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CONTACTLESS CARRIER-LIFETIME MEASUREMENT IN SILICON WAFERS, INGOTS, AND BLOCKS

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^E This standard was editorially modified in April 2010 to correct an error. A change was made to the notice following § 1, and Equation 5.

1 Forward

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2 Abstract

This white paper was written in an effort to create a concise summary of a common framework for contactless carrier lifetime measurement in silicon photovoltaics. The goal was to document methodologies that will allow for comparisons of results taken at various institutes, manufacturers, and universities that may use different measurement instruments. A description of lifetime measurements is discussed in terms of the device physics, focusing on the physical excess carrier lifetimes and (charge-)carrier densities that form the basis for any lifetime measurement. A standard analysis is presented. The application of this measurement methodology is described in the context of lifetime measurements on wafers, ingots, and blocks. Commonly-used interpretations of the measured lifetime to determine surface recombination velocities, emitter saturation current densities, and bulk lifetimes are described. The results of this white paper apply to any lifetime measurement technique that can demonstrate a calibration of measured data to excess-carrier density within the sample. One specific example that applies the methodology developed in this white paper is presented, using an eddy-current sensor to determine photoconductance. In this case, the calibration to absolute photoconductance is done with a traceable calibration of the instrument against wafers measured by four-point-probe. Standard equations for silicon mobility vs. carrier density are then used to convert conductance data into carrier density vs. time during a measurement. This data is then sufficient to evaluate carrier lifetimes and report the results as a function of the carrier density in the sample using the methods described in the white paper.

3 Acknowledgements

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4 Introduction

The carrier recombination lifetime is the central parameter to the device design, production, and process control for silicon solar cells. The longer an excess carrier lives in the excited state, the better the solar cell that will be made from this wafer, all other things being equal. For lifetimes greater than the transit time of the wafer, photogenerated current collection can be high. As the lifetime continues to increase from this benchmark, the current extraction can be maintained at higher voltages. This physical property is a major factor in the optimization of solar cell designs. It is used as the figure of merit for process control in as-grown material, wafers, and after each fabrication step, including phosphorus diffusion and the monitoring of surface passivation deposition parameters. The recombination lifetime in the wafer is one of the most important input parameters for any device model used in design optimization and efficiency prediction. Due to its importance, the photovoltaic community has developed several techniques to report this parameter in order to be able to determine bulk lifetime and surface recombination parameters with good accuracy.

For reference in this discussion, the carrier recombination lifetime which is typical of the photovoltaic technical literature is shown in Figure 1. This is a simulation from a 3 ohm-cm B-doped CZ wafer with nitride passivation, measured in the degraded state of the B:O defect using the defect recombination parameters determined by Bothe[1]. The lifetime is given as a function of the excess carrier density in the wafer.

