SEMI AUX017-0310[E]
CONTACTLESS CARRIER-LIFETIME MEASUREMENT IN SILICON WAFERS, INGOTS, AND BLOCKS

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

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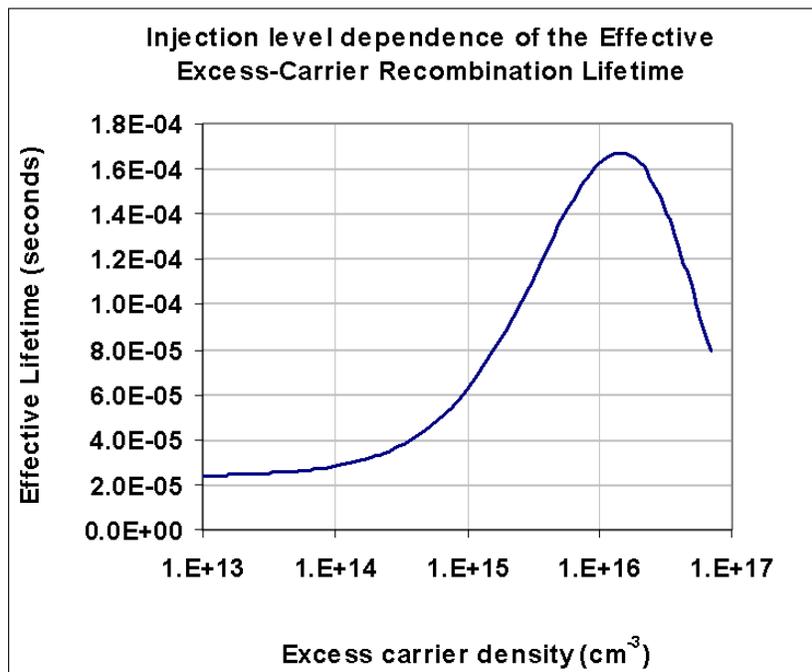
Figure 1
The Modeled Recombination Lifetime of a 3 Ω-cm B-doped CZ Sample
After Degradation of the B:O Defect Based on Studies by Bothe[1].

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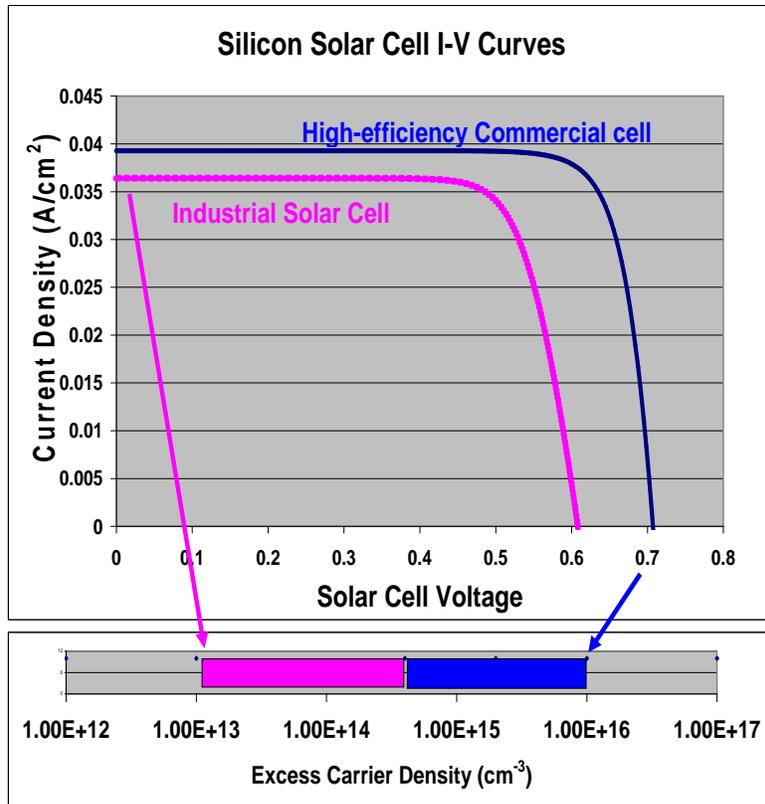
Figure 2
The Ranges of Carrier Density of Interest to Solar-cell Design and Production
Depend on the Injection Expected at the Maximum Power Point.

