Standard Test Method for
Carrier Recombination Lifetime in Silicon Wafers by Noncontact Measurement of Photoconductivity Decay by Microwave Reflectance[1]

This standard is issued under the fixed designation F 1535; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the measurement of carrier lifetime appropriate to carrier recombination processes in homogeneously doped, polished, *n*- or *p*-type silicon wafers with room-temperature resistivity greater than about 0.05 Ω·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.

1.2 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.

1.3 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 is assumed (see Appendix X1).

1.4 This test method is appropriate for the measurement of carrier recombination lifetimes 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, lifetimes as long as tens of milliseconds can be determined in polished wafers with thickness as specified in SEMI M1.

NOTE 1—Carrier recombination lifetime of large bulk specimens can be determined by Method A or B of Test Methods F 28. 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 Test Methods F 28 stipulates that the test be carried out under conditions of low injection to ensure that the minority-carrier lifetime is determined. Minority-carrier 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 Test Methods F 391. When carried out under low injection conditions, both the SPV method and the PCD method should yield the same values of minority-carrier lifetime (1)[2] under certain conditions. First, it is required that carrier trapping 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 Test Methods F 28) 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 Test Method F 1388 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 (≥70°C) using the same MOS capacitor structure (2).

1.5 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 is discussed in the appendices. Use of "injection level spectroscopy" (3) are discussed in Appendix X1 and use of the temperature dependence of the carrier recombination lifetime as determined with low-injection level (4) is discussed in Appendix X2. 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 Test Method F 978 or from other capacitance or current transient spectroscopy techniques provided that a suitable catalog of impurity characteristics is available (5).

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the*

[2] The boldface numbers in parentheses refer to a list of references at the end of this test method.

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responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use. Specific hazard statements are given in Section 9.

2. Referenced Documents

2.1 *ASTM Standards:*

D 5127 Guide for Ultra Pure Water Used in the Electronics and Semiconductor Industry[3]

F 28 Test Methods for Minority-Carrier Lifetime in Bulk Germanium and Silicon by Measurement of Photoconductive Decay[4]

F 42 Test Methods for Conductivity Type of Extrinsic Semiconducting Materials[4]

F 84 Test Method for Measuring Resistivity of Silicon Wafers With an In-Line Four-Point Probe [4]

F 391 Test Methods for Minority Carrier Diffusion Length in Extrinsic Semiconductors by Measurement of Steady-State Surface Photovoltage[4]

F 533 Test Method for Thickness and Thickness Variation of Silicon Slices[4]

F 673 Test Method for Measuring Resistivity of Semiconductor Slices or Sheet Resistance of Semiconductor Films with a Noncontact Eddy-Current Gage[4]

F 723 Practice for Conversion Between Resistivity and Dopant Density for Boron-Doped, Phosphorus-Doped, and Arsenic-Doped Silicon[4]

F 978 Test Method for Characterizing Semiconductor Deep Levels by Transient Capacitance Techniques[4]

F 1241 Terminology of Silicon Technology[4]

F 1388 Test Methods for Generation Lifetime and Generation Velocity of Silicon Material by Capacitance-Time Measurements of Metal-Oxide-Silicon (MOS) Capacitors[4]

F 1530 Test Method for Flatness, Thickness, and Thickness Variation of Silicon Wafers by Automated Noncontact Scanning

2.2 *SEMI Standards:*

SEMI C28 Specification for Hydrofluoric Acid[5]

SEMI C35 Specification for Nitric Acid[5]

SEMI M1 Specifications for Polished Monocrystalline Silicon Wafers[5]

2.3 *Other Standards:*

DIN 50 440 Part 1 Measurement of Carrier Lifetime in Silicon Single Crystals: Carrier Recombination Lifetime at Low Injection by Photoconductivity Decay[4,6]

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *injection level*—in an extrinsic semiconductor crystal or wafer, the ratio of the density of excess carriers generated by photons or other means to the equilibrium density of majority carriers.