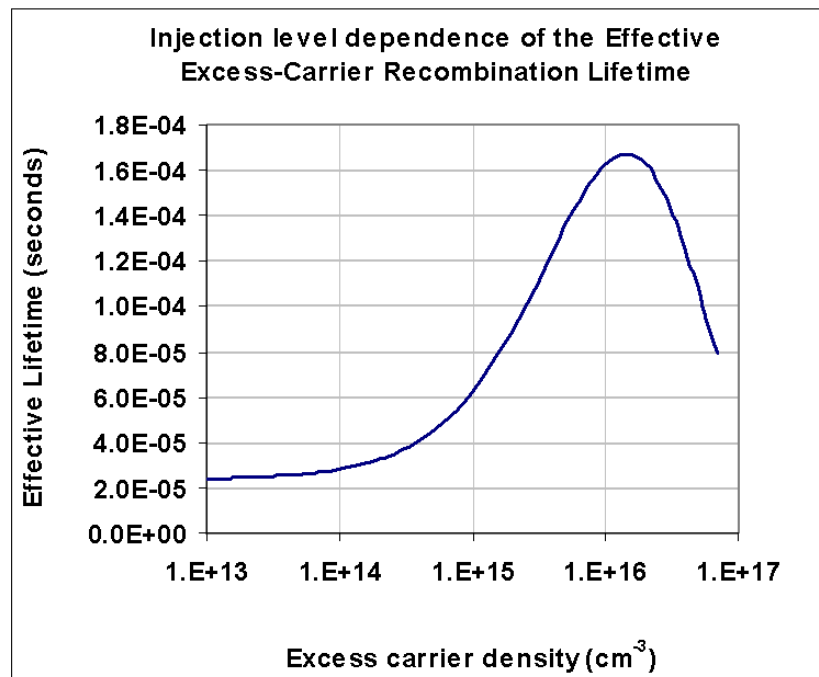


Figure 1
The Modeled Recombination Lifetime of a 3 Ω-cm B-doped CZ Sample
After Degradation of the B:O Defect Based on Studies by Bothe[1].

The main features on this curve are quite typical for Cz solar cell silicon, although the details depend on the boron and oxygen concentrations. The lifetime in a wafer or bulk sample can be a strong function of the minority-carrier density. Therefore, the lifetime must be reported at a specific carrier density in order to report a unique excess-carrier recombination lifetime value. Much of the information of interest to the solar cell developer or manufacturer is contained within the variation of the lifetime with the excess carrier density. In this case, B-Doped CZ, the variation is due to the B:O defect[1]. In other cases, it can indicate Fe contamination, emitter saturation current density from the surface dopant diffusions, or details of surface passivations such as PECVD nitride or amorphous silicon.

Figure 1 indicates the effective lifetime over a range of excess carrier densities spanning from 1×10^{13} up to 1×10^{17} cm^{-3} . This is the range of interest for solar cell applications. Standard production solar cells operate in a carrier density range from 1×10^{13} at the maximum power voltage and up to about 5×10^{14} at open-circuit voltage. High-efficiency silicon solar cells operate in a range from about 1×10^{15} up to 1×10^{16} , as depicted in Figure 2 below. Cells operating under concentrated sunlight can run at higher carrier densities, up to 1×10^{17} , and thin crystalline silicon solar cells can operate at less than 1×10^{13} cm^{-3} . These operating conditions define the desired range of carrier densities that an ideal excess-carrier lifetime measurement would accurately characterize. The carrier recombination lifetime of excess carrier densities outside of this range is useful for more fundamental studies.

