

BEST PRACTICE FOR MINORITY-CARRIER LIFETIME MEASUREMENTS OF SI WAFERS

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Abstract: Over the past 15 years, a broad consensus has developed in the R&D community on best practice for minority-carrier lifetime testing that permits the lifetime to be measured at laboratories worldwide with very good agreement. The basic requirements are well understood and simple to describe. A critical factor is the specification of the carrier density at which the lifetime is reported. As reviewed in this paper, a variety of measurement techniques and instruments exist that follow the established best practice and provide meaningful, consistent data. In contrast, pre-standards for minority-carrier lifetime measurement published in June 2007 by DKE/DIN differ from the commonly accepted best practice in several important ways. This paper discusses the differences and similarities between these pre-standards and the specifications generally accepted in the R&D and industrial community.
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1 INTRODUCTION

One of the fundamental physical properties of a silicon solar cell is the minority-carrier lifetime. In practice, measurements on wafers give an effective lifetime which then can be interpreted as a combination of bulk and surface recombination components. To do this correctly, the measurements of the effective lifetime must have a strong physical basis. In the last 10-15 years, the understanding of these measurements has evolved to the point where laboratories worldwide measure effective lifetime in wafers with excellent agreement between laboratories and between a variety of techniques. The resulting data is often used in physical models describing surface passivation quality, defects characterization, solar cell optimization, and industrial process control.

This paper describes the consensus on measurement requirements that meet best practice. On a parallel track, European industrial groups are currently working on standardization of lifetime measurements. In June 2007, the VDE/DIN published a set of standards including standards for wafer measurements of minority-carrier lifetime testing[1]. These standards are currently being considered by CENELEC for adoption as European standards. The process of developing these standards has been described in press releases and trade journals[2,3]. This process is not fully open or transparent to the worldwide scientific or engineering community. Significant differences are apparent between accepted best practice and the published pre-standards. It is timely and appropriate to discuss technical best practice for wafer lifetime measurements in an open technical forum. At this writing, a new European draft standard was nominally published, but was not readily available in the U.S.. Upon purchase from the publisher, it was not downloadable and physical delivery exceeded the 2-week window required to be included in this paper.

2 DISCUSSION

Transient, steady state, and quasi-steady state methods are defined by the way the sample excitation by light is used, either an abruptly terminated pulse, a long varying pulse (Quasi-Steady State) or a steady-state light

source. The analysis for all of these methods can be described by:

$$\text{Measured Effective lifetime} = \Delta n / (G - (d\Delta n/dt)). \quad (\text{eq 1})$$

Where G is the photogeneration within the wafer at time t [6].

Table 1. Essential elements that should be reported to enable a lifetime result to be useful for device physics and allow it to be reproduced at other laboratories.

	Transient	Steady State or Quasi-steady State
Measured lifetime	X	X
Carrier density (or range) to report lifetime	X	X
Analysis type (from eq 1, Transient, QSS, or SS)	X	X
Sensor type and calibration to Δn	X	X
Trapping correction method (if required).	X	X
Photogeneration calibration	Not needed	X
Surface passivation front/back, yes/no	X	X
Excitation wavelength (for data interpretation)	Not needed	X
Detection area, wafer thickness, number of points, method of averaging points	X	X

Table 1 represents the de-facto standard for lifetime measurement as developed over the last 15 years and used for research publications worldwide. The lifetime can be measured in this way by any tool that can be calibrated to measure minority-carrier density as is the required factor in eq. 1. With determination of the photogeneration, the measurement can be extended to QSS mode. The methods of detection of minority carrier density include IR transmission or emission, photoluminescence, eddy-current, capacitive coupling of

probes to the wafer, voltage measurements (suns-Voc), microwave power, and others. The methods have been implemented on a large number of instruments, both proprietary and non-proprietary. At least one of this class of instruments is used in most R&D laboratories and manufacturing facilities worldwide, including CDI/ILM, MFCA, RF QSSPC, RF transient, imaging PL, QSSPL, transient PL, suns-Voc, and μ -PCD. Well over 1000 publications have been presented that report data using these methods and implicitly or explicitly specify all the factors in Table 1.

