

SEMI MF1535-1015 (Reapproved 1121) TEST METHOD FOR CARRIER RECOMBINATION LIFETIME IN ELECTRONIC-GRADE SILICON WAFERS BY NONCONTACT MEASUREMENT OF PHOTOCONDUCTIVITY DECAY BY MICROWAVE REFLECTANCE

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NOTICE: Paragraphs entitled ‘NOTE:’ are not an official part of this Standard or Safety Guideline and are not intended to modify or supersede the official Standard or Safety Guideline. These have been supplied by the global technical committee to enhance the usage of the Standard or Safety Guideline.

NOTICE: The section symbol (§) is used to reference a numbered section, paragraph, or header and all subordinate paragraphs, headers, and embedded material (i.e., EXCEPTIONs, lists) therein. The paragraph symbol (§) is used to reference a particular numbered paragraph and embedded material therein. When duplicated (i.e., §§ and §§) the symbols are used to reference more than one section or paragraph, respectively.

1 Purpose

1.1 If the free carrier density of an electronic-grade 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 ($\approx 10^{10}$ atoms/cm³) reduce the carrier recombination lifetime and adversely affect device and circuit performance. Such impurities may be introduced into the wafer during manufacture or during various processing steps, especially those that involve high temperatures.

1.2 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, but for most electronic-grade silicon wafers in use today, the concern is simply with controlling the process so that such impurities are not present. Although this Test Method is generally nonselective, certain individual impurity species sometimes can be identified under very restricted conditions.

NOTE 1: This Test Method is technically equivalent to JEIDA-53-1999.

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 many of the experimental conditions including degree of surface passivation, injection level, and so forth. Therefore, when this Test Method is used for materials specification or acceptance, the supplier and the purchaser must agree fully on the experimental conditions used.

2 Scope

2.1 In this Test Method, the decay of the wafer conductivity following generation of excess carriers with a light pulse¹ is determined by monitoring the microwave reflectivity of the wafer. Since no contact is made to the specimen except for the mounting stage on which it rests, this Test Method is nondestructive. If wafer and stage cleanliness is maintained, wafers may be further processed following testing by this Test Method.

2.2 Measurement of the carrier recombination lifetime in the absence of surface recombination results in the determination of the bulk recombination lifetime (τ_b) provided that the excess carrier density is much less than the majority carrier density. This determination is not included in the main part of the Test Method, but information is given in Related Information 1 for those users who may wish to extend it to include the reduction of surface recombination to allow the determination of τ_b at low excess carrier density levels.

¹ Stevenson, D. T., and Keyes, R. J., “Measurement of Carrier Lifetimes in Germanium and Silicon.” *Journal of Applied Physics* (1955): pp. 190–195.

2.3 In general, however, it is very difficult to completely suppress surface recombination, and the lifetime measurement is in many cases done without any surface passivation or without confirming that the surface passivation is perfect. Consequently, two parameters, the $1/e$ lifetime (τ_e) and/or the primary mode lifetime (τ_1), which do not depend on surface passivation, are determined in this Test Method.

2.4 In addition, the initial injection level also affects the measured lifetime value. If the initial injection level is sufficiently low, the measured lifetime is not influenced by the injection level. However, to enhance the signal-to-noise (S/N) ratio, higher-level injection is often adopted. Therefore, this Test Method also allows measurement of these parameters when the injection level may influence the measured lifetime especially in the early stages of decay.

2.5 This Test Method covers the measurement of these lifetime parameters in homogeneously doped, polished, n - or p -type electronic-grade silicon wafers for the purpose of detecting small densities of metallic impurities that may be introduced into the manufacture or processing of such materials. 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 to 1 $\Omega \cdot \text{cm}$. This Test Method may also be applied to the measurement of these lifetime parameters in as-cut, lapped, or etched wafers, provided that the sensitivity of the conductivity detection system is adequate.

2.6 This Test Method is appropriate for the measurement of these lifetime parameters in the range from 0.25 μs 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 (see Related Information 1), lifetimes as long as tens of milliseconds can be determined in polished wafers with thickness as specified in SEMI M1.