3.1.2 *recombination lifetime*—in a homogeneous semiconductor, the average time interval between the generation and recombination of hole-electron pairs.

3.1.2.1 *Discussion*—In the Shockley-Read-Hall model, which applies for a small density of recombination centers, the recombination lifetime for centers with energy levels that are not too close to a band edge is the minority-carrier capture time constant provided that the density of excess carriers is very small compared with the density of majority carriers (low injection). 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 Appendix X1).

3.1.3 *surface recombination velocity—in a semiconductor crystal or wafer,* a measure of the recombination of excess minority carriers at the surface of the crystal or wafer given by the ratio of the surface-directed hole or electron current to the product of the hole or electron charge and hole or electron density at the surface.

3.2 Other terms related to semiconductor technology are defined in Terminology F 1241.

4. Summary of Test Method

4.1 Excess hole-electron pairs are locally created 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 energy gap at a specified power density (injection level). The specimen surface is conditioned in such a way that surface recombination has a negligible effect on the decay of the conductivity following cessation of the light pulse. This decay is monitored by means of microwave reflectance, and the carrier recombination lifetime is determined as the time constant of the appropriate portion of the exponential conductivity decay.

4.2 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.

4.3 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.

4.4 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.

5. Significance and Use

5.1 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^3) 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.

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[3] *Annual Book of ASTM Standards,* Vol 11.01.

[4] *Annual Book of ASTM Standards,* Vol 10.05.

[5] Available from Semiconductor Equipment and Materials International, 805 E. Middlefield Rd., Mountain View, CA 94043.

[6] Available from Beuth Verlag GmbH, Burggrafenstraße 4-10, D-1000 Berlin 30, Germany.

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5.2 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 4.4) is beyond the scope of this test method.

5.3 Although the test method is generally nonselective, certain individual impurity species can be identified under very restricted conditions (see 4.3, Appendix X1 and Appendix X2).

5.4 This test method is suitable for use in research and development, process control, and materials acceptance applications. 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.

5.5 Because the precision of this test method has not yet been established by interlaboratory test, it should be used for materials specification and acceptance only after the parties to the test have established reproducibility and correlation.

6. Interferences

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

6.2 If the lifetime of the carriers is such that the carrier diffusion length is greater than 0.1 times the wafer thickness, the effects of recombination at the surfaces of the wafer must be suppressed by thermal oxidation or by immersion in a suitable electrolyte (see Section 11).

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

6.2.2 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 6.4) thus rendering the test specimen unsuitable for measurement by this test method.

6.2.3 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.

6.3 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.

6.4 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).

6.5 The recombination characteristics of impurities in silicon are strongly temperature dependent. If comparisons between measurements are to be made (that is, before and after a process step or at a supplier and a user), both measurements

should be made at the same temperature.

6.6 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.

6.7 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 Appendix X3).

7. Apparatus

7.1 *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 (Note 2). It is preferred that the output power of the light source be variable such that photon densities between 2.5 by 10^{10} and 2.5 by 10^{15} photon/cm^2 are generated at the wafer surface during the pulse.

NOTE 2—The rise and fall times of the pulsed light source and the sampling time of the signal conditioner (see 7.5) should be ≤0.1 of the shortest lifetime to be measured.

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

7.3 *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 Fig. 1). The sensitivity of the detection system shall be as great as possible to permit measurement of photoconductivity decay at low injection levels.

