Background Statement for SEMI Draft Document 4738B

NEW STANDARD: TEST METHOD FOR CONTACTLESS EXCESS-CHARGE-CARRIER RECOMBINATION LIFETIME MEASUREMENT IN SILICON WAFERS, INGOTS, AND BRICKS USING AN EDDY-CURRENT SENSOR

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Background information — In the field of silicon photovoltaics, carrier recombination lifetime measurements are often obtained using eddy-current sensing of the photoconductance in order to characterize silicon bulk and surface recombination. Despite widespread use of this lifetime-test technique for roughly 30 years, it has not been published as a SEMI test method. This draft standard documents the technique for obtaining excess carrier recombination lifetime data silicon for wafers, ingots, and bricks in the format of a SEMI test method. The commonly-used interpretations of the resulting lifetime data including the separation into bulk recombination, surface recombination, and emitter-saturation-current densities are also specified.

A previous version of this document was voted in Cycle 1, 2010, and adjudicated at the Berlin Meeting of the EU technical committee in March, 2010. The Analytical Test Methods Task Force at that meeting discussed the negatives and comments in detail, and unanimously approved a revised document 4738A for ballot in cycle 3. Two reject votes were recorded in the cycle 3 ballot. This revision addresses the negatives from these two votes. The principle changes were to reformat the document and make revisions to better meet the details in the SEMI style guide, and to clarify that the mobility functions used in the QSSPC method must be explicitly specified in the report. This new version was approved for ballot at the technical committee meeting at Intersolar, in San Francisco, on 14 July, 2010. Adjudication of this ballot in cycle 5, 2010, will occur at the PV Committee meeting in Dresden in October 2010 in conjunction with SEMICON Europe. Check [www.semi.org/standards](http://www.semi.org/standards) for the latest meeting schedule.

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1 Purpose

1.1 The excess charge carrier (hereafter referred to as “excess carrier”) recombination lifetime is the central parameter to silicon solar cell device design, production, and process control. The measurement of this lifetime as it depends on excess-carrier density yields physically significant results, which allows for design optimization and efficiency prediction in solar cells. The test method also describes how this recombination lifetime can be further analyzed in terms of more fundamental parameters of importance to solar cells, such as the bulk lifetime, surface recombination velocity, or the emitter saturation current density of the dopant diffusion. This test method includes measurement by Quasi-Steady-State Photoconductance, QSSPC, and transient techniques using an eddy-current sensor.

2 Scope

2.1 This standard describes methods for measuring the excess-carrier lifetime in silicon wafers, ingots, and bricks with carrier recombination lifetime in the range of 0.1 to 15,000 μs.

2.2 The measurements are applicable in the excess-carrier density range from $1 \times 10^{13}$ cm$^{-3}$ to $2 \times 10^{16}$ cm$^{-3}$ for wafer specimens, and $1 \times 10^{15}$ cm$^{-3}$ to $5 \times 10^{15}$ cm$^{-3}$ for bulk specimens (thicker than 1 cm).

2.3 The method described here is used for specimens with resistivity in the range from $0.1 \Omega$·cm to 10000 Ω·cm.

2.4 This standard describes four measurement methodologies; two each for the assessment of wafered or bulk silicon specimens. All measurement techniques are performed using an inductive-coil (eddy-current) sensor energized at a radio frequency and an illumination source. Two of the methods use a Quasi-Steady-State PhotoConductance (QSSPC) technique that requires a light-intensity detector to measure the photogeneration. The scope of this document also addresses the calibration method to be used.

2.4.1 Transient Mode for Wafers: This test method is appropriate for a silicon specimen in wafer form, of a thickness not to exceed 1 mm. As described in this standard, the transient mode is used for excess carrier lifetimes which are long compared to the cut-off time of the illumination.

2.4.2 QSSPC Mode for Wafers: This test method is appropriate for wafer specimens of a thickness not to exceed 1 mm. As described in this standard, the QSSPC Mode is used to determine lifetime by analyzing data taken during photoexcitation.

2.4.3 Transient Mode for Bulk Material: This test method shall be used to measure specimens with a thickness greater than 1 cm and is used to measure carrier lifetimes that are much longer than the cut-off time of the illumination.

2.4.4 QSSPC Mode for Bulk Material: This test method shall be used for specimens greater than 1 cm and determines carrier recombination lifetime by analyzing data taken during photoexcitation.

NOTICE: This standard does not purport to address safety issues, if any, associated with its use. It is the responsibility of the users of this standard to establish appropriate safety and health practices and determine the applicability of regulatory or other limitations prior to use.
3 Limitations

3.1 Carrier lifetime is, in general, a strong function of the excess carrier density.\textsuperscript{1} Therefore, in order to compare data, different users need to report the lifetime at the same excess carrier density.

