

SEMI MF28-0317^E (Reapproved 0622) TEST METHOD FOR MINORITY CARRIER LIFETIME IN BULK GERMANIUM AND SILICON BY MEASUREMENT OF PHOTOCONDUCTIVITY DECAY

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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 Minority carrier lifetime is one of the essential characteristics of semiconductor materials. Many metallic impurities form recombination centers in germanium and silicon; in many cases, these recombination centers are deleterious to device and circuit performance. In other cases, the recombination characteristics must be carefully controlled to obtain the desired device performance.

1.1.1 If the free carrier density is not too high, minority carrier lifetime is controlled by such recombination centers; however, because it does not distinguish the type of center present, a measurement of minority carrier lifetime provides only a nonspecific, qualitative test for metallic contamination in the material.

1.1.2 When present in sufficient quantity, free carriers control the lifetime; thus, these test methods do not provide a reliable means for establishing the presence of recombination centers due to unwanted metallic or other non-dopant impurities when applied to silicon specimens with resistivity below 1 $\Omega \cdot \text{cm}$.

1.2 This Test Method is suitable for use in research, development, and process control applications; it is not suitable for acceptance testing of polished wafers since it cannot be performed on specimens with polished surfaces.

2 Scope

2.1 This Test Method covers the measurement of minority carrier lifetime appropriate to carrier recombination processes in bulk specimens of extrinsic single-crystal germanium or silicon.

2.2 This Test Method is based on the measurement under low-level conditions of the filament lifetime of the decay of the specimen conductivity after generation of carriers with a light pulse. If the decay is exponential from the initial time, the filament lifetime is the time (in μs) between the peak or saturation of the photoconductivity voltage, ΔV_0 , and the time where the photoconductivity voltage is equal to ΔV_0 divided by e . For an exponential decay curve, this lifetime is equal to the $(1/e)$ lifetime of SEMI MF1535. However, as noted in that standard and in § 3.5 of this Standard, the initial part of the decay curve is frequently not exponential in nature so under these circumstances, the filament lifetime determined from the initial portion of the decay curve cannot be used to determine the minority carrier lifetime, which must then be determined from an exponential portion of the curve (refer to § 11.7) occurring some time into the decay. Under these circumstances, the filament lifetime is the same as the primary mode lifetime of SEMI MF1535.

2.3 The following two test methods are described:

2.3.1 *Test Method A* — Pulsed Light Method,¹ that is suitable for both silicon and germanium.

2.3.2 *Test Method B* — Chopped Light Method, that is specific to silicon specimens with resistivity $\geq 1 \Omega \cdot \text{cm}$.

¹ This Test Method is based in part on IEEE 225.

2.4 Both test methods are non-destructive in the sense that the specimens can be used repeatedly to carry out the measurement, but these methods require special bar-shaped test specimens of size (refer to Table 1) and surface condition (lapped) that would be generally unsuitable for other applications.

Table 1 Dimensions of Three Recommended Bar-Shaped Specimens

<i>Type</i>	<i>Length, mm</i>	<i>Width, mm</i>	<i>Thickness, mm</i>
A	15.0	2.5	2.5
B	25.0	5.0	5.0
C	25.0	10.0	10.0

2.5 The shortest measurable lifetime values are determined by the turn-off characteristics of the light source while the longest values are determined primarily by the size of the test specimen (refer to Table 2).

Table 2 Maximum Measurable Values of Bulk Minority Carrier Lifetime, τ_B , μs

<i>Material</i>	<i>Type A</i>	<i>Type B</i>	<i>Type C</i>
<i>p</i> -type germanium	32	125	460
<i>n</i> -type germanium	64	250	950
<i>p</i> -type silicon	90	350	1300
<i>n</i> -type silicon	240	1000	3800

2.6 Because special test specimens are required, it is not possible to perform this test directly on the material to be employed for subsequent device or circuit fabrication. Furthermore, the density of recombination centers in a crystal is not likely to be homogeneously distributed. Therefore, it is necessary to select samples carefully in order to ensure that the test specimens are representative of the properties of the material being evaluated.

