

# SEMI MF1535-0707

## TEST METHOD FOR CARRIER RECOMBINATION LIFETIME IN SILICON WAFERS BY NON-CONTACT MEASUREMENT OF PHOTOCONDUCTIVITY DECAY BY MICROWAVE REFLECTANCE

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### 1 Purpose

1.1 If the free carrier density of a semiconductor is not too high, the carrier recombination lifetime is controlled by impurity centers that have energies located in the forbidden energy gap. Many metallic impurities form such recombination centers in silicon. In most cases, very small densities of these impurities ( $\approx 10^{10}$  to  $10^{13}$  atoms/cm<sup>3</sup>) reduce the carrier recombination lifetime and adversely affect device and circuit performance. In some cases, such as very fast bipolar switching devices and high power devices, the recombination characteristics must be carefully controlled to obtain the desired device performance.

1.2 This test method covers a procedure for measuring carrier recombination lifetime in a variety of types of silicon wafers. Because electrical contact is not made to the wafer during the test, additional processing steps can be carried out following the test if wafer cleanness is maintained.

1.3 This test method is suitable for use in research and development, process control, and materials acceptance applications. However, the results obtained by this test method depend on degree of surface passivation. Therefore, when this test method is used for materials specification or acceptance, the supplier and the purchaser need to agree on the surface treatment for the test.

### 2 Scope

2.1 This test method covers the measurement of carrier lifetime appropriate to carrier recombination processes in homogeneously doped, polished, *n*- or *p*-type silicon wafers. The room-temperature resistivity of the specimen should be greater than a limit that is determined by the sensitivity of the detection system and is normally in a range from 0.05–1  $\Omega \cdot \text{cm}$ . This test method may also be applied to the measurement of carrier recombination lifetime in as-cut, lapped, or etched wafers, provided that the sensitivity of the conductivity detection system is adequate.

2.2 In this test method, the decay of the wafer conductivity following generation of excess carriers with a light pulse is determined by monitoring the microwave reflectivity of the wafer. Since no contact is made to the specimen, this test method is nondestructive. If wafer cleanness is maintained, wafers may be further processed following testing by this test method.

2.3 Measurement of the carrier recombination lifetime in the absence of surface recombination results in the determination of the "ideal" bulk recombination lifetime ( $\tau_b$ ). In general, however, it is very difficult to completely suppress surface recombination, and the lifetime measurement is in most cases done without any surface passivation or without confirming that the surface passivation is perfect. In addition, the injection level also affects the measured lifetime value. If the injection level is low, the measured lifetime is not influenced by the injection level and the bulk recombination lifetime is the minority carrier lifetime (see Note 1). However, to enhance the signal-to-noise (S/N) ratio, high-level injection is often adopted. Therefore, this test method also includes measurement of carrier recombination lifetime under "non-ideal" conditions, where the surface recombination is finite and/or the injection level is not low. Two such determinations are included:

2.3.1 The primary mode lifetime  $\tau_1$ , which is influenced by both bulk and surface properties,

2.3.2 The  $1/e$  lifetime  $\tau_e$ , which depends on both the injection level and the laser penetration depth as well as being strongly influenced by the surface condition, because just after injection, the excess carriers are distributed near to the surface. On the other hand,  $\tau_e$  is measured easily and quickly owing to good signal-to-noise ratio in the initial part of the decay curve and simplicity of the data analysis.

NOTE 1: Depending on the level of photoexcitation, the carrier recombination lifetime determined by this test method may be the minority-carrier lifetime (low injection level) or a mixture of minority- and majority-carrier lifetimes (intermediate and high injection levels). In the latter case, the minority and majority carrier lifetimes may be separated under some conditions if a single recombination center that follows the Shockley-Read-Hall model which applies for a small density of recombination centers, is assumed. When the density of injected carriers greatly exceeds the density of the majority carriers (high injection), the recombination lifetime is the sum of the minority and majority carrier capture time constants (see Related Information 1).

2.3.3 The above three lifetimes coincide ( $\tau_b = \tau_1 = \tau_e$ ) if the surface recombination is negligible and the injection level is low enough. In the case that the surface recombination is negligible,  $\tau_b = \tau_1$  even if the injection is not of low level just after the laser irradiation.