3.2 Carrier trapping may be present in silicon at room temperature. If trapping of either electrons or holes occurs in the specimen, the excess concentration of the other type of carrier remains high following cessation of the light pulse (in the Transient method), or for low light intensity (for the QSSPC method). Methods avoid reporting lifetime based upon the low excess carrier density range when a trapping characteristic is present, unless a correction technique is applied\textsuperscript{2} (see Appendix 1). The characteristic indicative of trapping is when the measurement lifetime sharply increases with decreasing excess carrier density, for excess-carrier densities in the range of $1 \times 10^{12}$ to $2 \times 10^{14}$ cm$^{-3}$. This apparently high lifetime at low carrier density is not indicative of high excess-carrier lifetime.\textsuperscript{3} Showing the entire lifetime vs. excess-carrier density curve is good practice if corrections are required, with both corrected and uncorrected data displayed. Users comparing data need to specify the trapping correction, if any (see Appendix 1).

3.3 If there are junctions in the device, either dopant-diffused junctions or inversion layers created by surface charge, then do not report data at low carrier densities where the Depletion-Region Modulation (DRM) characteristic is present, unless a correction is applied as in Appendix 1.\textsuperscript{4, 5} Users comparing data specify the correction, if any.

3.4 Carrier mobility in silicon has a negative temperature coefficient. Therefore, heating of the specimen appears as a negative photoconductance that integrates the photoexcitation, and then returns to the dark photoconductance baseline with a very long (thermal) time constant. This effect can be seen on thin, heavily-doped specimens especially if high light intensities are used to see a signal from a low-lifetime specimen.

3.5 Specimens very close to intrinsic (undoped) silicon (where sheet resistance is greater than 2000 Ohms/square) can depart from the quadratic calibration curve described in this standard.\textsuperscript{6}

3.6 In the case that the diffusion length and absorption depth of the light in a wafer specimen are much less than the wafer thickness, then the effective thickness to be used when calculating the excess carrier density is twice the sum of diffusion length and absorption depth in place of the wafer thickness.\textsuperscript{7}

3.7 For samples where the mobility is unknown, the uncertainty in QSSPC lifetime is proportional to the uncertainty in mobility.

3.8 Bulk measurements by the transient or QSSPC method, with surface excitation and surface sensing, measure only the local near-surface lifetime defined by the excitation depth, diffusion length, and sensing depth. This measured volume extends 1-5 mm into the silicon bulk.

3.9 Transient measurements on bulk specimens give a lower bound on the actual bulk lifetime.

3.10 The transfer function from measured to bulk lifetime used for QSSPC bulk measurements needs to be agreed between parties.

3.11 This test method describes a methodology for wafers thinner than 0.1 cm, and for bulk material greater than 1 cm. Samples in the range 0.1 to 1 cm can be measured, but the analysis of the data may require computer simulation.

\textsuperscript{3} SEMI MF28-0707.
since simplifying assumptions may not apply. The application of wafer or bulk analysis as described here is approximate only for specimens in the 0.1 to 1 cm range.

3.12 This test method is most accurate when the eddy-current sensor is placed sufficiently far (1-3 mm in the plane of the sensor) from a specimen’s edges.

4 Referenced Standards and Documents

4.1 SEMI Standards

SEMI M59 — Terminology for Silicon Technology
SEMI MF28 — Test Methods for Minority Carrier Lifetime in Bulk Germanium and Silicon by Measurement of Photoconductivity Decay
SEMI MF43 — Test Methods for Resistivity of Semiconductor Materials
SEMI MF84 — Test Method for Measuring Resistivity of Silicon Wafers With an In-Line Four-Point Probe
SEMI MF723 — Practice for Conversion Between Resistivity and Dopant Density for Boron-Doped, Phosphorus-Doped and Arsenic-Doped Silicon

4.2 SEMI Auxiliary Information

SEMI AUX017 — Contactless Lifetime Measurements in Silicon Wafers, Ingots, and Blocks

4.3 EN Standard

EN50513 — Solar Wafers – Data sheet and product information for crystalline wafers for solar cell manufacturing

NOTICE: Unless otherwise indicated, all documents cited shall be the latest published versions.

5 Terminology

5.1 Abbreviations and Acronyms

5.1.1 QSSPC — Quasi-Steady-State Photoconductance
5.1.2 IQE — Internal Quantum Efficiency
5.1.3 RF — Radio-frequency
5.1.4 DRM — Depletion-region Modulation
5.1.5 B-Cz — Boron-doped Czochralski silicon
5.1.6 FZ — Float zone (floating zone) silicon

5.2 Symbols

5.2.1 \( \tau_{\text{eff}} \) — The effective measured carrier recombination lifetime in a specimen; the average time interval spent by the excess charge carrier in the valence or conduction band before an electron-hole recombination event.
5.2.2 \( \tau_{\text{bulk}} \) — The bulk carrier recombination lifetime in a specimen; the average time interval that would be spent by the excess charge carrier in the valence or conduction band before an electron-hole recombination event if the surface recombination were reduced to negligible levels.
5.2.3 \( \Delta n(t) \) — (Time-dependent) average excess carrier density.
5.2.4 \( G(t) \) — (Time-dependent) photogeneration rate for electron-hole pairs
5.2.5 \( S_{\text{front/back}} \) — Front or back surface recombination velocity
5.2.6 \( J_{n} \) — Emitter saturation current density of a dopant diffused layer

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8 EN 50513 European Standard, CENELEC, European Committee for Electrotechnical Standardization, Ave. Marnix 17, B-1000 Brussels, EN 50513 specifies a special case of the QSSPC for wafer specimens described here.
5.2.7 \( w \) — Wafer thickness

5.2.8 \( D \) — Diffusion coefficient

5.2.9 \( \mu_{np} \) — (Dopant and excess carrier density dependent) carrier mobility of electrons or holes.