2.7 If a narrow-beam light source is used, the illuminated area in this Test Method is small compared with the area of the polished wafers under test, and so it is possible to construct wafer maps of either of the lifetime parameters by making measurements repeatedly at different localized points on the wafer surface.

2.8 Interpretation of measurements to identify the cause or nature of the contaminating impurity centers is beyond the scope of this Test Method (see Note 2). However, some aspects of deriving this information from carrier recombination lifetime measurements alone are discussed in Related Information 1 for the benefit of users of this Test Method who wish to extend it for these purposes.

NOTE 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.²

NOTICE: SEMI Standards and Safety Guidelines do not purport to address all safety issues associated with their use. It is the responsibility of the users of the Documents to establish appropriate safety and health practices, and determine the applicability of regulatory or other limitations prior to use.

3 Limitations

3.1 General Limitations of Photoconductive Decay Measurements

3.1.1 The method is not suitable for measurement of 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.

3.1.2 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).

3.1.3 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.

² 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.

3.1.4 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 lifetime parameters deduced from such a decay curve may not be representative of any of the individual centers.

3.1.5 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.

3.1.6 Higher mode decay of photo injected carriers influences the shape of the decay signal, particularly in its early phases.³ These effects can be minimized by measuring the decay after the higher modes have died away (beginning below 50% of the maximum decay signal).

3.2 *Limitations on the Measurement of the Photoconductive Decay by Microwave Reflectance*

3.2.1 The initial shape of the microwave reflectance decay signal is affected by the lack of complete equivalence between the microwave reflectance decay and the decay of the photo-injected excess carriers at medium to high injection levels.⁴ The first of these referenced papers, however, also indicates that further down the decay curve, this lack of equivalence disappears and the decay becomes that of the photo-injected carriers.⁵ A similar conclusion was reached by Schöffthaler and Brendel.⁶

3.2.2 Lauer *et al.*⁷ studied this lack of equivalence extensively and found that excess conductivity can reach up to 30% of the dark conductivity without losing the proportionality between the microwave signal and the excess carrier density. They also found that in the region where the nonlinearity of the microwave reflectance the maximum error in the microwave reflection signal leads to a maximum error in the measurement of the lifetime of about 10% and that this error decreases significantly during the decay of the photoconductivity.

4 Referenced Standards and Documents

4.1 *SEMI Standards and Safety Guidelines*

SEMI M1 — Specification for Polished Single Crystal Silicon Wafers

SEMI M59 — Terminology for Silicon Technology

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

SEMI MF42 — Test Method 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 Method 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 Method for Measuring Resistivity of Semiconductor Wafers or Sheet Resistance of Semiconductor Films with a Noncontact 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 Method for Generation Lifetime and Generation Velocity of Silicon Material by Capacitance-Time Measurements of Metal-Oxide-Silicon (MOS) Capacitors

³ Blakemore, J. S., *Semiconductor Statistics*, Dover Publications, New York, 1987, § 10.4.

⁴ Kunst, M. and Beck, G., "The study of charge carrier kinetics in semiconductors by μw conductivity measurements." *Journal of Applied Physics* (1986): pp. 3558–3567 and *Journal of Applied Physics* (1988): pp. 1093–1098.

⁵ See the discussion in section II of the first Kunst and Beck paper in reference 4.

⁶ See Figure 12 and the associated discussion of M. Schöffthaler and R. Brendel, "Sensitivity and transient response of microwave reflection measurements." *Journal of Applied Physics* (1995): pp. 3162–3173. Note that the remainder of this paper deals with variations of the distance between the specimen and the reflector plate that are not permitted by this Test Method.

⁷ Lauer, K., Laades, A., Übensee, H., Metzner, H., and Lawrenz, A., "Detailed analysis of the microwave-detected photoconductance decay in crystalline silicon." *Journal of Applied Physics*, 104503-1–104503-9, 2008.

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

4.2 JEIDA Standards⁸

JEIDA-53 — 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 Terms, acronyms, and symbols associated with silicon wafers and silicon technology are listed and defined in SEMI M59.