NOTE 2: This test method is appropriate for the measurement of carrier recombination lifetimes in the range from 0.25  $\mu$ s to >1 ms. The shortest measurable lifetime values are governed by the turn-off characteristics of the light source and by the sampling frequency of the decay signal analyzer while the longest values are determined by the geometry of the test specimen and the degree of passivation of the wafer surface. With suitable passivation procedures, such as thermal oxidation or immersion in a suitable solution, lifetimes as long as tens of milliseconds can be determined in polished wafers with thickness as specified in SEMI M1.

NOTE 3: Carrier recombination lifetime of large bulk specimens can be determined by Method A or B of SEMI MF28. These test methods, which are also based on measurement of photoconductivity decay (PCD), require electrical contacts to the specimen. In addition, they assume large surface recombination on all surfaces and so the upper limit of measurable lifetime is governed by the size of the test specimen. Method B of SEMI MF28 stipulates that the test be carried out under conditions of low injection to ensure that the minority-carrier lifetime is determined. Minority carrier recombination lifetime can also be deduced from the carrier diffusion length as measured by the surface photovoltage (SPV) method in accordance with Method A or B of SEMI MF391. When carried out under low injection conditions, both the SPV method and the PCD method should yield the same values of minority-carrier lifetime<sup>1</sup> under certain conditions. First, it is required that carrier trapping does not occur. Second, correct values of absorption coefficient and minority-carrier mobility must be used in analyzing the SPV measurements. Third, surface recombination effects must be eliminated (as in the present test method) or properly accounted for (as in SEMI MF28) in carrying out the PCD measurements. The generation lifetime, which is another transient characteristic of semiconductor materials, is typically orders of magnitude larger than the recombination lifetime. Although SEMI MF1388 covers the measurement of the generation lifetime in silicon wafers, the recombination lifetime can also be deduced from capacitance-time measurements made at temperatures above room temperature ( $\geq 70^\circ\text{C}$ ) using the same MOS capacitor structure.<sup>2</sup>

2.4 Interpretation of measurements to identify the cause or nature of impurity centers is beyond the scope of this test method. However, some aspects of deriving this information from carrier recombination lifetime measurements alone are discussed in the related information sections. Use of “injection level spectroscopy”<sup>3</sup> is discussed in Related Information 1 and use of the temperature dependence of the carrier recombination lifetime as determined with low-injection level<sup>4</sup> is discussed in Related Information 2. The identity and density of impurity centers found to be present in the wafer by means of recombination lifetime measurements may usually be determined more reliably from deep-level transient spectroscopy (DLTS) measurements made in accordance with SEMI MF978 or from other capacitance or current transient spectroscopy techniques provided that a suitable catalog of impurity characteristics is available<sup>5</sup>.

2.5 Metallic impurities that affect the carrier recombination lifetime may be introduced into the wafer during various processing steps, especially those that involve high temperatures. Analysis of procedures for detection of contamination sources (see ¶ 6.4) is beyond the scope of this test method. Although the test method is generally nonselective, certain individual impurity species can be identified under very restricted conditions (see ¶ 6.3, Related Information 1 and Related Information 2).

1 Saritas, M., and McKell, H. D., “Comparison of Minority-Carrier Diffusion Length Measurements in Silicon by the Photoconductive Decay and Surface Photovoltage Methods,” *J. Appl. Phys.* 63, 4562–4567 (1988)

2 Schroder, D. K., Whitfield, J. D., and Varker, C. J., “Recombination Lifetime using the Pulsed MOS Capacitor,” *IEEE Trans. Electron Devices* ED-31, 462–467 (1984)

3 Ferenczi, G., Pavelka, T., and Tüttő, P., “Injection Level Spectroscopy: A Novel Non-Contact Contamination Analysis Technique in Silicon,” *Jap. J. Appl. Phys.* 30, 3630–3633 (1991)

4 Kirino, Y., Buczkowski, A., Radzinski, Z. J., Rozgonyi, G. A., and Shimura, F., “Noncontact Energy Level Analysis of Metallic Impurities in Silicon Crystals,” *Appl. Phys. Lett.* 57, 2832–2834 (1990)

5 Schulz, M., ed, in *Semiconductors: Impurities and Defects in Group IV Elements and III-V Compounds*, Landolt-Börnstein, New Series III/22b, (Springer Verlag, Heidelberg, 1989) § 4.2.3.1

**NOTICE:** This standard does not purport to address safety issues, if any, associated with its use. It is the responsibility of the user 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 If the lifetime of the carriers is such that the carrier diffusion length is greater than 0.1 times the wafer thickness the surface recombination influences the conductivity decay. Then the effects of recombination at the surfaces of the wafer must be suppressed by thermal oxidation or by immersion in a suitable electrolyte (see § 11) to measure the bulk recombination lifetime.