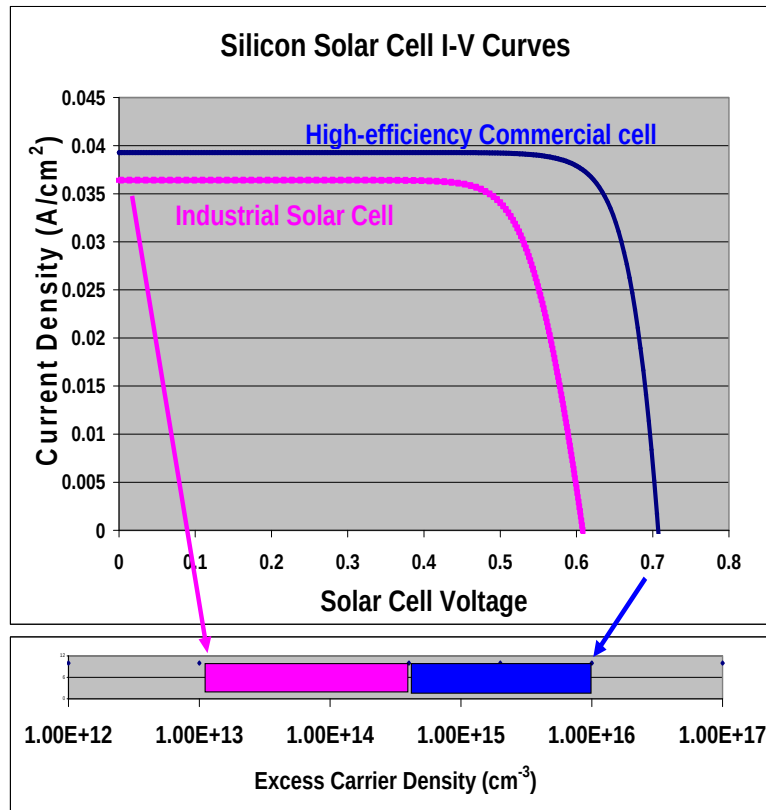


Figure 2
The Ranges of Carrier Density of Interest to Solar-cell Design and Production Depend on the Injection Expected at the Maximum Power Point.

5 Measurement of Carrier Recombination Lifetime in a Sample

The measurement of carrier lifetime in a wafer can be accomplished by monitoring the carrier-density balance as a function of the photogeneration of excess carriers. This carrier density can be monitored under constant illumination (the steady-state between excess carriers and photogeneration), after illumination (the excess carrier density transient decay), or during a time of varying light intensity, the “Quasi-Steady-State”, or “Generalized” case[2].

For a silicon wafer with steady state or transient light incident on the sample, solving the continuity equation gives the effective lifetime[2]

$$\tau_{eff}(\Delta n) = \frac{\Delta n(t)}{G(t) - d\Delta n(t)/dt} \quad (1)$$

where $\Delta n(t)$ is the time-dependent average excess carrier density and G the photogeneration rate for electron-hole pairs. This “generalized” equation permits a “quasi-steady-state” (QSS) measurement during which the light can be scanned over a wide intensity range. This can result in a lifetime measurement vs. excess carrier density, Δn , in the range of interest as shown in Figure 1.

In the transient photoconductance decay (PCD) method, the photogeneration is abruptly terminated, then after the light is fully off,

$$\tau_{eff}(\Delta n) = -\frac{\Delta n(t)}{d\Delta n(t)/dt} \quad (2)$$

This method also results in a lifetime measurement as a function of the excess carrier density as in Figure 1 if Equation 2 is evaluated at each point during the decaying photoconductance trace.

In the steady-state method, with $G(t) \gg d\Delta n(t)/dt$,

$$\tau_{eff}(\Delta n) = \frac{\Delta n}{G} \quad (3)$$

giving a single point on the effective lifetime vs. carrier density curve in Figure 1 for each steady-state light photogeneration rate, G .

Equation 1 can be used for any time-dependent light pulse. However, it is often used to effect a small correction for a nominally steady-state measurement with a slowly varying generation, or a nominally transient measurement where the light turn-off time is not sufficiently abrupt to immediately take the photogeneration to be negligible. Equation 1 is frequently referred to in the literature as the “generalized” analysis.

These methodologies are firmly established in the photovoltaic community. The data is frequently displayed as the full curve, as shown Figure 1. This can be $1/\tau_{eff}$ vs. carrier density, in the case that the purpose is to separate recombination mechanisms (as in Equations 4 and 5, in the section on interpretation of lifetime data), or τ_{eff} vs. carrier density if the purpose is to display the effective lifetime of the measured wafer. As shown in these equations, there is often an injection-level dependence to the measured effective lifetime as Figure 1. Therefore these equations determine a unique lifetime when the carrier density is uniform across the sample so that there is a unique carrier density for the entire sample.

From Equations 1–3, any sensor that can be calibrated to measure average carrier density in the sample can report lifetimes from Equation 2. If used with a light-intensity sensor and a calculation or measurement of resulting photogeneration in the sample under test, then the sensor can measure QSS or steady-state data using Equation 1 or Equation 3.

Some examples of the sensors that can be used to monitor the carrier density are microwave reflectance[3], RF eddy-current sensors[4], IR absorption or emission from the excess carriers in the sample[5], or luminescence sensors that detect light from the excess carriers when they recombine through a radiative mechanism[6,7]. All of these sensors can be used with the analysis modes defined in Equations 1–3 once the relationship between measured signal and carrier density is known.