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]

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

(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,

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

(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 $G(t) >> d\Delta n(t)/dt$;

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

(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

Method	*How is Carrier Density Sensed?*	*Issues: Pros/Cons*
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

texture, and light-trapping properties of the wafer. Both the surface recombination velocities and the bulk lifetime have injection dependence, and will depend on the local carrier density.

A transient measurement has all of the same dependencies, along with others. In general, the analysis will also depend on the time profile of the light pulse, and the fully-time-dependent solution of the continuity equation as the photogenerated carriers move through the sample and recombine at the front surface, in the bulk, and at the back surface. The only simplification is that the photogeneration, G, need not be calculated unless this is the method used to calculate the carrier density.

The effective (measured) lifetime of an excess carrier in silicon is determined by the recombination rates in the bulk of the wafer as well as at the surface. These two recombination rates add to give the total recombination rate.

In order to interpret a measured lifetime in terms of its recombination components, special cases are used that simplify the analysis and reduce the number of independent parameters. In some very special cases the results are simple. For example, the measurement can be engineered to have a uniform carrier density. In this case (shown here for p-type silicon)[8]:

$$\frac{1}{\tau_{eff}(\Delta n)} = \frac{1}{\tau_{bulk}(\Delta n)} + \frac{S_{front}(\Delta n) + S_{back}(\Delta n)}{W}$$

(4)

$$\frac{1}{\tau_{eff}(\Delta n)} = \frac{1}{\tau_{bulk}(\Delta n)} + \frac{J_{oe\,front} + J_{oe\,back}}{qn_i^2 W}\left[N_A + \Delta n\right]$$

(5)

where W is the wafer thickness, S is the surface recombination velocity, and J_{oe} is the emitter saturation current density of a dopant diffusion, either a junction or a back-surface field.

The uniform carrier density can be self-consistently confirmed from the data if the measured effective lifetime is much greater than a transit time for the wafer.

$$\tau_{eff}(\Delta n) >> \frac{W^2}{2D}$$

(6)

This ensures that no recombination sink (surface or bulk) is transport limited in order to be at a carrier density significantly lower than the average carrier density. In the case that Equation 6 is true, then the transient method becomes independent of the light excitation details such as wavelength and duration. By waiting a transit time before analyzing the data, the carrier density profile can spread across the wafer in the case that non-uniform photogeneration was used during the pulse.

The diffusion coefficient used here should be the one that determines the rate at which carriers diffuse to the surfaces to recombine. In the general case, this is[9]

$$D = \frac{(n + p)D_n D_p}{nD_n + pD_p}$$

(7)

For low-injection conditions in p-type material, this approaches D_n, for example. This diffusion coefficient can vary in the approximate range of 9–30 cm^2/s, indicating that the type and doping density of a wafer determine the transit time as well as the wafer thickness dependence that is more obvious in Equation 6.

If the measured lifetime is less than the transit time for the wafer, then a thinner wafer or a better surface passivation can be used in order to comply with Equation 6, and permit the use of this simple analysis. Otherwise, numerical evaluation of the measured lifetime data may be required for an accurate analysis. This approach is described in more detail in the next section on the measurement of bulk lifetime in bulk samples.

Equations 4 and 5 can be used in one of two ways:

1. You can "bound" the limits on surface recombination and lifetime. For example, by setting S or Joe=0 (front and back) in Equations 4 and 5, the lower bound of bulk lifetime is determined by Equation 4 or 5. By setting

the bulk lifetime to be infinity (or at the "intrinsic" limit for pure silicon accounting for Auger and radiative recombination[10]), an upper bound of S or Jo can be reported. These bounds can approach the actual physical bulk lifetime or surface recombination parameter if high-bulk-lifetime thin substrates are used to characterize surfaces, and good surface passivations are used to characterize bulk lifetimes.