3.1.1 Treatments with electrolyte solutions must result in a stable surface for the test method to produce reliable results.

3.1.2 A further caution is in order if thermal oxidation is employed. Particularly in high oxygen wafers, oxide precipitates may form in the bulk of the wafer during oxidation. The presence of such precipitates can alter the recombination properties of the wafer (see also ¶ 3.3) thus rendering the test specimen unsuitable for measurement by this test method.

3.1.3 Externally gettered wafers may, under some conditions, yield erroneous values of carrier recombination lifetime when measured by this test method. Results of measurements on such wafers should be checked very thoroughly for validity.

3.2 The method is not suitable for measurement of recombination lifetime in very thin films of silicon. If the thickness of the test specimen is comparable with or smaller than the inverse of the absorption coefficient of the incident radiation, the decay curve may be distorted by the spatial dependence of the generation of excess carriers.

3.3 Variations in carrier recombination properties in the direction perpendicular to the wafer surface may result in inaccurate determinations of the bulk recombination lifetime. These variations may arise because of the presence (1) of  $p$ - $n$  or high-low ( $p$ - $p^+$  or  $n$ - $n^+$ ) junctions parallel with the surface or (2) of regions of dissimilar recombination characteristics (such as a wafer with oxide precipitates and a surface denuded region free of such precipitates).

3.4 The recombination characteristics of impurities in silicon are strongly temperature dependent. If comparisons between measurements are to be made (i.e., before and after a process step or at a supplier and a customer), both measurements should be made at the same temperature.

3.5 Different impurity centers have different recombination characteristics. Therefore, if more than one type of recombination center is present in the wafer, the decay may consist of contributions with two or more time constants. The recombination lifetime deduced from such a decay curve may not be representative of any of the individual centers.

3.6 The recombination characteristics of an impurity center depend on the dopant type and density of the wafer as well as the position of the energy level of the impurity center in the forbidden energy gap (see Related Information R3-2).

3.7 Higher mode decay of photoinjected carriers influences the shape of the decay signal, particularly in its early phases.<sup>6</sup> These effects are minimized by measuring the decay after the higher modes have died away (beginning below 50% of the maximum decay signal).

### 4 Referenced Standards and Documents

#### 4.1 SEMI Standards

SEMI C28 — Specifications and Guidelines for Hydrofluoric Acid

SEMI C35 — Specifications and Guideline for Nitric Acid

SEMI M1 — Specifications for Polished Monocrystalline Silicon Wafers

SEMI M59 — Terminology for Silicon Technology

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<sup>6</sup> Blakemore, J. S., *Semiconductor Statistics*, (Dover Publications, New York, 1987) § 10.4

SEMI MF28 — Test Methods for Minority-Carrier Lifetime in Bulk Germanium and Silicon by Measurement of Photoconductive Decay

SEMI MF42 — Test Methods for Conductivity Type of Extrinsic Semiconducting Materials

SEMI MF84 — Test Method for Measuring Resistivity of Silicon Wafers With an In-Line Four-Point Probe

SEMI MF391 — Test Methods for Minority Carrier Diffusion Length in Extrinsic Semiconductors by Measurement of Steady-State Surface Photovoltage

SEMI MF533 — Test Method for Thickness and Thickness Variation of Silicon Wafers

SEMI MF673 — Test Methods for Measuring Resistivity of Semiconductor Slices or Sheet Resistance of Semiconductor Films with a Non-contact Eddy-Current Gage

SEMI MF723 — Practice for Conversion Between Resistivity and Dopant Density for Boron-Doped, Phosphorus-Doped, and Arsenic-Doped Silicon

SEMI MF978 — Test Method for Characterizing Semiconductor Deep Levels by Transient Capacitance Techniques

SEMI MF1388 — Test Methods for Generation Lifetime and Generation Velocity of Silicon Material by Capacitance-Time Measurements of Metal-Oxide-Silicon (MOS) Capacitors

SEMI MF1530 — Test Method for Flatness, Thickness, and Thickness Variation of Silicon Wafers by Automated Noncontact Scanning