5.2 Additional Terms Used in this Test Method

5.2.1 *1/e lifetime* (τ_e) — the time duration from the end of the laser pulse injection to the instant that the measured microwave decay signal decreases to $1/e$ of its initial value.

5.2.2 *primary mode lifetime* (τ_1) — the decay time constant obtained from an exponential part of the decay curve of the microwave reflectance in the small-signal range.

6 Comprehensive Explanation of Terms

6.1 As indicated in ¶¶ 3.1.6 and 3.2.1, the initial part of the decay curve may be affected by a number of things in addition to the change in carrier density following the injecting pulse. Therefore, τ_e is affected by 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. Therefore, it is often not possible to obtain physically meaningful quantities from this portion of the decay curve. On the other hand, τ_e is measured easily and quickly owing to its good signal-to-noise ratio and simplicity of its determination (see ¶¶ 11.7.1 and 13.3).

6.2 The term, injection level, is defined in SEMI M59 as “the ratio of the density of excess carriers generated by photons or other means to the equilibrium density of majority carriers in an extrinsic semiconductor crystal or wafer.” This term relates to the initial excess carrier density immediately after cessation of the exciting pulse. It conveniently is denoted by the symbol, η_{init} . At later times during the measurement, including for the portion of the curve where τ_1 is reported, the ratio of the excess carrier density to the equilibrium majority carrier density, η , is considerably lower than the initial injection level, η_{init} .

NOTE 3: The term, injection level, is widely used in the literature to indicate the excess carrier density in carrier lifetime measurements. It apparently derives from the early transistor days when carriers were injected from a heavily doped emitter to a less heavily doped base region of type opposite to that of the emitter in the transistor. It must be emphasized that in the photoconductive decay method, the light actually excites carriers across the forbidden gap so that there are generally equal numbers of excess holes and electrons (see Appendix 1).

6.3 Small-signal conditions are frequently described as low-level injection conditions. In the case for which the decay of excess carriers is fully exponential from the cessation of the injecting pulse, this is indeed the case. However, even if low-level injection is not used, and the shape of the decay curve changes with time after the cessation of the injecting pulse, and the decay can still be measured over a portion of the decay curve where the excess carrier density is small compared with the equilibrium density of majority carriers. Thus, over this portion of the decay curve, the decay becomes closely exponential and small-signal conditions apply.

7 Summary of Test Method

7.1 Excess free electrons and holes are generated in equal concentrations in the wafer for a very brief time by a short pulse (width ≤ 200 ns, rise and fall times ≤ 25 ns) of light with energy slightly greater than the width of the forbidden

⁸ Miyazaki, M., Kawai, K., and Ichimura, M. “Measurement of Minority Carrier Recombination Lifetime in Silicon Wafers by Measurement of Photoconductivity Decay by Microwave Reflectance: Result of Round Robin Test.” *Recombination Lifetime Measurements in Silicon*, ASTM STP 1340, D. C. Gupta, F. R. Bacher, and W. M. Hughes, eds., American Society for Testing and Materials (1998): pp. 347–66, contains an authorized English language version of this Standard. A Japanese language version of this standard can be obtained from SEMI Japan, 4-7-15 Kudan-Minami, Chiyoda-ku, Tokyo 102-0074, Japan, email: semi-japan@semi.org.

energy gap at a specified power density. The decay of the conductivity following cessation of the light pulse is monitored by means of microwave reflectance, and the τ_e or τ_1 or both are determined.

7.2 In the case that it is desired to extend this Test Method in order 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 part of the decay curve (see Related Information 1).

7.3 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 τ_e and/or τ_1 .

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

7.5 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, assuming that identical surface passivation and other experimental conditions are used in the two cases.

8 Apparatus

8.1 *Pulsed Light Source* — A laser diode with wavelength between 0.9 and 1.1 μm . Pulse length is nominally ≤ 200 ns, and the rise and fall times are ≤ 25 ns (see Note 4). It is preferred that the output power of the light source be variable such that photon densities between 2.5×10^{10} and 2.5×10^{15} photon/cm² are generated at the wafer surface during the pulse (see Note 5).