7.4 *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
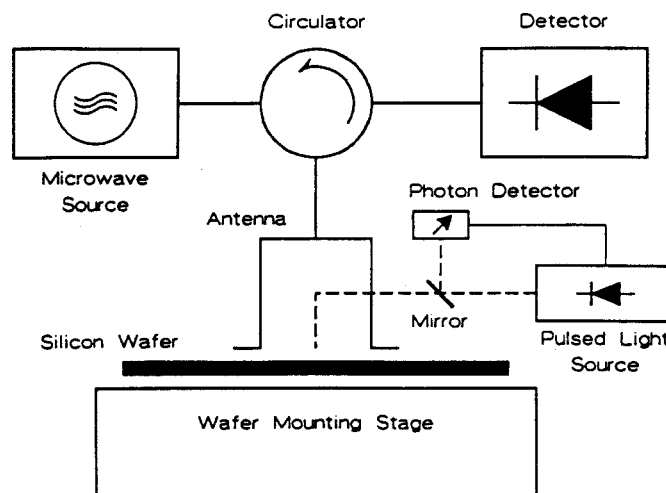

FIG. 1 Example Block Diagram of Pulsed Light and Microwave Systems

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to provide *x-y* or *r-θ* 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.

7.5 *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 (Note 2). 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.

7.6 *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.

7.7 *Facilities for Etching or Passivating Wafer Surfaces*—if required.

7.7.1 For chemical passivation:

7.7.1.1 *Fume Hood*—equipped with an acid-proof sink and suitable beakers or other containers for holding wet chemicals, including hydrofluoric acid at room temperature.

7.7.1.2 *Protective Gear*— appropriate to the chemicals used.

7.7.2 For oxidation:

7.7.2.1 *Furnace*—clean furnace capable of high quality dry oxidations at temperatures of 950° to 1050°C.

7.7.2.2 *Associated Cleaning, Drying, and Wafer Handling Facilities*.

7.8 *Wafer Holder*— if required. In some cases, it may be necessary to measure the wafer while it is immersed in a passivating solution (see Section 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.[7] 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 deionized water meeting the resistivity and impurity specifications of Type I Reagent Water in Specifications D 5127.

8.3 The recommended chemicals shall have the following nominal assays:

8.3.1 *Ethanol (CH$_3$CH$_2$OH)*, absolute, ≥99.9 %.

8.3.2 *Iodine (I$_2$)*, >99.8 %.

8.3.3 *Hydrofluoric Acid (HF)*, concentrated, 49.00 ± 0.25 %. **Warning:** see 9.3.1 for warning statement.

8.3.4 *Nitric Acid (HNO$_3$)*, concentrated, 70.0–71.0 %.

8.4 *Iodine-Ethanol Passivating Solution*—Mix 1 g iodine with 100 mL ethanol **(7)**.

NOTE 3—Other passivating solutions may be utilized provided that they (1) reduce the surface recombination velocity to a value at which surface recombination no longer interferes with the determination of the bulk recombination lifetime (see Section 11), and (2) result in stable surfaces (see 6.2.1).

8.5 *Bright Etching Solution*, for etching non-polished surfaces—Mix 95 mL concentrated HNO$_3$ with 5 mL concentrated HF. **Warning**—See 9.3.1 for warning statement.

8.6 *Dilute HF Solution*, for etching surface oxide films—To obtain 100 mL of a 2 % solution of HF, mix 4 mL concentrated HF with 96 mL of water. **Warning**—See 9.3.1 for warning statement.

9. Hazards

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

9.2 The microwave system should 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.

9.3 The chemicals used for etching and for some surface passivating solutions are potentially harmful and must be handled in an acid exhaust fume hood, with proper protective gear including safety goggles, and with utmost care at all times.

9.3.1 **Warning**—Hydrofluoric acid solutions are particularly hazardous. **Warning:** HF solutions should not be used by anyone who is not familiar with the specific preventive measures and first aid treatments given in the appropriate Material Safety Data Sheet.

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 the procedures for sampling 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 recombination lifetime 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. Test Specimen Preparation

11.1 The required test specimen preparation depends on both the surface condition of the test specimen and the expected magnitude of the bulk recombination lifetime, τ_b, to be measured.

11.2 No test specimen preparation is required if the value of

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[7] *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 *Analar 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.