The detector types and instrument setups are largely interchangeable, and nominally identical lifetime will be reported for many samples if the information in the above table is complete. For example, samples with $L > W$ and reasonable surface passivation have a uniform carrier density independent of excitation wavelength and an effective lifetime that is rather easy to measure. These samples are easily compared across methods and laboratories using Table 1. For complex sample types (non-homogeneous lifetime, very low lifetime, no surface passivation, etc.) the details of illumination wavelength, detection method, sensor size, light pulse time envelope etc., do matter in the margins but these differences can be understood with physical models since the measurements are calibrated in known physical units.

A recent study compared μ -PCD, QSSPC, Transient PC, and QSS photoluminescence[8]. Good agreement was obtained on a wide variety of samples in the carrier densities where all of the techniques are valid. The strengths and weakness of the various techniques in different injection regimes were discussed.

This general agreement in measurement results between laboratories is in relatively sharp contrast with the situation 10 or 15 years ago. The understanding of the effective lifetime in silicon has greatly improved and this has contributed to the ability to understand the complexity of lifetime data.

For long-lifetime wafers, the transient method (measurement after the light is extinguished) is preferred since it does not require knowledge of the photogeneration in the sample (reflection and absorption of photons in the sample) or the excitation wavelength. The QSS method, (measurement with the light varying) has been found to be useful for lower-lifetime materials as are often used in production PV cells. When both analysis methods are available on the same instrument, then in some cases the transient method can be used to confirm the additional parameter required for QSS calibration. For example, simple in-situ absolute calibration of the lifetime instrument can always be done with a set of uniformly doped wafers of known sheet resistance for the transient RF-PCD method, and can usually be done for the RF QSSPC method as well.

The QSS-PL method has been found to be especially useful for the very low injection regime, where photoconductance methods can have artifacts due to Depletion Region Modulation (DRM) or "trapping". However, it is common practice to calibrate the QSS-PL method using the QSSPC method in a region common to

both instruments since the QSS-PL can be difficult to calibrate in some cases[8,9]. Simple, traceable, and transparent calibration is a definite advantage for any measurement method.

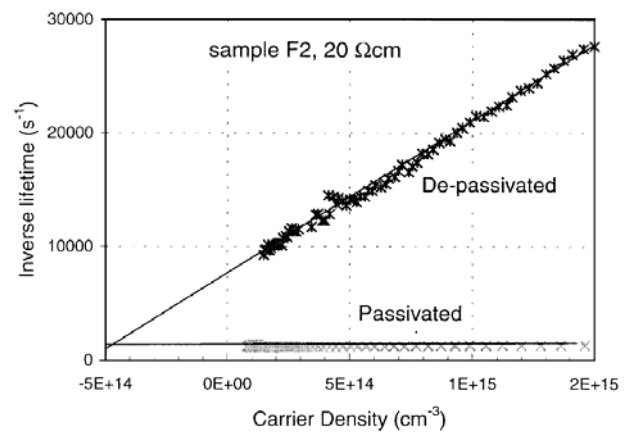
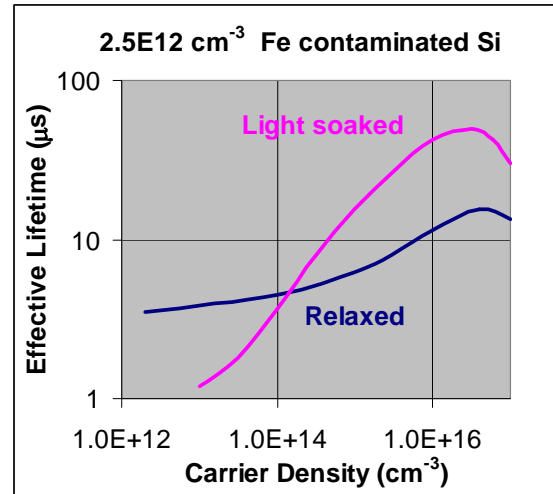


Fig. 1 and 2. At top, the use of lifetime vs. carrier density to study B:Fe defects (following ref[4]). At bottom, the use of lifetime vs. minority-carrier density to find the bulk lifetime and emitter saturation current density of a phosphorus diffused wafer[5]. In each case, the lifetime changes by 5X to 50X over a range of minority-carrier density, even under low-injection conditions. The carrier density is **REQUIRED** in order to report a unique lifetime for most silicon samples. (RF QSSPC measurements).