5.2.10 \( N_{A/D} \) — Concentration of dopant acceptors or donors

5.2.11 \( \Delta \sigma \) — Excess conductivity due to photo-excitation

5.3 Acronyms, terms, and symbols related to silicon technology, including those used in this practice, are listed and defined in SEMI M59.

## 6 Summary of Test Methods

### 6.1 Methods for Wafer Specimens

A wafer specimen is placed in repeatable proximity to the calibrated eddy-current sensor and illuminated with a time-dependent light profile.

#### 6.1.1 Transient Mode for Wafers

After the light is abruptly terminated, the resulting eddy-current sensor output voltage is measured as a function of time. The data from the eddy-current sensor is converted into units of photoconductance, using the instrument calibration (§ 9), and then converted into carrier densities using the mobility functions for silicon as agreed between the parties and recorded in the report. This data is analyzed at each point into the carrier density decay, providing the carrier recombination lifetime as a function of carrier density.

#### 6.1.2 QSSPC Mode for Wafers

As the wafer specimen is illuminated, the illumination and eddy-current sensor output voltage are simultaneously measured. The data from the eddy-current sensor is converted into units of photoconductance using the instrument calibration (§ 9). This data is then converted into carrier densities using the mobility functions for silicon as agreed between the parties and recorded in the report. The light intensity incident upon the specimen is converted to photogeneration using a calibration function for the light intensity detector (¶ 9.4.1). This additional input permits the calculation of the excess carrier lifetime during illumination as well as during the decay after the illumination is terminated.

### 6.2 Methods for Bulk Specimens

A bulk silicon specimen is placed in repeatable proximity to the calibrated eddy-current sensor and illuminated with a time-dependent light profile.

#### 6.2.1 Transient Mode for Bulk Specimens

After the light is abruptly terminated, the resulting eddy-current sensor output voltage decay is measured. The data from the eddy-current sensor is converted into units of photoconductance, using the instrument calibration (§ 9), and then converted into carrier densities using the mobility functions for silicon as agreed between the parties and recorded in the report. This data is analyzed at each point during the carrier density decay, providing the carrier recombination lifetime as a function of carrier density. For specimens with high surface recombination, the measured lifetime asymptotically approaches the bulk lifetime as the carriers near the surface are depleted, and the peak carrier density moves away from the surface into the bulk.

#### 6.2.2 QSSPC Mode for Bulk Specimens

As the bulk specimen is illuminated, the illumination and eddy-current sensor output voltage are simultaneously measured. The data from the eddy-current sensor, taken during photogeneration, is converted into units of photoconductance using the instrument calibration (§ 9). This data is then converted into carrier densities using the mobility functions for silicon as agreed between the parties and recorded in the report. The light intensity incident upon the specimen is converted to photogeneration using a calibration function for the light intensity detector (¶ 9.4.1). The effects of the surface recombination are reliably calculated in some cases, resulting in a transfer function that permits the reporting of a bulk lifetime value \( \tau_{\text{bulk}} \) based on the measured excess-carrier density recombination lifetime.

## 7 Apparatus

### 7.1 Instrument

The instrument consists of four components.

#### 7.1.1 RF-eddy-current sensor

A sensor that outputs a voltage that is monotonic in the sheet resistance of a silicon specimen. This sensor has a mechanical configuration that allows it to be placed in known proximity to the silicon specimen.
7.1.2 A light source — This light source is monochromatic, with wavelength between 350 and 1150 nm, or may be broadband, for example a broadband light source with filters. In either case, the spectrum of the light source is characterized.

7.1.3 A reference light-intensity detector (hereafter “light-intensity detector”). This light-intensity detector has response in the entire range of the silicon specimen for all wavelengths available in the light. The light-intensity detector time response must be ten times faster than the time response of the light source used in the QSSPC method. For use in the QSSPC method, the reference light-intensity detector must have known spectral response for the range of the light source wavelengths that create electron-hole pairs in the specimen, 300 to 1150 nm.

7.1.4 A data acquisition system. This system is capable of recording the voltages from the light intensity detector and instrument with sufficient time and voltage resolution. The sampling rate must be ten times higher than the time constant of the lifetime for the transient technique, or the light intensity variation for the QSSPC technique.

7.1.5 A block diagram of the instrument is shown in Figure 1.

7.1.5.1 For wafer specimens, the eddy-current sensor can be placed below the wafer to allow completely unobstructed illumination of the sample from above.

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**Figure 1**

Apparatus for RF-QSSPC and RF-Transient Mode Lifetime Measurements

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8 Test Specimen

8.1 The test specimen for the wafer (transient-mode and QSSPC-mode) lifetime measurements may be any silicon wafer of thickness from 10 μm to 1 mm, with area larger than the sense area of the eddy-current sensor. The wafer may be passivated or unpassivated.