NOTE 4: The rise and fall times of the pulsed light source and the sampling time of the signal conditioner (see ¶ 6) should be ≤ 0.1 of the shortest lifetime to be measured.

NOTE 5: Typically a photon density of 5×10^{13} photons/cm² is used (see ¶ A1-2.4).

8.1.1 *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.

8.2 *Microwave Pick-Up System* — Including a microwave source operating at a nominal frequency of 10 ± 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.

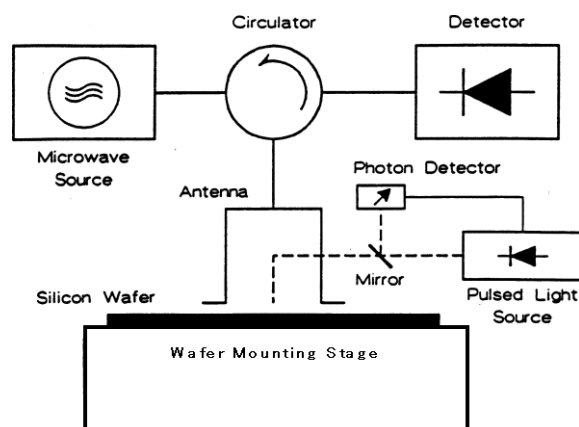


Figure 1
Example Block Diagram of Pulsed Light and Microwave Systems

8.3 *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 - θ motion for mapping capability over the wafer surface and may have an automatic wafer loader and transport to facilitate automatic sequential measurement of a group of wafers.

NOTE 6: If the wafers are to be used following measurement by this method, adequate cleanliness of the wafer mounting stage and surrounding area must be maintained.

8.4 *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 ≥ 40 MHz, or a minimum sampling time ≤ 25 ns (see Note 4). 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.

8.5 *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.

9 Hazards

9.1 The laser illumination system shall be interlocked so that direct observation of the laser beam is prevented. **WARNING:** Do not operate the laser illumination system with the interlock disabled.

9.2 The microwave system shall be shielded and interlocked so that personnel cannot come into contact with the beam. **WARNING:** Do not operate the microwave system with the interlock disabled.

10 Sampling

10.1 If the Test Method is not used on a 100% inspection basis, sampling procedures shall be agreed upon by the parties to the test.

10.2 If sampling by lot is required, the determination of what constitutes a lot and the procedures for sampling and by lot shall be agreed upon by the parties to the test.

10.3 Because the concentration of recombination centers in a wafer may be nonuniform, it is desirable to determine the lifetime parameters at various points across the wafer surface. The point density and location of points measured shall be agreed upon by the parties to the test.

11 Procedure

NOTE 7: The following procedures are given in sufficient detail for manual data collection and analysis. However it is strongly recommended that instrument setup, data collection, and analysis be carried out using computer-controlled equipment, with data storage and display capabilities (see ¶ 8.5). In such cases, the procedures and algorithms employed must be equivalent to those given in this section.

11.1 If they are not known, determine the conductivity type in accordance with SEMI MF42, the center-point wafer thickness in accordance with SEMI MF533 or SEMI MF1530, and the center-point resistivity in accordance with SEMI MF84 or SEMI MF673. Convert the resistivity to the density of the majority carriers (n_{maj} , in carriers/cm³) in accordance with SEMI MF723. Record these data together with the nominal diameter and the condition (polished, etched, lapped, as-cut, etc.) of the front and back surfaces.

11.1.1 If the specimen surface has been prepared to reduce surface recombination (see § R1-6), record the details of the surface preparation process.

11.2 Record the temperature of the room, or if the stage is temperature-controlled, the temperature of the stage surface.

11.3 Load the wafer onto the stage so that the light pulse strikes the desired region.

11.4 Switch on the pulsed laser light source (see ¶ 8.1).

11.5 Adjust the intensity as follows so that the initial injection level, η_{init} , is at the specified value.

NOTE 8: If the injection level has not been specified, preferably set it to less than unity. A higher injection level can also be used if the injection level is accurately measured and reported. In general, a higher injection level has the advantage of better signal-to-noise ratio.