There are several other extremely-useful lifetime-measurement techniques in widespread use that do not report the injection-level dependence directly. Some of these are not easy to calibrate absolutely as a function of injection level. These include SPV, microwave PCD, and LBIC. They are often used to map spatial non-uniformities in the lifetime. In cases where it is difficult to report a lifetime at a specific calibrated carrier density with these methods, many of these publications report a calibrated measurement of lifetime vs. injection level using a different tool in addition to the spatial map.

Table 2: A summary of VDE 0126-18-4-1 and VDE 0126-18-4-2.[1]

Laser intensity	10 ¹² photons/mm ² inline, 10 ¹¹ lab
Wavelength	904 nm
Pulse duration	150 ns
Microwave frequency	90 mW at 13 or 22 GHz
Spot size	2 mm ² , 1-2 for lab
Bias light	None inline, 500 mW for lab
Detection area, wafer thickness, number of points, method of averaging points	Should be reported with result.
Tolerance	+/-10%

In contrast to the lifetime best practice specification represented by Table 1, in the published pre-standard from June 2007, DIN/VDE took a different approach. In this pre-standard, microwave PCD was defined as the standard “inline measurement method”, and microwave PCD with a bias light as the “Lab measurement method”. Both are transient methods that obey the eq. 1 with no generation term.

The critical missing factor in this specification is the carrier density at which the lifetime is reported. In reference to figure 1 and figure 2, the methods described in the standard are not useful for reporting a unique physical lifetime at a specific carrier density that can be reproduced with other instruments or used in physical models (for example, for J_{oc} extraction in fig. 2). In the VDE strategy, the proxy for specifying the minority carrier density is to count photons. By specifying that 10¹² photons are delivered in less than 150 ns, this gives an approximate carrier density at $t=0$. However, the lifetime is not well defined and not reported at $t=0$. It is generally reported at a later time (not specified in this standard). After $t=0$, the carriers will spread in three dimensions across the sample and recombine at the front and rear surfaces and in the bulk according to the sample properties. So, this specification of injection level is monotonic in the initial photon count, but only bounded to be greater than 0 and less than the total number of photons divided by the sample thickness. Holding to these specifications, the lifetime will be measured at a different minority-carrier density for each sample. No provision is made for differences in sample reflectance or absorption from sample to sample.

The approach in these published pre-standards is narrowly empirical. If everyone uses the same instrument with the same settings on the same samples, then they will report the same numbers. However, these numbers are not necessarily the actual or unique physical minority-carrier effective lifetimes in these samples. This strategy also has the effect of defining a majority of instrument currently in use, including a broad variety of detectors and excitation sources, to be “not compliant” with “the standard”; including many instruments that are widely available and broadly accepted as calibrated lifetime-measurement tools.

In the laboratory, the μ -PCD method described in the VDE standard can be used in a well-calibrated fashion

that agrees well with other measurements[7,8]. In brief, the procedure is:

- 1) Measure with a bias light and small signal laser pulse at several different bias light levels.
- 2) Convert the resulting differential lifetimes to minority-carrier lifetime and calculate the carrier densities where the measurements were made using iterative calculations until self-consistent result are obtained. [8].

This is normally considered to be tedious and is not commonly done in practice. There are easier methods for obtaining lifetime vs. injection level curves. It is simply not correct [7] to redefine measured differential lifetime to be the effective minority-carrier lifetime as is done in VDE V 0126-18-4-2 [1].

3 CONCLUSIONS

A broad consensus exists on standards for minority-carrier lifetime measurements in silicon for photovoltaics. Using a set of universal physical principles, good agreement is obtained for measurements taken with different instruments and methods at different laboratories worldwide. One unifying principle that is central to this agreement is that the lifetime must be reported at a specific minority-carrier density, or a range of carrier densities, in order to permit comparison between laboratories and techniques. Some recently published pre-standards have neglected this very important point. Without this, lifetime data should not be expected to agree between laboratories or companies even if both facilities use the same instrument.

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