NOTE 1: Minority carrier lifetime may also be deduced from the diffusion length as measured by the surface photovoltage (SPV) method made in accordance with SEMI MF391. The minority carrier lifetime is the square of the diffusion length divided by the minority carrier diffusion constant which can be calculated from the drift mobility. SPV measurements are sensitive primarily to the minority carriers; the contribution from majority carriers is minimized by the use of a surface depletion region. As a result lifetimes measured by the SPV method are often shorter than lifetimes measured by the photoconductivity decay (PCD) method because the photoconductivity can contain contributions from majority as well as minority carriers. In the absence of carrier trapping, both the SPV and PCD methods should yield the same values of lifetime² providing that the correct values of absorption coefficient are used for the SPV measurements and that the contributions from surface recombination are properly accounted for in the PCD measurement.

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3 Limitations

3.1 Carrier trapping may be significant in silicon at room temperature and in germanium at lower temperatures. If trapping of either electrons or holes occurs in the specimen, the excess concentration of the other type of carrier remains high for a relatively long period of time following cessation of the light pulse, contributing a long tail to the photoconductivity decay curve. Measurements made on this portion of the decay curve result in erroneously long time constants.

3.1.1 Trapping can be identified by increases in the time constant as the measurement is made further and further along the decay curve.

² Saritas, M., and McKell, H. D. "Comparison of Minority-Carrier Diffusion Length Measurements in Silicon by the Photoconductive Decay and Surface Photovoltage Methods." *Journal of Applied Physics* vol. 63 (1988): pp. 4562–4567.

3.1.2 Trapping in silicon may be eliminated by heating the specimen to a temperature between 50°C and 70°C or by flooding the specimen with steady background light.

3.1.3 The minority carrier lifetime should not be determined from a specimen in which trapping contributes more than 5% to the total amplitude of the decay curve (Test Method A) or in which the decay curve is non-exponential (Test Method B).

3.2 The measurement is affected by surface recombination effects, especially if small specimens are used. The specified specimen preparation results in an infinite surface recombination velocity. Corrections for surface recombination for specimens with infinite surface recombination velocity and specific recommended sizes are given in Table 3. A general formula for establishing the correction is also provided in the calculations section; use of this correction is especially important when the ratio of the surface area to volume of the specimen is large.

3.2.1 If the correction for surface recombination is too large, the accuracy of the minority carrier lifetime determination is severely degraded. It is recommended that the corrections applied to the observed decay time not exceed one-half of the reciprocal of the observed value of decay time. Maximum bulk lifetimes that can be determined on the standard bar-shaped specimens are listed in Table 2.

3.3 The conductivity modulation in the specimen must be very small if the observed decay, that is actually the decay of the potential across the specimen, is to be equal to the decay of the photoinjected carriers.

Table 3 Surface Recombination Rate, R_s , μs^{-1}

<i>Material</i>	<i>Type A</i>	<i>Type B</i>	<i>Type C</i>
<i>p</i> -type germanium	0.03230	0.00813	0.00215
<i>n</i> -type germanium	0.01575	0.00396	0.00105
<i>p</i> -type silicon	0.01120	0.00282	0.00075
<i>n</i> -type silicon	0.00420	0.00105	0.00028

3.3.1 Test Method A allows the use of a correction when the maximum modulation of the measured direct current voltage across the specimen, $\Delta V_0/V_{dc}$, exceeds 0.01.

3.3.2 Test Method B does not permit the use of this correction. In this test method, the condition for low-level photoinjection is that the ratio of the density of injected minority carriers in the specimen that exists in the steady state under constant illumination to the equilibrium majority carrier density be less than 0.001 (refer to ¶ 12.10). If the photoinjection cannot be reduced to a low-level value, the specimen is not suitable for measurement by this Test Method.

