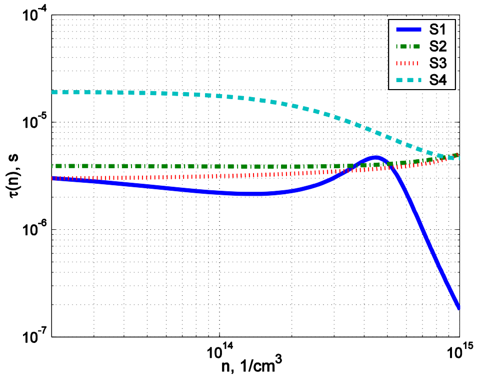


Fig. 3. Carrier lifetimes as functions of optically-injected excess carrier concentrations for a set of multicrystalline Si wafers.

As one can see from Figure 3, the lifetimes measured at low injection for boron-doped Si samples S1-S3 are significantly lower than those for the phosphorus-doped sample S4. However, this is not the case at higher optically-injected carrier concentrations. It is highly unlikely that the dominant mechanism for the reduction of lifetime at high optical injection could be an Auger process due to its low capture cross-sections. The plausible mechanism can be a combination of several contaminants in mc-Si that leads to the formation of multiple defect levels, for which regular Shockley-Read-Hall equations for a single defect type will not hold [4]. Applying multiple rate equations for NR recombination may help explain these dependences.

One can argue that transient photoluminescence methods, such as QSSPL [5], can be used together with TPC to obtain high-injection diffusion lengths. However, the success of that approach will strongly depend on the knowledge of the non-radiative recombination rate dependence on excess carrier concentration in equations (2) and (3).

IV. Conclusions, Relevance to the Field and Future Work

Non-radiative recombination in mc-Si was studied at relatively low optical injection levels using the band-to-band photoluminescence images. This technique is highly suitable for the detection of distributed point defects that act like shunts, however, at high illumination intensities, the carrier lifetimes may depend on the carrier concentration in various ways. Thus, the IR PL images at intensities of about 1 Sun are not always helpful in the prediction of how the carrier recombination proceeds in semiconductors under the concentrated illumination. Transient photoconductance is a more informative characterization method for semiconductor materials used for concentrator photovoltaics.

This work is useful to those PV engineers and scientists who design concentrator solar cells, and the approach taken is suitable for various types of semiconductors with defects that cause non-radiative recombination. The future work will focus on explaining the experimental recombination rate dependences on injection levels by theoretical calculations.

References

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