τ_b is no greater than one-tenth of the surface recombination lifetime, τ_s. The surface recombination lifetime is composed of two terms, a diffusion term, τ_{diff}, which accounts for the diffusion of carriers to the surface, and a surface recombination term, τ_{sr}, which accounts for the recombination at the surface. The surface recombination lifetime may be computed from the following approximate relation (7):

$$\tau_s = \tau_{diff} + \tau_{sr} \tag{1}$$

$$= \frac{L^2}{\pi^2 D} + \frac{L}{2S}$$

where:
D = minority carrier diffusion coefficient, in cm^2/s.
L = wafer thickness, in cm, and
S = surface recombination velocity, in cm/s, assumed equal on both surfaces.

Electron and hole surface recombination lifetimes are shown in Fig. 2 as a function of surface recombination for wafers with different thickness[8] (Note 4).

NOTE 4—If S is very large (>10^4 cm/s) excess carriers recombine immediately on striking the surface so the surface recombination lifetime is dominated by τ_{diff}. A well polished surface has a surface recombination velocity of ~10^4 cm/s (7) while for an abraded (lapped) surface the surface recombination velocity is even larger (~10^7 cm/s, the carrier saturation velocity). In such cases, the maximum bulk recombination lifetime that can be measured to 10 % accuracy in wafers of standard thickness is about 1μ s for p-type wafers and about 2 μs for n-type wafers. In spite of this limitation of accurate determination of the bulk recombination lifetime, it is possible to detect relative variations of bulk recombination lifetime on unpassivated polished wafers that have bulk recombination lifetime as large as 0.5 to 1 ms provided that the following conditions are met:
(1) the diffusion coefficient and surface recombination velocity are uniform over the wafer, and
(2) the microwave system is sensitive enough to resolve measured lifetimes which differ by 1 %.
Under these same conditions, relative measurements can be made on lapped wafers with bulk recombination lifetimes up to about 100 μs. In this case, it may be necessary to etch the surfaces in bright etching solution (see 8.5) for about 1 min in order to obtain sufficient uniformity of the surface recombination velocity.

11.3 If bulk recombination lifetimes larger than about 0.1 τ_s are to be measured, the wafer surfaces must be passivated by one of the following methods (Note 5) to obtain accurate measurements.

11.3.1 *Oxidation*—Bulk recombination lifetimes up to about 1 ms can be measured on wafers ≥0.5-mm thick that have a very high quality (dry) thermal oxide (D$_{it}$< 10^{10}/ cm^2·eV). (Note 6) Ensure that the oxidation conditions are such that significant numbers of oxide precipitates do not form during the oxidation cycle (see 6.2.2). For measurement of lifetimes between about 1 ms and 10 ms, strip the oxide in dilute HF (see 8.6) and make the measurement within 15 min.
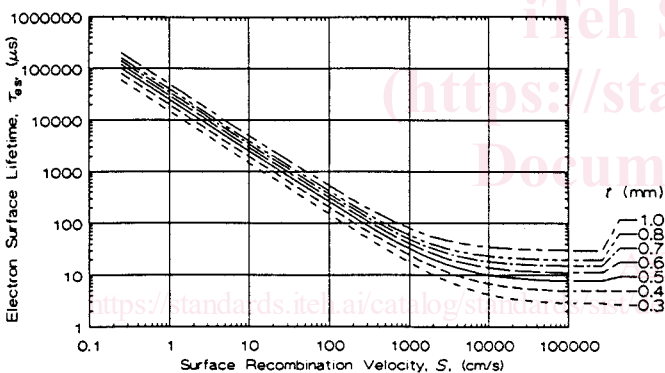
11.3.2 *Immersion in Passivating Solution*—To measure bulk recombination lifetimes up to ~1 ms on a bare polished wafer ≥0.5-mm thick, first pretreat the wafer in iodine-ethanol passivating solution (see 8.4) or an alternative passivating solution. Then enclose the wafer in a small plastic bag or other fixture containing enough of the passivating solution to coat the surface with a thin film while the measurement is being made. Ensure that the passivation technique results in stable and repeatable measurements before proceeding with the test (see 6.2.1).