3.4 Inhomogeneities in the specimen may result in photovoltages that distort the photoconductivity decay signal. Tests for the presence of photovoltages are provided in both test methods (refer to ¶¶ 11.5 and 12.6). Specimens that exhibit photovoltages in the absence of current are not suitable for minority carrier lifetime measurement by these test methods.

3.5 Higher mode decay of photoinjected carriers can influence the shape of the decay curve, particularly in its early phases.³ This phenomenon is more significant when a pulsed light source is used because the initial density of injected carriers is less uniform than when a chopped light source is used. Consequently, Test Method A requires the use of a filter (to increase the uniformity of the injected carrier density) and measurement of the decay curve after the higher modes have died away to establish the filament lifetime.

3.6 If minority carriers are swept out of an end of the specimen by the electric field generated by the current, they do not contribute to the decay curve. Both test methods require the use of a mask to shield the ends of the specimen from illumination and have tests to ensure that sweep-out effects are not significant.

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

3.7 The recombination characteristics of impurities in semiconductors are strongly temperature dependent. Consequently, it is essential to control the temperature of the measurement. If comparisons between measurements are to be made, both measurements should be made at the same temperature.

3.8 Different impurity centers have different recombination characteristics. Therefore, if more than one type of recombination center is present in the specimen, the decay may consist of two or more exponentials with different time constants. The resulting decay curve is not exponential; a single minority carrier lifetime value cannot be deduced from photoconductivity decay measurements on such a specimen.

4 Referenced Standards and Documents

4.1 SEMI Standards and Safety Guidelines

SEMI M59 — Terminology for Silicon Technology

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

SEMI MF43 — Test Method for Resistivity of Semiconductor Materials

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

SEMI MF1535 — Test Method for Carrier Recombination Lifetime in Silicon Wafers by Noncontact Measurement of Photoconductivity Decay by Microwave Reflectance

4.2 ASTM Standards⁴

ASTM D5127 — Guide for Ultra-Pure Water Used in the Electronics and Semiconductor Industries

4.3 IEEE Standards⁵

IEEE 225 — Measurement of Minority-Carrier Lifetime in Germanium and Silicon by the Method of Photoconductive Decay

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

5 Terminology

5.1 Terms relating to silicon and other semiconductor technology are defined in SEMI M59.

6 Summary of Test Methods

6.1 Test Method A

6.1.1 By means of ohmic contacts at each end, direct current is passed through a bar-shaped homogeneous monocrystalline semiconductor specimen with lapped surfaces.

6.1.2 The voltage drop across the specimen is observed on an oscilloscope.

6.1.3 Excess carriers are created in the specimen for a very brief time by a short pulse of light with energy near the energy of the forbidden gap.

6.1.4 An oscilloscope trace is triggered by the light pulse and the time constant of the voltage decay following cessation of the light pulse is measured from the oscilloscope trace.

6.1.5 If the conductivity modulation of the specimen is very small, the observed voltage decay is equivalent to the decay of the photoinjected carriers. Thus the time constant of the voltage decay is equal to the time constant of excess carrier decay.

6.1.6 The minority carrier lifetime is determined from this time constant; trapping effects are eliminated and corrections are made for surface recombination and excess conductivity modulation, as required.

⁴ ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, USA; Telephone: +1.610.832.9585, Fax: +1.610.832.9555, <http://www.astm.org>

⁵ *Proceedings IRE* vol. 49 (1961): pp. 1292–1299.

6.2 Test Method B

6.2.1 This test method, that is specific to silicon, is similar to Test Method A except that the excess carriers are generated by a chopped rather than a pulsed light source.

6.2.2 The wavelength of the light is specified to be between $1.0\ \mu\text{m}$ and $1.1\ \mu\text{m}$. In addition, it is required that low-injection-level conditions are employed so that excess conductivity modulation effects are avoided. Special contacting procedures are given to ensure the formation of ohmic contacts, and signal conditioning may be employed before the oscilloscope.