2. By using at least 2 thicknesses of wafers, the surface and bulk effects can be uniquely determined. In the case of Equation 5, the emitter-saturation-current-density term has a different dependence than the bulk term. This can allow the separation of surface and bulk terms with a single wafer. In the case that the 1/tau measured curve has a linear dependence on Δn as seen in Equation 5, then the emitter and bulk contributions can be separated. This is frequently the case with n-type wafers, due to the relative lack of injection dependence in the bulk lifetime, and the lower substrate dopant density for the same resistivity compared to p-type wafers. The method generally works for both *p*- and *n*-type silicon as the injection level approaches or exceeds the dopant density in the wafer.

For cases of symmetric wafers with the same surface passivation on both sides, the requirement of uniform carrier density can be relaxed for the steady-state method[11].

Two other special cases are often used in the limit of very high surface recombination velocity. These are relevant specifically for non-passivated surfaces such as ingots, bricks, or as-cut wafers.

$$\frac{1}{\tau_{eff}(\Delta n)} = \frac{1}{\tau_{bulk}(\Delta n)} + \frac{\pi^2 D}{W^2}$$

(8)

This is the lifetime for a transient measurement after the light has been off for a time of at least the time represented by the 2nd term in Equation 8, which is 1/5th of Equation 6, or more quickly if uniform photogeneration was used during the illumination pulse. This equation is often used to find the bulk lifetime in thick wafers using uniform photogeneration. The second term can be made small by using thick wafers, increasing the accuracy of the bulk lifetime measurement. This procedure would be equivalent to SEMI MF28. The diffusion coefficient, D, in this equation is the appropriate ambipolar diffusion coefficient, Equation 7, and approaches the minority-carrier diffusion coefficient in the case of low injection in the wafer. In practice, Equation 8 can be problematic for strongly-absorbed light if the diffusion length is less than the wafer thickness, since the carriers are mostly gone by the time they are distributed symmetrically across the wafer and many sensors will not have the sensitivity to characterize this limit.

Equation 9 is the corresponding steady-state equation for uniform photogeneration in a sample with unpassivated surfaces. Unfortunately, it is not in closed form and the equation must be iterated to self-consistency, since the diffusion length, L, is a function of the bulk lifetime[12].

$$\tau_{eff} = \tau_{bulk}\left(1 - \frac{2L}{W}\tanh(\frac{W}{2L})\right)$$

(9)

Equations 4 and 5 are widely used in the photovoltaic community for developing, optimizing and maintaining process control for surface passivations and emitter saturation current densities, and for measuring the bulk lifetime. Equations 8 and 9 are less broadly applied, but can be useful for the interpretation of carrier lifetime data from as-cut or as-cut and cleaned wafers[3,12]. For more general cases, numerical simulation can be used to interpret transient or steady-state lifetime-test data[12,13].

7 Interpretation of Lifetime Data Taken on Ingots or Blocks

The methodology has been described above for wafer samples. It can be extended for use in bulk materials with high surface recombination.

One challenge when measuring bulk samples is to define the average density that appears in Equation 1–3. For a wafer, it is simply the integral of the carriers in the wafer divided by the wafer thickness in most cases, unless the light excitation is absorbed at the surface and L<<W. However, in a bulk sample, the excitation and sensing of carriers may be near the surface of the sample only.

The carrier concentration in the bulk sample is better described by a weighted average rather than using the simple arithmetic mean of carriers per unit sample thickness. The weighted average carrier concentration, Δn_{avg}, that has been proposed is the carrier concentration weighted by the carrier concentration[13].

$$\Delta n_{avg} = \frac{\int_0^\infty \Delta n^2 \, dx}{\int_0^\infty \Delta n \, dx}$$

(10)

The weighted average then takes into account only those sections of the device that have an excess light-induced carrier concentration. Areas of the device (such as the back section of a bulk sample) that have no excess carriers are automatically discarded from the analysis.