#### 4.2 *ASTM Standard*<sup>7</sup>

D 5127 — Guide for Ultra Pure Water Used in the Electronics and Semiconductor Industry

#### 4.3 *DIN Standard*<sup>8</sup>

DIN 50440 — Measurement of carrier lifetime in silicon single crystals: carrier recombination lifetime at low injection by photoconductivity method

#### 4.4 *JEITA Standard*<sup>9</sup>

JEITA EM-3502 (JEIDA-53-1999) — Test Method for Carrier Recombination Lifetime in Silicon Wafers by Measurement of Photoconductivity Decay by Microwave Reflectance

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

## 5 Terminology

5.1 Definitions of terms used in silicon technology may be found in SEMI M59.

## 6 Summary of Test Method

6.1 Excess hole-electron pairs are locally created in the wafer for a very brief time by a short pulse (width  $\leq 200$  ns, rise and fall times  $\leq 25$  ns) of light with energy slightly greater than the width of the forbidden energy gap at a specified power density (injection level). The decay of the conductivity following cessation of the light pulse is monitored by means of microwave reflectance, and the carrier recombination lifetime is determined as follows:

6.1.1 In the case that it is desired to obtain the bulk recombination lifetime, the specimen surface is conditioned in such a way that surface recombination has a negligible effect on the decay of the conductivity, and the carrier recombination lifetime is determined as the time constant of an appropriate portion of the exponential conductivity decay.

<sup>7</sup> *Annual Book of ASTM Standards*, Vol 11.01, ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428. Telephone: 610-832-9500; Fax: 610-832-9555; <http://www.astm.org>

<sup>8</sup> Available in both German and English editions from Deutsches Institut für Normung e.V., Beuth Verlag GmbH, Burggrafenstrasse 4-10, D 10787 Berlin, Germany; <http://www.din.de>

<sup>9</sup> Japan Electronics and Information Technology Industries Association, 3<sup>rd</sup> floor, Mitsui Sumitomo Kaijo Bldg. Annex, 11, Kanda-Surugadai 3-chome, Chiyoda-ku, Tokyo 101-0062, Japan. Telephone: 81.3.3518.6434; Fax: 81.3.3295.8727; <http://www.jeita.or.jp>

6.1.2 The primary mode lifetime is taken as the decay time constant determined from an exponential portion of the decay curve.

6.1.3 The  $1/e$  lifetime is taken as the time duration from the laser pulse injection to the instant that the excess carrier density decreases to  $1/e$ .

6.2 A narrow-beam light source may be used so that measurements may be made repeatedly at different localized points on the wafer to obtain a map of the distribution of carrier recombination lifetime.

6.3 The measurement may be repeated at several different values of specific parameters, such as injection level (light source intensity) or temperature in order to obtain more detailed information about the nature of the recombination centers.

6.4 A process step that acts as a contamination source can sometimes be identified by comparing measurements of carrier recombination lifetime made before and after the step.

## 7 Apparatus

7.1 *Pulsed Light Source* — A laser diode with wavelength between 0.9 and 1.1  $\mu\text{m}$ . Pulse length is nominally  $\leq 200$  ns, and the rise and fall times are  $\leq 25$  ns (see Note 3). It is preferred that the output power of the light source be variable such that photon densities between  $2.5 \times 10^{10}$  and  $2.5 \times 10^{15}$  photon/cm<sup>2</sup> are generated at the wafer surface during the pulse.

NOTE 4: The rise and fall times of the pulsed light source and the sampling time of the signal conditioner (see ¶ 7.4) should be  $\leq 0.1$  of the shortest lifetime to be measured.

7.1.1 *Photon Detector* — It is often desirable that a suitable means, such as a semitransparent mirror in the light path at an angle of 45° and a silicon photodetector, be used to provide feedback control to maintain the laser power at a constant level appropriate to the specified injection level.

7.2 *Microwave Pick-Up System* — Including a microwave source operating at a nominal frequency of  $10 \pm 0.5$  GHz and an apparatus for measuring reflected power, such as a circulator, an antenna, and a detector (see Figure 1). The sensitivity of the detection system shall be as great as possible to permit measurement of photoconductivity decay at low injection levels.