6.2.3 Correction for surface recombination is required.

6.2.4 Test specimens that yield non-exponential signals under the conditions of the test are deemed to be unsuitable for the measurement.

7 Apparatus (refer to Figure 1)

7.1 *Light Source* — Pulsed (Test Method A) or chopped (Test Method B) light source. The turn-off time of the light source must be such that the light intensity decreases to 10% of its maximum value or less in a time less than 0.2 times the filament lifetime of the specimens to be measured. The maximum of the spectral distribution of the light source shall lie in the wavelength range $1.0\ \mu\text{m}$ to $1.1\ \mu\text{m}$ for measurement of silicon specimens.

NOTE 2: Turn-off times less than $1\ \mu\text{s}$ may be measured by performing either procedure of these test methods on a filament of silicon $0.1\ \text{mm}$ thick and with length and width $\geq 10\ \text{mm}$ and $\geq 4\ \text{mm}$, respectively, or by performing the procedure of Test Method A on a filament of germanium 0.25-mm thick and with length and width $\geq 10\ \text{mm}$ and $\geq 4\ \text{mm}$, respectively. If all surfaces of the filament are lapped, either filament has a filament lifetime of less than $1\ \mu\text{s}$ regardless of the bulk minority carrier lifetime of the specimen.

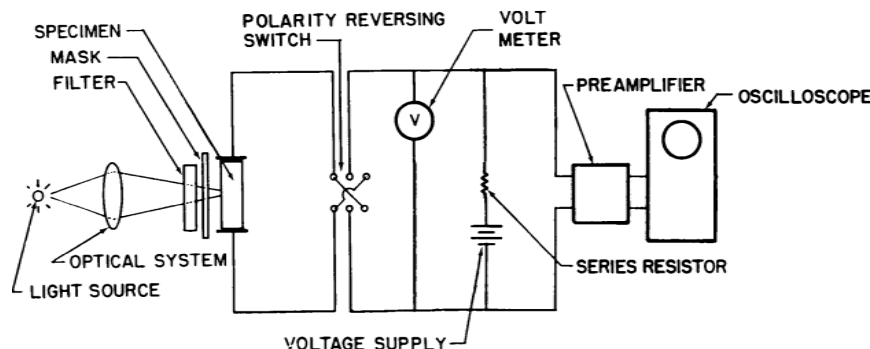


Figure 1
Schematic Circuit Arrangement for Minority Carrier Lifetime Measurement

7.1.1 *Test Method A: Xenon Flash Tube or Spark Gap* — With a capacitor and high voltage power supply with a pulse repetition rate of 2 to $60\ \text{s}^{-1}$. With a $0.01\ \mu\text{F}$ capacitor charged to several thousand volts, a bright discharge is obtained; maximum intensity is reached within $0.3\ \mu\text{s}$ and the intensity decreases to less than 5% of its maximum value in less than $0.5\ \mu\text{s}$. To measure filament lifetimes less than $5\ \mu\text{s}$, it is preferable to use a smaller capacitor for a shorter pulse duration, even though the resulting total available light flux is smaller.

7.1.2 *Test Method B: Light Source with Pulse Generator*⁶ — For the creation of a periodic rectangular light pulse. The pulse amplitude, pulse height and pulse interval must be separately adjustable. The adjustment range of the pulse length and interval shall be at least $5\ \mu\text{s}$ to $20\ \text{ms}$, respectively. The maximum radiative power from the source shall be sufficiently large that the measured signal is at least $1\ \text{mV}$. The time constants of both the rising and falling edges of the light pulse shall be less than 0.2 times the shortest filament lifetime to be measured. The pulse generator must supply a trigger signal for the subsequent signal conditioner and oscilloscope.

⁶ Graff, K., Piefer, H., and Goldbach, G. "Carrier Lifetime Doping of *p*-Type Silicon by Annealing Processes." *Semiconductor Silicon*, 1973, Huff, H. H., and Burgess, R. R., eds., *The Electrochemical Society*, 1973, pp. 170–178.