An effective width, W_{eff}, for the high concentration region can also be defined which is the total excess carrier concentration divided by the average carrier concentration as determined in Equation 10.

$$W_{eff} = \frac{\left(\int_0^\infty \Delta n \, dx \right)^2}{\int_0^\infty \Delta n^2 \, dx}$$

(11)

In practice, the effective width for the carrier density distribution is an extremely useful parameter. This construct represented by Equations 10 and 11 transforms a measurement of bulk silicon into a standard wafer measurement as far as the lifetime analysis is concerned. The total carrier concentration is then the product of n_{avg} and W_{eff}.

$$\int_0^\infty \Delta n \, dx = \Delta n_{avg} W_{eff}$$

(12)

The above equations can be calculated for the steady state mode with monochromatic light. In general, these functions should be done by computer simulation of the carrier density profiles. These profiles are dependent upon the diffusion length in the material as well as the distribution of light wavelengths incident upon the sample. Therefore the measurement of lifetime (with Equations 1–3) and carrier density (with Equations 10 and 11) becomes an iterative calculation to self consistency.

This procedure can be used to measure the lifetime within a thick wafer, ingot, or block. In the case that the carrier-density profile exceeds the sensing depth into the block, a lower bound on the lifetime is reported unless numerical modeling accounts for the sensitivity vs. depth profile of the detector.

In the case of an unpassivated front surface, the measured effective lifetime that will result from this measurement will be lower than the bulk lifetime due to surface recombination. For example, for steady-state illumination with monochromatic light and infinite surface recombination[13]:

$$\tau_{eff} = \frac{\tau_{bulk}}{\alpha L + 1}$$

(13)

and

$$W_{eff} = 2 \left[L + \frac{1}{\alpha} \right]$$

(14)

where L is the diffusion length of carriers in the sample and α is the absorption coefficient for the light. Equation 13 indicates that the measured lifetime is a lower bound on the bulk lifetime, which can approach the bulk lifetime only for absorption depths in the silicon that are greater than the diffusion length in the material. Equation 13 also permits the calculation of the bulk lifetime of a very thick sample based on the measurement of effective lifetime at a specific wavelength. Equation 14 offers a figure of merit for the practical sensors. For this method, the sensor would ideally have sensitivity exceeding W_{eff} in depth for the light wavelength and diffusion length range of interest for the measurement.

A corresponding relationship between τ_{eff}, τ_{bulk}, and W_{eff} can also be determined by computer simulation of a broadband light source, such as the combination of a xenon flash lamp with IR-pass filters. The numeric correction, corresponding to Equation 13 but generalized for multiple wavelengths, is smallest in the case of excitation by long-wavelength light. Additionally, surface damage to some depth has less influence on the photoconductance from longer wavelengths. If the calculated bulk lifetimes agree for two different wavelengths of light, then this can be taken as evidence of minimal depth of surface damage. The computer simulations require an input of the front-surface recombination velocity. For *p*-type materials, this can be assumed to be high, greater than 10^5 cm/s in most cases, which simplifies and generalizes the calculations to apply to most *p*-type materials. This can be checked by using a QSS measurement under visible light. If the effective lifetime from Equation 3 is much lower for visible light than for IR light, in accordance with Equation 13 or the numeric simulation for the broadband light sources, then the assumption of high-surface recombination is validated[3,13,14].

For the case of transient measurements after termination of a long-duration illumination pulse, the measured lifetime from Equation 2 will begin at the steady-state result from Equation 13, and then approach the actual bulk lifetime after the surface recombination depletes the near-surface region and the surface recombination becomes transport limited. The main limitation is the ability of the sensor to measure carriers deep into the sample. Carriers that diffuse out of range of the sensor result in an apparent loss in conductance, and a lower reported lifetime and carrier density.