8.2 The test specimen for the bulk (transient-mode and QSSPC-mode) lifetime measurements is any silicon specimen of thickness greater than 1 cm, with area larger than the sense area of the eddy-current sensor by at least 5 mm outside of the sense area. The surface can be as-cut, but best results are obtained for surfaces polished to 1200 grit or finer.⁹

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9 Calibration and Standardization

9.1 A wafer set of at least four specimens are prepared from uniformly-doped monocrystalline wafers. Measure the thickness by a method agreed between the parties, for example, SEMI MF533. Then measure the resistivity values by 4-point-probe (SEMI MF84). The sheet resistance is the resistivity divided by specimen thickness. This calibration set spans the intended measurement range of conductance and photoconductance.

9.2 Determine the output of the eddy-current sensor for each calibration wafer under non-illuminated conditions by placing each wafer in repeatable proximity to the sensor. Record the distance between the wafers and the sensor. Using a quadratic fit with least-squares optimization, determine a relationship for conductance as a function of output signal for the calibrated wafer set. The resulting curve is used to convert measured data to absolute units of sheet conductance.

9.3 QSSPC and Transient Mode for Bulk Specimens: In addition to obtaining the curve for wafer specimens, repeat the process described in 9.1 and 9.2 using a silicon specimen set of at least four 15 mm thick (or thicker), uniformly doped specimens, to determine a quadratic relationship for bulk conductivity (inverse bulk resistivity) as a function of output signal. In the case of bulk conductivity, the method of SEMI MF43 is used, with temperature controls and corrections as given in SEMI MF84.

9.3.1 Determine the sense depth for the sensor. The sense depth is the resistivity (Ω·cm) reported by 4-point-probe divided by the sheet resistance (Ohms per square) reported by the instrument for a bulk sample at least 15 mm thick.

9.4 Illumination source calibration:

9.4.1 Determine a constant of proportionality for photogeneration in the specimen under test as a function of the output signal of the reference light-intensity detector, using one of the following four methods. This calibration is not required for the Transient measurement mode.

9.4.1.1 Use a wafer similar to the device under test with carrier recombination lifetime in the range of 100 to 1000 µs. Measure the carrier recombination lifetime of this wafer using the transient method (which requires no reference light-intensity detector) and by the QSSPC method. Determine the calibration for the reference light-intensity detector that duplicates the lifetime measured by the transient method.\textsuperscript{10, 11}

9.4.1.2 Use a set of wafers with known lifetime based upon measurements with a calibrated instrument. Determine the calibration for the new instrument that duplicates the known values.

9.4.1.3 Using the illumination spectrum of the light source, simulate both the photogeneration in the test specimen and the output signal from the light-intensity detector.\textsuperscript{12} This is done by constructing a model solar cell (using PC1D\textsuperscript{13} or another program agreed between parties) in which the known spectral response of the light-intensity detector is used to determine its output signal. Then the photogeneration in a model of the specimen (with the correct silicon thickness and dielectric layers) is compared to the light-intensity detector signal output for the same spectral input file from the light source. The ratio of the results is the calibrated photogeneration in the specimen per unit signal from the light-intensity detector for the same light source.

9.4.1.4 If the spectral transmission and reflection of the specimen under test is known, then the photogeneration for the spectrum of the light source can be calculated as the sum of absorbed photons multiplied by the charge on an electron. This value, divided by the voltage signal from the light-intensity detector for the same light source is the constant of proportionality.

10 Procedure

10.1 Transient Method Measurements on Wafer Specimens:


\textsuperscript{13} D. A. Clugston and P. A. Basore (1997). \textit{Proceedings}. 26\textsuperscript{th} IEEE Photovoltaic Specialist Conference. PC1D is available free of charge from the University of New South Wales (Australia). The source code is also available.
10.1.1 Measure and record the wafer thickness, substrate resistivity, and temperature.

10.1.2 Place the specimen on the sensor at the distance recorded during the conductance calibration using eq. 1.

10.1.3 Use an illumination source which is on for duration longer than the expected lifetime in the wafer, illuminate the specimen, then abruptly terminate the illumination.

10.1.4 Measure the change in conductance after the illumination terminates.

10.1.5 Convert the photoconductance into average injected carrier density as described in eq. 2, 3, and 4.

10.1.6 Using the eq. 6, determine the effective lifetime as a function of excess-carrier density for the range of carrier densities available in the measurement.

10.1.7 Optionally, calculate interpretation parameters (such as \( J_{\text{src}}, S, \) and \( \tau_{\text{bulk}} \)) from the measured effective lifetime as indicated in Appendix 2.

10.2 QSSPC method Measurements on Wafer Specimens

10.2.1 Measure and record the wafer thickness, substrate resistivity, and temperature.

10.2.2 Place the specimen on the sensor at the distance recorded during the conductance calibration.

10.2.3 Use an illumination source with a 1/e decay time at least three times greater than the expected effective lifetime in the wafer, illuminate the specimen and the calibrated light-intensity detector.

10.2.4 Simultaneously measure the change in illumination intensity and the change in conductance (converted from sensor signal as described in ¶ 11.1.1).