For carrier-density sensors such as photoluminescence with CCD imaging[6,7], or CDI/ILM[5], a steady-state method (Equation 3) is often used with constant illumination during a measurement. In this case, the lifetime is mapped with a different carrier density for each pixel since areas with lower lifetimes will have proportionately lower carrier densities at constant photogeneration as seen in Equation 3. So a different $\{\tau_{eff}, \Delta n\}$ pair would be shown for each pixel, and the injection-level dependence shown in Figure 1 (for each pixel) would require images at multiple intensities. Microwave PCD measurements often use a steady state light source to establish an injection level, and then use the pulsed excitation in a small signal mode to sense the carrier recombination lifetime[3]. Another method is to use pulsed excitation with uniform photogeneration through the wafer in very-low injection, so that microwave signal is relatively linear in photoconductance, and determine the carrier density based on the number of incident photons in a very short pulse. Similarly, microwave-detected photoconductance (MDP) measurements are done with pulsed excitation that can be short or long compared to the bulk lifetime, so that both quasi-steady-state and transient results can be reported from a measurement[23].

The table below summarizes some of the advantages and disadvantages of the commonly used sensors and methods:

Table 1 List of Contactless Sensors in Relatively Widespread Use in 2009 for Determining Lifetime in Silicon Using the Methodology in Equations 1–3

<i>Method</i>	<i>How is Carrier Density Sensed?</i>	<i>Issues: Pros/Cons</i>
RF-QSSPC: RF Quasi-Steady-State Photoconductance	- Eddy current sensing of photoconductance. - Conversion to Δn using known mobility function.	- Simple calibration that is valid for a wide range of samples. - Requires mobility and photogeneration calculation or measurement. - Non mapping or coarse mapping only. - Trapping and Depletion Region Modulation (DRM) artifacts at low carrier density.
RF Transient: RF Transient Photoconductance	- Eddy current sensing of photoconductance. - Conversion to Δn using known mobility function.	- Simple calibration. - Can be subject to trapping and DRM artifacts at low carrier density.
ILM/CDI: Infrared Lifetime Mapping Carrier Density Imaging	IR free-carrier absorption or emission.	- High-resolution imaging capability. - Surface texture complicates interpretation. - Subject to trapping and DRM artifacts.
μ -PCD: Microwave Photoconductance Decay	- Microwave reflectance sensing of photoconductance. - Carrier density can be set by bias light, or by injecting known number of photons in a very short pulse.	- High-resolution mapping capability. - Non-linear detection of photoconductance in some injection-level or dopant ranges. - Skin-depth comparable to sample thickness in some cases. - DRM and trapping artifacts at low carrier density.
PL: Photoluminescence	- Band-gap light emission, model for coefficient of radiative emission. - Model for re-absorption.	- Artifact-free data available even below the intrinsic carrier density. - Used in both non-imaging and high-resolution imaging applications. - Strong doping dependence. - Photon reabsorption depends on surface texture. - Dependence on detector EQE. - Dependence of wafer thickness.
MDP : Microwave-detected Photoconductance	Microwave absorption sensing.	- High resolution mapping capability. - Steady-state and transient analysis. - See μ-PCD.

6 The Interpretation of Lifetime Data in Wafers

Equations 1, 2, and 3 indicate how to measure a critical and real physical property, the lifetime of an excess carrier in a wafer. This can be done accurately without any regard to the mechanism of recombination in the wafer. This result in itself is often very useful. However, it is even more useful if the recombination mechanisms, bulk, surface, and emitter recombination can be individually identified. This section discusses how this is often done for wafers.

In the general case, a steady state method reports an effective carrier lifetime which is a function of the front-surface recombination, S_{front} , the back surface recombination, S_{back} , the bulk lifetime, the wavelength of light incident upon the sample and the quantity of light absorbed in the sample. This absorbed light depends on the surface layers, front