7.3 *Wafer Mounting Stage* — For holding the wafer (with vacuum hold down) in the desired position under the pulsed light source. The stage may contain a heater for controlling its temperature over a small temperature range above room temperature. It may be driven by computer-controlled motors to provide x-y or r- $\theta$  motion for mapping capability over the wafer surface and may have automatic wafer loader and transport to facilitate automatic sequential measurement of a group of wafers.

7.4 *System for Analysis of the Decay Signal* — Appropriate signal conditioners and display unit (real or virtual oscilloscope with suitable time sweep and signal sensitivity). The signal conditioner shall have a bandwidth  $\geq 40$  MHz, or a minimum sampling time  $\leq 25$  ns (see Note 3). The display unit shall have a continuously calibrated time base with accuracy and linearity better than 3%. The system shall be such that the time constant of user-specified portions of the decay signal can be established independently.

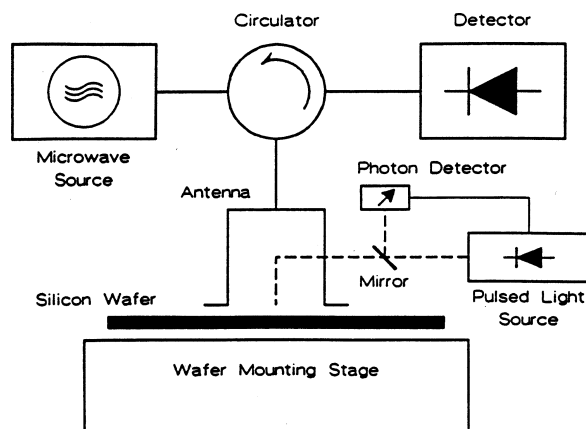


**Figure 1**  
**Example Block Diagram of Pulsed Light and Microwave Systems**

7.5 *Computer System* — Although the measurement can be made manually, it is recommended that it be carried out using a suitable computer system that controls the wafer loading, stage motion, the pulse and detector operation, decay signal analysis, statistical analysis of the data, data logging and storage, and printing or plotting of results.

7.6 *Facilities for Etching or Passivating Wafer Surfaces* — If required.

7.6.1 *For Chemical Passivation* — A fume hood equipped with an acid-proof sink and suitable beakers or other containers for holding wet chemicals, including hydrofluoric acid at room temperature and protective gear appropriate to the chemicals used.

7.6.2 *For Oxidation* — A clean furnace capable of high quality dry oxidations at temperatures of 950–1050°C and associated cleaning, drying, and wafer handling facilities.

7.7 *Wafer Holder* — If required. In some cases, it may be necessary to measure the wafer while it is immersed in a passivating solution (see § 11). In this case, a flat chemically inert, optically transparent holder is required to contain both the wafer and the passivating solution.

## 8 Reagents

8.1 *Purity of Reagents* — All chemicals for which such specifications exist shall conform to Grade 1 SEMI specifications for those specific chemicals. Other chemicals shall conform to reagent grade, as specified in Reagent Chemicals.<sup>10</sup> Other grades may be used, provided it is first determined that the chemical is of sufficiently high purity to permit its use without lessening the accuracy of the test.

8.2 *Purity of Water* — Reference to water shall be understood to mean Type E-3 or better water as described in ASTM Guide D 5127.

8.3 The recommended chemicals shall have the following nominal assays:

8.3.1 *Ethanol (CH<sub>3</sub>CH<sub>2</sub>OH)* — Absolute, ≥99.9%.

8.3.2 *Iodine (I<sub>2</sub>)* — >99.8%.

8.3.3 *Hydrofluoric Acid (HF)* — Concentrated, 49.00 ± 0.25% in accordance with Grade 1 of SEMI C28. **WARNING:** see ¶ 9.3 for warning statement.

8.3.4 *Nitric Acid (HNO<sub>3</sub>)* — Concentrated, 70.0–71.0% in accordance with Grade 1 of SEMI C36.

8.4 *Iodine-Ethanol Passivating Solution* — Iodine content 0.02mol/L - 0.2mol/L.

<sup>10</sup> *Reagent Chemicals, American Chemical Society Specifications*, American Chemical Society, Washington, DC. For suggestions on the testing of reagents not listed by the American Chemical Society, see *Analard Standards for Laboratory Chemicals*, BDH Ltd., Poole, Dorset, U.K., and the *United States Pharmacopeia and National Formulary*, U.S. Pharmacopeial Convention, Inc. (USPC), Rockville, MD.