10.2.5 Convert the photoconductance into average injected carrier density as described in eq. 2, 3 and 4.

10.2.6 Convert the change in illumination into photogeneration in the specimen, as described in eq. 5.

10.2.7 Using eq. 7, determine the effective lifetime as a function of excess-carrier density for the range of carrier densities available in the measurement.

10.2.8 If desired, increase or reduce the illumination levels to expand the available range of carrier densities.

10.2.9 Optionally, calculate interpretation parameters (such as \( J_{\text{src}}, S, \) and \( \tau_{\text{bulk}} \)) from the measured effective lifetime as indicated in Appendix 2.

10.3 Transient Measurement on Bulk Specimens

10.3.1 Measure and record the specimen thickness, substrate resistivity, and temperature.

10.3.2 Place the specimen on the sensor at the distance recorded during the conductance calibration.

10.3.3 Illuminate the silicon, with high intensity and pulse duration lasting until the photoconductance reaches the highest possible value for the available light source. Terminate the light as quickly as possible with a sharp cutoff that has a 1/e decay time less than 1/5 of the reported lifetime. The average excess carrier density in the specimen is reported from the photoconductance as in eq. 4, using the sensor depth as the effective w in the equation.

10.3.4 Report the lifetime at \( 5 \times 10^{14} \text{ cm}^{-3} \) excess carrier density, report the entire curve, or state the specific carrier density where the lifetime is reported. Use an analysis defined in eq. 4 and eq. 6, with the sense depth as the effective width.

10.4 QSSPC Measurements on Bulk Specimens:

10.4.1 Measure and record the specimen thickness, substrate resistivity, and temperature.

10.4.2 Place the specimen on the sensor at the distance recorded during the conductance calibration.

10.4.3 Illuminate the silicon, with a pulse duration and decay rate that exceeds the longest expected bulk lifetime in the material by at least 3 times, using a light source with significant illumination greater than 950 nm.

10.4.4 Calculate the photogeneration calibration constant as indicated in ¶ 9.4.1.
10.4.5 Report the measured lifetime, based on the expected diffusion length as defined in eq. 10, using an analysis defined by eqs. 8 and 9, or a numerical analysis (described in Appendix 3) that produces analogous equations to 8 and 9 and is agreed between the parties and recorded in the report.

10.4.6 Calculate the diffusion length with eq. 10. Iterate the effective specimen width and bulk lifetime to self-consistency using a transfer function between measured and bulk lifetimes, eq. 7, and utilizing eq. 8 and 9 or analogous numerical analysis (Appendix 3).

10.4.7 Use a trapping correction if required\(^{14}\) (see Appendix 1).

10.4.8 Report the measured lifetime and calculated bulk lifetime as well as the carrier density where it was evaluated. Fill out the report as in Table 1 in § 12.

11 Calculations

11.1 From data taken on a wafer using a photoconductance sensor, the photoconductance is converted to average carrier density using the relationship between mobility and carrier density as agreed between the parties and recorded in the report.

11.1.1 The relationship between conductance \((1/R_{sh})\) and instrument eddy-current sensor voltage \((V)\) is

\[
\frac{1}{R_{sh}} = aV^2 + bV + c
\]  

(1)

where \(a\), \(b\), and \(c\) were determined as in section 9 by fitting instrument output to wafers of known conductance, \((1/R_{sh})\) as indicated in ¶ 9.1.

11.1.2 For wafers specimens, the sample thickness, \(w\), is determined by a method as agreed between parties, for example, as specified by SEMI MF533.

11.1.3 The mobility is a function of the excess-carrier density, \(\Delta n\), and the doping densities \(N_A\), and \(N_D\). The mobility to use in these calculations is to be agreed between the parties and consists of the sum of electron and hole mobilities in the specimen;

\[
\left( \mu_n + \mu_p \right) = \mu_n \left( \Delta n, N_A, N_D \right) + \mu_p \left( \Delta n, N_A, N_D \right)
\]  

(2)

11.1.4 A frequently-used mobility model for a specimen at 300K is based on data from highly-injected silicon\(^{15,16}\), and evaluated at the approximate net density of majority carriers, \(N_{maj}\), (in carriers cm\(^{-3}\)) added to the excess-carrier density. For example,

\[
\left( \mu_n + \mu_p \right) = 1800 + \exp \left[ 0.8431 \ln \left( \frac{\Delta n + N_{maj}}{1.2 \times 10^{18}} \right) \right] \\
1 + 8.36 \exp \left[ 0.8431 \ln \left( \frac{\Delta n + N_{maj}}{1.2 \times 10^{18}} \right) \right]
\]  

(3)


Alternatively, a temperature-dependent model is specified\textsuperscript{17}. The approximate majority-carrier density is determined from the resistivity using SEMI MF723.

11.1.5 The average excess carrier density in the wafer is reported from the absolute photo-conductance as

\[
\Delta n = \frac{\Delta \sigma}{q \left( \mu_n + \mu_p \right)} = \frac{1}{R_{sh}} \frac{\Delta}{R_{sh}} = \frac{\Delta}{q w \left( \mu_n + \mu_p \right)}
\]

(4)

where

\[R_{sh} = \text{sheet resistance},\]
\[q = \text{elementary charge}.\textsuperscript{20}\]

In order to calculate \(\Delta n\) from the conductance, it may be necessary to iterate equations 3 and 4 two or more times to converge on a unique \(\Delta n\) due to the weak \(\Delta n\) dependence in Eq. 3.