To best measure the bulk lifetime with a transient measurement, the sample should be illuminated with an IR light source for a time duration exceeding the bulk lifetime of the sample, to the highest photoconductance possible from the hardware. Then after waiting at least 1 bulk lifetime after the pulse is terminated, a lower bound on bulk lifetime is determined. This measured lower bound can be very practically relevant, as long as the sensor and excitation level permits measurements of lifetimes greater than the range of interest for characterizing the material. For lifetimes much less than this observed limit for the hardware, the measurement will be an accurate absolute measurement of the bulk lifetime. Short pulses can also be used. However, the carrier density distribution after a very-short pulse is determined by the absorption depth into the sample for the wavelength used. After a pulse that is longer than the bulk lifetime, the distribution is a diffusion length deeper into the sample. Therefore long pulses give the advantage that surface recombination effects are much reduced, permitting longer measured lifetimes closer to the true bulk lifetime in accordance with the Equation 13.

The transient technique has fewer assumptions than the QSS technique for use on blocks or ingots and can be used equally well on passivated surfaces, unpassivated surfaces or surfaces with unknown passivation qualities. However, the calculation of the average carrier density is more complex, as it is a function of time after the pulse is terminated (as well as pulse time, intensity, and wavelength distribution). Therefore the reported carrier density may have larger uncertainties in this case. Due to long diffusion lengths that justify the use of this transient method, the effective width can be taken in most cases to be the carrier density that results from assuming the sensor sense depth into the sample. QSS and transient measurements are complementary to each other in characterizing the bulk lifetime of the sample since the approaches are quite distinct in their dependence on the surface recombination and carrier density profiles.

The capability to measure high-lifetimes in bulk material is optimized by using a sensor that can measure some depth into the sample. In the case of steady-state measurements, the ideal sensor would measure several diffusion lengths into the sample and allow the use of long wavelength excitation to minimize surface recombination effects (see Equation 13). In the case of transient measurements, the accurate determination of lifetime and carrier density is better if the sensor continues to sense the carriers even as the carrier distribution moves away from the surface.

8 Synopsis of Lifetime Investigation

In summary, the parameters that should be reported from a lifetime measurement to make it unique and reproducible between laboratories and different measurement techniques are displayed in the following example table and report:

Table 2 List of Lifetime Parameters to Report. Some, like instrument parameters, remain constant for a particular technique.

Results	• Measured lifetime • Carrier density or range • Interpretation (if any)
Sample Parameters	• Thickness • Temperature • Doping concentration • Dopant type • Surface passivation • Defect state
Analysis Type	• Transient, QSS, or Generalized • Excitation wavelengths • Trapping or DRM correction (if any)
Instrument Parameters	• Light time profile • Sensor type and calibration to excess carrier density • Sense depth • Photogeneration calibration • Detection area, number of points, method of averaging points (if any)

Results:

Result description	Symbolic	Value	Units
Measured effective lifetime	τ_{eff}		seconds, ms, µs
Carrier density range	Δn		cm^{-3}
Interpretation parameters [if any]			
Surface recombination	S		cm^2/s
Bulk lifetime	τ_{bulk}		seconds, ms, µs
Emitter saturation current	J_{oe}		A/cm^2
Other			

Interpretation Notes:

Sample Parameters:

Parameter description	Symbolic	Value	Units
Sample thickness	w		cm, µm
Sample temperature	T		K, °C
Doping concentration	N_A (N_D)		cm^{-3}
Doping type	n / p		
Surface passivation, front and back	-		
Defect state [if applicable]	-		
Fe dissociation level	-		
B:O degradation level	-		
Other			

Analysis type:

☐ Transient
☐ Quasi-steady-state (QSS)
☐ Generalized

Excitation wavelengths/frequencies	
Transfer function τ_{eff} to τ_{bulk}	
Trapping or DRM correction [if any]	

Instrument Parameters:

Parameter description	Value	Units
Sensor model & software version		
Light time profile		
Calibration of photogeneration		
Sensor type		
Calibration to Δn		
Sense depth		cm, µm
Detection area		
Area		
Number of points		
Method of averaging points [if any]		

Figure 3
Sample Lifetime Measurement Report

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9 Specific Example: Description of an RF-Photoconductance Measurement Technique

In the RF-QSSPC or RF transient methods, an eddy current sensor is used.