11.3.2.1 If the wafer is oxidized, passivate it with iodine-ethanol, an alternative passivating solution, after first removing the oxide by etching in dilute HF solution for a time that depends on oxide thickness; etch times range from about 30 s for thin oxide (<5 nm) to about 10 min for thick oxide (~200 nm).
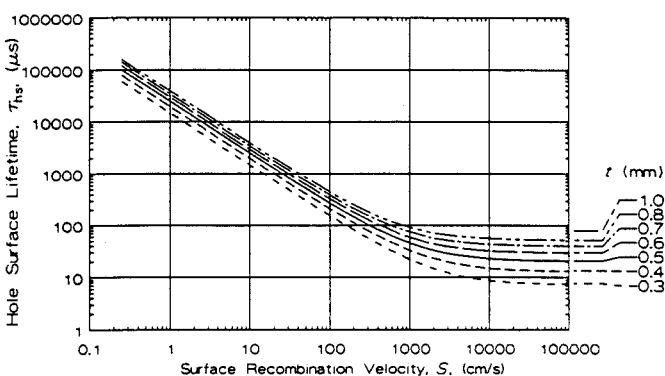
11.3.2.2 Again, ensure that the passivation technique results in stable and repeatable measurements before proceeding with the test (see 6.2.1).

NOTE 5—Polished surfaces that have been oxidized or passivated with certain chemical solutions have much reduced surface recombination

a. Electron Surface Recombination Lifetime (D_n = 33.5 cm^2/s)

b. Hole Surface Recombination Lifetime (D_p = 12.4 cm^2/s)

NOTE 1—The maximum bulk recombination lifetime that can be accurately measured is about 1/10 of the surface lifetime.

FIG. 2 Surface Recombination Lifetime as a Function of Surface Recombination Velocity for Constant Diffusion Coefficient and Selected Values of Wafer Thickness

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[8] For these estimates, the diffusion coefficients were assumed to be constant at the following limiting values: D$_n$ = 33.5 cm^2/s and D$_p$ = 12.4 cm^2/s. These values are somewhat smaller than the limiting values given in the 1993 edition of DIN 50 440, Part 1.

velocity. For example, carefully prepared thermally oxidized silicon surfaces have surface recombination velocity as low as 1.5 to 2.5 cm/s while the surface recombination velocity can be as low as 0.25 cm/s following stripping of the oxide in hydrofluoric acid **(8)**. This reference also outlines a procedure for determining surface recombination velocity. Immersion in the iodine-ethanol passivating solution (8.4) has been shown to reduce surface recombination velocity of a chemically polished, oxide-free silicon wafer to ≤10 cm/s **(7)**.

NOTE 6—The density of interface trapped charge (D_{it}) can be measured by a variety of techniques described in the literature **(9)**; however, none of these techniques has been standardized.

12. 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. In such cases, the procedures and algorithms employed must be equivalent to those given in this test method.

12.1 If they are not known, determine the conductivity type in accordance with Test Methods F 42, the center-point wafer thickness in accordance with Test Method F 533 or F 1530, and the center-point resistivity in accordance with Test Method F 84 or F 673. Convert the resistivity to the density of the majority carriers (n_{maj}, in carriers/cm^3) in accordance with Practice F 723. Record these data together with the nominal diameter and the condition (polished, etched, lapped, as-cut, etc.) of the front and back surfaces.

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

12.3 Load the wafer onto the stage so that the light pulse will strike the desired region.

12.4 Switch on the pulsed laser light source (see 7.1).

12.5 Adjust the intensity so that the injection level, η, is at the specified value. If an injection level has not been specified, set it to 100. If it is not adjusted automatically by the apparatus, set the injection level as follows:

12.5.1 If the test specimen is oxidized and the thickness of the oxide layer is not known, measure or estimate it, using a method acceptable to the parties to the test.