11.2 The photogeneration in the wafer sample is calculated as in \textsect \textsuperscript{9.4}.

11.2.1 For a voltage \(V\) from the light-intensity detector,

\[G(t) = K_1 \ast V\]

(5)

Where \(K_1\) = the constant of proportionality between photogeneration in the sample and the light intensity detector output voltage as calibrated in \textsect \textsuperscript{9.4}.

11.3 The measurement of carrier lifetime in a wafer is accomplished by monitoring the carrier-density balance as a function of the photogeneration of excess carriers. This carrier density is 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\textsuperscript{18}.

11.3.1 In the transient photoconductance decay (PCD) method, the photogeneration is abruptly terminated, then

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

(6)

after the light is fully off.

\textsuperscript{17} J. M. Dorkel and Ph. Leturcq (1981). Carrier mobilities in silicon semi-empirically related to temperature, doping and injection level, Solid-St Electron, 24(9), 821-825.
11.3.2 For a silicon wafer with steady state or Quasi-steady-state (slowly varying) light incident on the specimen solving the continuity equation without simplifying into the transient or steady-state special cases gives the effective lifetime.

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

(7)

where \(\Delta n(t)\) is the time-dependent average excess carrier density and \(G\) is the photogeneration rate for electron-hole pairs.

11.3.3 For steady state, monochromatic illumination and infinite surface recombination, effective lifetime in bulk specimens is

\[
\tau_{\text{eff}} = \frac{\tau_{\text{bulk}}}{\alpha L + 1}
\]

(8)

with effective width of

\[
w_{\text{eff}} = 2 \left[ L + \frac{1}{\alpha} \right]
\]

(9)

where the diffusion length is defined by

\[
L = \frac{D \tau_{\text{bulk}}}{\sqrt{\alpha}}
\]

(10)

The diffusion coefficient, \(D\), to be used here is defined in Appendix 2. A more detailed discussion of eq. 8, 9, and 10 is given in Appendix 3.

12 Reporting Results

12.1 Reported information includes numerical results as well as parameters relating to the apparatus details.

12.1.1 Measured effective lifetime.

12.1.2 Carrier density or range at which lifetime is calculated.

12.1.3 Interpretation parameters (if any, such as \(J_{\text{ne}}, S, \text{and } \tau_{\text{bulk}}\)).

12.1.4 Specimen thickness.

12.1.5 Specimen temperature.

12.1.6 Specimen doping concentration (if known).

12.1.7 Specimen doping type (if known).

12.1.8 Specimen passivation, (if any).

12.1.9 Defect state of known defects (if any).

12.1.10 Method (RF-QSSPC, RF-Transient, Wafer, Bulk).

12.1.11 Excitation wavelength or wavelengths (attach light source spectrum).

12.1.12 Trapping or DRM correction, (if any).

12.1.13 Illumination time profile and calibration.

12.1.14 Sensor type and calibration, specifically including the mobility model used to convert conductance to carrier density.

12.1.15 Sense depth (for bulk measurements).
12.1.16 Detection area.

12.1.17 Number, spatial position, and averaging method of detected points.

12.1.18 Transfer function for measured to bulk lifetime with key modeling assumptions. Attach transfer function and simulation file (for example, PC1D “.prm” file).

12.1.19 Instrument model number and software version.

NOTE 1: It is recommended to report the entire carrier-density-dependent lifetime curve for B-CZ or multicrystalline silicon, or other specimens that have excess carrier dependent lifetime, since there is significant information in the details of the excess-carrier density dependence.
Table 1  Example Report with Information Required to Reproduce Results with Similar or Alternative Test Methods

<table>
<thead>
<tr>
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| Interpretation Notes: |

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13 Uncertainty

13.1 Uncertainty for reporting lifetime on wafers and bulk specimens.

13.1.1 Wafer specimens: This uncertainty is estimated to be 10% in lifetime for QSSPC lifetime measurements, and 5% for transient measurements. These uncertainties for wafer measurements are limited primarily by the uncertainties in mobility models. The uncertainty in reporting carrier density for both methods is estimated to be 10%\(^6\). These limits were calculated for typical measurements reported at an excess carrier density in the range of \(1 \times 10^{15}\) cm\(^{-3}\). Additional sources of error would be due to uncertainties in the lateral and vertical placement of the wafer relative to the sensor.

13.1.2 Bulk specimens: There are no published studies for uncertainties on bulk samples.
APPENDIX 1
THE CORRECTION OF PHOTOCONDUCTANCE EXCESS-CARRIER LIFETIME AT LOW EXCESS CARRIER DENSITY

NOTICE: The material in this appendix is an official part of SEMI (doc#) and was approved by full letter ballot procedures on (date of approval).