The calibration of the signal to carrier density is done as follows.

1. A wafer set is prepared from uniformly-doped wafers. These are measured by 4-point-probe (SEMI MF84-0307). This calibration should span the intended measurement range of conductance and photoconductance. The instrument is calibrated with these wafers, using a quadratic calibration curve, so that any measured signal from the instrument can be reported in absolute, calibrated units of conductance.

2. The average carrier density in the wafer (as in Equations 1–3) is reported from the absolute conductance as where W is the wafer thickness.

3. A light sensor measures the incoming light intensity (required for QSSPC and generalized measurements). The photogeneration in the sample is scaled by the intensity measured at the sensor, with a correction for spectral response of the sample compared to the intensity sensor. This calibration for spectral response can be done by simulation of the photogeneration in the sample under test, by modeling for wafer coating transmission and reflections and to account for light trapping properties of the wafer. Alternatively, if the sample can be measured by both the transient and QSSPC method, the resulting lifetimes can be matched using the photogeneration coefficient as a free parameter[15,16]. It is best to use a reference cell for intensity measurement that is similar to the sample under test, with the same band gap.

4. The lifetime is calculated from Equations 1–3, and reported as in Figure 1.

$$\Delta n = \frac{\Delta \sigma}{qW\left(\mu_n\left(\Delta n, N_A, N_D\right) + \mu_p\left(\Delta n, N_A, N_D\right)\right)}$$
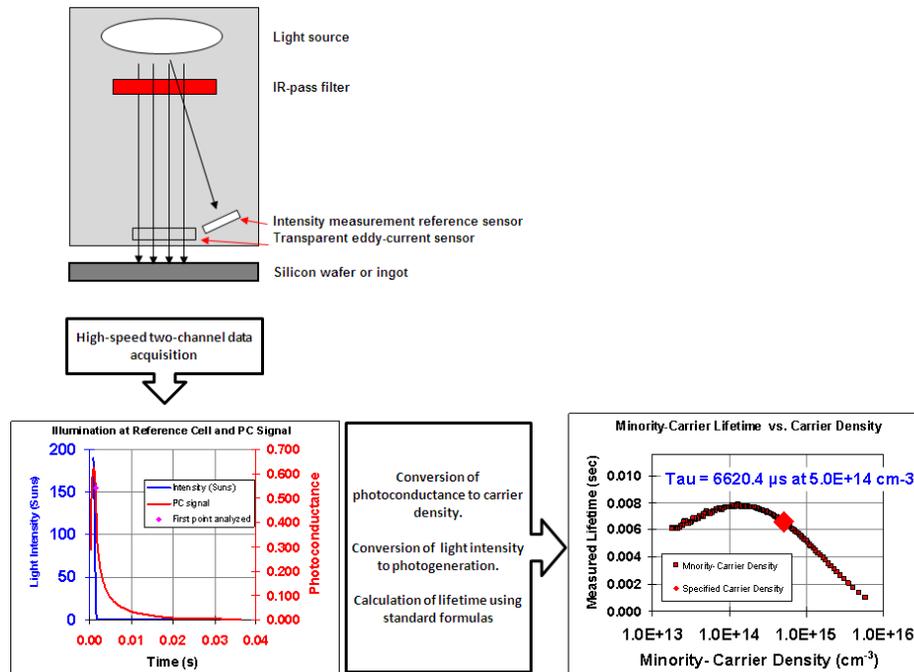
(15)

Figure 4
Example of a Lifetime Measurement Technique
An RF eddy current sensor is used to measure photoconductance. The geometry as shown here is suitable for measurements on very thick samples such as blocks and ingots. For wafer measurements, the sensor can also be beneath the wafer so that the wafer illumination light path is completely unobstructed. This data was taken on a bulk 3 Ωcm n-type sample without surface passivation using the transient method (Equation 2), analyzing data after the light pulse had extinguished.

10 References

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