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AMERICAN SOCIETY FOR TESTING AND MATERIALS
100 Barr Harbor Dr., West Conshohocken, PA 19428
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Standard Test Methods for Minority-Carrier Lifetime in Bulk Germanium and Silicon by Measurement of Photoconductivity Decay[1]

This standard is issued under the fixed designation F 28; 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 These test methods cover the measurement of minority carrier lifetime appropriate to carrier recombination processes in bulk specimens of extrinsic single-crystal germanium or silicon.

1.2 These test methods are based on the measurement of the decay of the specimen conductivity after generation of carriers with a light pulse. The following two test methods are described:

1.2.1 *Test Method A*—Pulsed Light Method, that is suitable for both silicon and germination.[2]

1.2.2 *Test Method B*—Chopped Light Method, that is specific to silicon specimens with resistivity ≥1 Ω·cm.[3]

1.3 Both test methods are nondestructive 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 (see Table 1) and surface condition (lapped) that would be generally unsuitable for other applications.

1.4 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 (see Table 2).

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 Test Methods F 391. 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 lifetime **(1)**[4] 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.

TABLE 1 Dimensions of Three Recommended Bar-Shaped Specimens

Type	Length, mm	Width, mm	Thickness, mm
A	15.0	2.5	2.5
B	25.0	5.0	5.0
C	25.0	10.0	10.0

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

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

1.5 *This standard does not purport to address all of the safety concerns, 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 limitations prior to use.* Specific hazard statements are given in Section 9.

2. Referenced Documents

2.1 *ASTM Standards:*

D 1125 Test Method for Electrical Conductivity and Resistivity of Water [5]

F 42 Test Method for Conductivity Type of Extrinsic Semiconducting Materials [6]

F 43 Test Method for Resistivity of Semiconductor Materials [6]

F 391 Test Methods for Minority Carrier Diffusion Length in Extrinsic Semiconductors by Measurement of Steady-State Surface Photovoltage[6]

2.2 *Other Standards:*

DIN 50440/1 Measurement of Carrier Lifetime in Silicon Single Crystals by Means of Photoconductive Decay: Measurement on Bar-Shaped Test Specimens [3]

[1] These test methods are under the jurisdiction of ASTM Committee F-1 on Electronicsand are the direct responsibility of Subcommittee F01.06 on Silicon Materials and Process Control.

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[2] This test method is based in part on IEEE Standard 225, Proceedings IRE, Vol 49, 1961, pp. 1292–1299.

[3] DIN 50440/1 is an equivalent test method. It is the responsibility of DIN Committee NMP 221, with which Committee F-1 maintains close liaison. DIN 50440/1, is available from Beuth Verlag GmbH, Burggrafenstrasse 4-10, D-1000 Berlin 30, FRG.

[4] The boldface numbers in parenthesis refer to a list of references at the end of these test methods.

[5] Annual Book of ASTM Standards, Vol 11.01.

[6] Annual Book of ASTM Standards, Vol 10.05.

IEEE Standard 225 Measurement of Minority-Carrier Lifetime in Germanium and Silicon by the Method of Photoconductive Decay [2]

3. Terminology

3.1 *Definitions:*

3.1.1 *minority carrier lifetime— of a homogeneous semiconductor*, the average time interval between the generation and recombination of minority carriers.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *filament lifetime*—the time constant, τ_F, (in µs) of the decay of the photoconductivity voltage, as defined by:

$$\Delta V = \Delta V_0 \exp(-t/\tau_F)$$

where:

ΔV = the photoconductivity voltage (V),
ΔV_0 = the peak or saturation value of the photoconductivity voltage (V), and
t = time (µs).

4. Summary of Test Methods

4.1 *Test Method A*—By means of ohmic contacts at each end, direct current is passed through a bar-shaped homogeneous monocrystalline semiconductor specimen with lapped surfaces. The voltage drop across the specimen is observed on an oscilloscope. 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. 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. 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. 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.

4.2 *Test Method B*—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. The wavelength of the light is specified to be between 1.0 and 1.1 µm. 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. Correction for surface recombination is required. Test specimens that yield non-exponential signals under the conditions of the test are deemed to be unsuitable for the measurement.

5. Significance and Use

5.1 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.

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

5.1.2 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 Ω·cm.

5.2 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.

5.3 These test methods are suitable for use in research, development, and process control applications; they are not suitable for acceptance testing of polished wafers since they cannot be performed on specimens with polished surfaces.

6. Interferences

6.1 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.

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

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

6.1.3 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).

6.2 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.

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

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

6.2.1 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.

6.3 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.

6.3.1 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.

6.3.2 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 (see 12.10). If the photoinjection cannot be reduced to a low-level value, the specimen is not suitable for measurement by this test method.

6.4 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 (see 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.

6.5 Higher mode decay of photoinjected carriers can influence the shape of the decay curve, particularly in its early phases **(2)**. 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.

6.6 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.

6.7 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.

6.8 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.

7. Apparatus (see Fig. 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 ⅕ or less of 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 to 1.1 µm for measurement of silicon specimens.

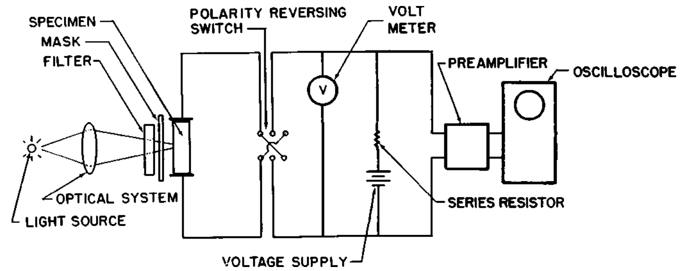

FIG. 1 Schematic Circuit Arrangement for Minority Carrier Lifetime Measurement

NOTE 2—Turn-off times less than 1 µs may be measured by performing either procedure of these test methods on a filament of silicon 0.1 mm thick and with length and width ≥10 mm and ≥4 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 ≥ 10 mm and ≥ 4 mm, respectively. If all surfaces of the filament are lapped, either filament has a filament lifetime of less than 1 µs regardless of the bulk minority carrier lifetime of the specimen.

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 s^{-1}. With a 0.01 µF capacitor charged to several thousand volts, a bright discharge is obtained; maximum intensity is reached within 0.3 µs and the intensity decreases to less than 5 % of its maximum value in less than 0.5 µs. To measure filament lifetimes less than 5 µs, 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* **(3)**, 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 µs to 20 ms. The maximum radiative power from the source shall be sufficiently large that the measured signal is at least 1 mV. The time constants of both the rising and falling edges of the light pulse shall be less than ⅕ of the shortest filament lifetime to be measured. The pulse generator must supply a trigger signal for the subsequent signal conditioner and oscilloscope.

NOTE 3—The preferred light source with these characteristics is a silicon-doped gallium arsenide light emitting diode (LED). The turn-off time of this type of diode is about 0.1 µs; this turn-off time cannot be measured by the procedure given in Note 2. A6-V, 8-A tungsten ribbon filament lamp chopped mechanically at 15, 45, or 77 Hz has also been found to be suitable for measurement of filament lifetimes ≥5 µs **(4)**.

7.2 *Regulated, Well-Filtered Current Supply*, for providing a direct current through the specimen sufficient to develop a direct current voltage of up to 5 V across the specimen. This supply may take the form of a constant current source or, alternatively, a constant voltage source in combination with a nonreactive series resistance, R_s, that is at least 20 times as