A1-1 Correction for Trapping Effects at Low Excess Carrier Density

A1-1.1 In multicrystalline material, especially prior to high-temperature processing, some specimens indicate a characteristic where the apparent lifetime from Equation 6 or 7 increases dramatically at low excess carrier densities, as shown in Figure A1-1. This is generally referred to as trapping, and has been characterized in detail.2, 14 The apparent high-lifetimes are an artifact, and are not due to excess free electron-hole pairs. This high lifetime (exceeding 80 μs in Figure A1-1) should not be reported as carrier recombination lifetime as this excess photoconductance does not correspond to the lifetime of free electron-hole pairs in the silicon and does not significantly improve current or voltage in a solar cell.

Figure A1-1
QSSPC results for lifetime vs. carrier density for uncorrected, and trap-corrected data for an as-cut p-type 1.3 Ω·cm wafer with a thickness of 275 μm. The high apparent lifetime in the uncorrected data is a common artifact of any photoconductance excess-carrier lifetime measurement.2, 14

A1-1.1.1 A simple data correction for the QSSPC technique is illustrated in Figure A1-1. The methodology for this correction is shown in Figure A1-2. The photoconductance vs. light intensity data is shown. A light intensity is specified at the point where the photoconductance becomes relatively linear in light intensity above the steep initial increase in photoconductance for low light intensity. Using this point, referred to as the “bias light intensity”, and the point where the lifetime is to be reported (1 x 10¹⁵ in this case), the slope of photoconductance vs. light intensity is found. The intercept of this line with the photoconductance axis is an approximate measure of the trap photoconductance. Subtracting this from the total photoconductance results in a trap-corrected value that is quite accurate for reporting lifetime and carrier density.
Figure A1-2

The data, photoconductance vs. light intensity for the wafer in Figure A1-1.

Replace the photoconductance in Equation 4 with the corrected photoconductance shown in Equation A1-1.

\[
\Delta \sigma_{\text{corrected}} = \Delta \sigma - \Delta \sigma_{\text{traps}}
\]

A1-1.2. The corrected excess carrier lifetime shown in Figure A1-1 is insensitive to the precise choice of the bias point intensity. It is seen in Figure A1-2 that any choice greater than 14 suns would give nominally the same intercept for this specimen, resulting in the same correction and therefore the same reported lifetime and carrier density.

A1-2 Correction for Depletion Region Modulation Effect

A1-2.1 The correction in Equation A1-1 is also used for the Depletion Region Modulation effect, when the same characteristic shown in Figure A1-1 is seen in specimens with junctions. Discriminating between these two possibilities, trapping and DRM, for the excess photoconductance at low carrier density in multicrystalline wafers or bulk material is not always clear. However, the same correction applies to either or both.

APPENDIX 2
THE INTERPRETATION OF LIFETIME DATA IN WAFERS

NOTICE: The material in this appendix is an official part of SEMI (doc#) and was approved by full letter ballot procedures on (date of approval).

A2-1 The Interpretation of Lifetime Data in Passivated Wafers

A2-1.1 The Equations 6 and 7 indicate how to measure a critical and real physical property, the lifetime of an excess carrier in a wafer. This is 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.

A2-1.1.1 For example, one special case is a uniform carrier density. In this case (shown here for p-type silicon)\(^20,21\):

\[
\frac{1}{\tau_{\text{eff}}(\Delta n)} = \frac{1}{\tau_{\text{bulk}}(\Delta n)} + \frac{S_{\text{front}}(\Delta n) + S_{\text{back}}(\Delta n)}{w} \quad A2-1
\]

\[
\frac{1}{\tau_{\text{eff}}(\Delta n)} = \frac{1}{\tau_{\text{bulk}}(\Delta n)} + \frac{J_{0e,\text{front}} + J_{0e,\text{back}}}{qn^2w} \left[ N \Delta n + \Delta n \right] \quad A2-2
\]

\(w\) is the wafer thickness, \(S\) is the surface recombination velocity, and \(J_{0e}\) is the emitter saturation current density of a dopant diffusion, either a junction or a back-surface field.

A2-1.1.2 The uniform carrier density is self-consistently confirmed from the data if the measured effective lifetime is much greater than a transit time for the wafer:

\[
\tau_{\text{eff}}(\Delta n) > \frac{w^2}{2D} \quad A2-3
\]

This ensures that no recombination sink (surface or bulk) is transport limited and situated at a carrier density significantly lower than the average carrier density. If Equation A2-3 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 spreads across the wafer in the case that non-uniform photogeneration was used during the pulse.

A2-1.1.3 The diffusion coefficient that determines the rate at which carriers diffuse to the surface is\(^22\):

\[
D = \frac{(n + p)D_nD_p}{nD_n + pD_p} \quad A2-4
\]

Where \(D_n\) and \(D_p\) are the diffusion coefficients for electrons and holes, respectively.

For low-injection conditions in p-type material, Eq. A2-4 approaches \(D_n\), for example. This diffusion coefficient varies 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 A2-3. If the measured lifetime is less than the transit time for the wafer, then a thinner wafer or a better surface passivation is used in order to comply with Equation A2-3 and permit the use of this simple analysis. Otherwise, numerical evaluation of the measured lifetime data is required for an accurate analysis. This approach is described in more detail in Appendix 3:

The Interpretation of Ingot and Brick Lifetime Data. For 1 Ω·cm boron p-type material, $D_n$ is 31 cm$^2$/s, and $D_p$ is 11 cm$^2$/sec$^{-1}$.