12.5.2 Determine the fraction of the incident light that penetrates the oxide and is absorbed by the specimen from the dashed curve in Fig. 3.

12.5.3 Adjust the light source intensity so that the photon density absorbed in the silicon during the pulse, φ, is equal to η n_{maj}, where η is the desired injection level and n_{maj} is the density of majority carriers in the wafer as determined in 12.1. The photon density, φ, in photons/cm^3, is given by:

$$\phi = \frac{f \int_0^{t_p} \phi_i \, dt}{L} \qquad (2)$$

where:
f = the fraction absorbed found from Fig. 3 (see 12.5.2),
ϕ_i = the intensity of the incident light, in photons/cm^2·s,
t_p = the length of the light pulse, in s, and
L = wafer thickness, in cm.

12.6 Turn on the microwave power source and view the photoconductivity decay on the display unit. Adjust the time and voltage scales so as to display the desired portion of the decay signal. In the absence of indications to the contrary,
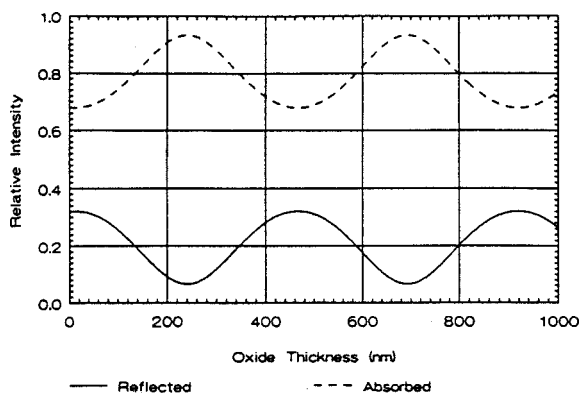
NOTE 1—For these calculations the wavelength of the incident radiation, λ, is assumed to be 905 nm, the index of refraction of silicon is taken as 3.610, and the index of refraction of SiO_2 is taken as 1.462. Maximum absorption occurs at an oxide thickness $d = (2n + 1)\lambda/4$ while minimum absorption occurs at an oxide thickness $d = n\lambda/2$, when $n = 0, 1, 2$, etc. Therefore, if the wavelength of the incident radiation, λ_1, differs from 905 nm, these curves can be used by determining the relative intensity for an effective oxide thickness $d_0 = 905 \, d_1/\lambda_1$ where d_1 is the actual thickness of the oxide.

FIG. 3 Fraction of Incident Radiation Reflected from (solid line) or Absorbed in (dashed line) a Silicon Wafer Covered with a SiO_2 Layer between 0 and 1 µm Thick

observe the decay signal from 45 to 5 % of the peak voltage.

12.7 Determine that the decay is exponential over the desired range. Determine the time constant by fitting an exponential curve to the voltage, V, as a function of time, t, or (for manual data collection) a straight line to the curve of ln V as a function of t.

12.8 Take this time constant as the recombination lifetime.

12.9 If desired, move the wafer position and repeat 12.6 through 12.8 as required to obtain a wafer map, noting the point spacing and pattern together with the radius of the mapped area.

12.10 Alternatively, if desired, repeat 12.2 and 12.6 through 12.8 at the same location for different temperatures or repeat 12.5 through 12.8 at the same location for different values of injection level.

13. Report

13.1 Report the following information:

13.1.1 Date and location of the test,

13.1.2 Operator,

13.1.3 Instrument type, model number, and, if computer controlled, software version,

13.1.4 Wafer description including any identification markings, center-point resistivity, center-point thickness, conductivity type, surface condition (front and back), and nominal diameter,

13.1.5 Portion of the decay signal from which the time constant was determined,

13.1.6 Injection level, η, as established in 12.5,

13.1.7 Surface passivation procedure used (see Section 11), and

13.1.8 Carrier recombination lifetime, τ, in µs.

13.2 If measurements were made at several injection levels, report τ for each value of η.