**A2-2 The Interpretation of Lifetime Data in Non-passivated Wafers**

A2-2.1 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.$^{23}$

A2-2.1.1 Equation A2-5 is the lifetime for a transient measurement after the light has been off for a time of at least the time represented by the $2^{nd}$ term in Equation A2-5, which is $1/5^{th}$ of Equation A2-3, or more quickly if uniform photogeneration was used during the illumination pulse.

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

Equation A2-5

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. The diffusion coefficient, $D$, in this equation is the appropriate ambipolar diffusion coefficient, Equation A2-4, and approaches the minority-carrier diffusion coefficient in the case of low injection in the wafer. In practice, Equation A2-5 is 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 uniformly across the wafer.

A2-2.1.2 Equation A2-6 is the corresponding steady-state equation for uniform photogeneration in a specimen with unpassivated surfaces.$^{24}$

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

Equation A2-6

A2-2.1.3 Equations A2-1 and A2-2 are widely used for developing, optimizing and maintaining process control for surface passivations and emitter saturation current densities, and for measuring the bulk lifetime. Equations A2-5 and A2-6 are less broadly applied, but are useful for the interpretation of carrier lifetime data from as-cut or as-cut and cleaned wafers.$^{7, 23}$ For more general cases, numerical simulation is used to interpret transient or steady-state lifetime-test data.$^{7, 24}$

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APPENDIX 3
THE INTERPRETATION OF INGOT AND BRICK LIFETIME DATA

NOTICE: The material in this appendix is an official part of SEMI (doc#) and was approved by full letter ballot procedures on (date of approval).

A3-1 The Interpretation of Lifetime Data Taken on Ingots and Bricks with Steady-state Measurements

A3-1.1 The methodology for measuring lifetime has been described in the calculation section, section 11, for wafer specimens. It can be extended for use in bulk materials with high surface recombination. One challenge when measuring bulk specimens is to define the average excess carrier density that appears in Equations 3, 4, 6, and 7. 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 specimen, the excitation and sensing of carriers may be near the surface of the specimen only. This information in this appendix is presented in more detail in the document SEMI AUX017.

A3-1.1.1 The carrier concentration in the bulk specimen is described by a weighted average rather than using the simple arithmetic mean of carriers per unit specimen thickness. The weighted average carrier concentration, \( \Delta n_{avg} \), is

\[
\Delta n_{avg} = \frac{\int_{0}^{\infty} \Delta n^2 \, dx}{\int_{0}^{\infty} \Delta n \, dx}
\]

A3-1

the carrier concentration weighted by the carrier concentration. The weighted average then takes into account only those sections of the device that have an excess light-induced carrier concentration.

A3-1.1.2 An effective width, \( w_{eff} \), for the high concentration region is defined which is the total excess carrier concentration divided by the average carrier concentration as determined in Equation A3-1.7

\[
w_{eff} = \left( \frac{\int_{0}^{\infty} \Delta n \, dx}{\int_{0}^{\infty} \Delta n^2 \, dx} \right)^2
\]

A3-2

A3-1.1.3 In practice, the effective width for the carrier density distribution is an extremely useful parameter. This construct represented by Equations A3-1 and A3-2 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 \( w_{eff} \).

\[
\int_{0}^{\infty} \Delta n \, dx = n_{avg} w_{eff}
\]

A3-3

In general, these functions are evaluated 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 specimen. Therefore the measurement of lifetime and carrier density (with Equations 4, A3-2, 6 and 7) becomes an iterative calculation to self consistency.

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

A3-1.1.4 In the case of an unpassivated front surface, the measured effective lifetime that results from this measurement is lower than the bulk lifetime due to surface recombination. For example, for steady-state illumination with monochromatic light and infinite surface recombination

\[
\tau_{eff} = \frac{\tau_{bulk}}{ed} + 1
\]

A3-4
\[ w_{eff} = \frac{2}{L + \frac{1}{\alpha}} \quad \text{A3-5} \]
\[ L = \frac{D \tau_{bulk}}{\tau} \quad \text{A3-6} \]

where \( L \) is the diffusion length of carriers in the specimen and \( \alpha \) is the absorption coefficient for the light. Equation A3-4 indicates that the measured lifetime is a lower bound on the bulk lifetime, which approaches the bulk lifetime only for absorption depths in the silicon that are greater than the diffusion length in the material. Equation A3-4 also permits the calculation of the bulk lifetime of a very thick specimen based on the measurement of effective lifetime at a specific wavelength. Equation A3-5 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 \( \tau_{eff}, \tau_{bulk}, \) 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 Equations A3-4 and A3-5 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. 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.

A3-2 The Interpretation of Lifetime Data Taken on Ingots or Bricks with the Transient Method

A3-2.1 For the case of transient measurements after termination of a long-duration illumination pulse, the measured lifetime from Equation 6 begins at the steady-state result from Equation A3-4 and then approaches the actual bulk lifetime after the surface recombination depletes the near-surface region and the surface recombination becomes transport limited.

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