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AMERICAN SOCIETY FOR TESTING AND MATERIALS
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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 $\geq 1\ \Omega\cdot$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 ⅕or 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.

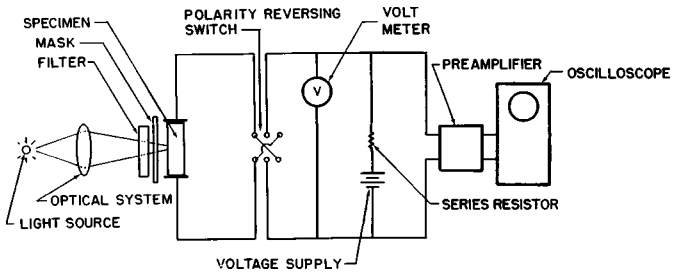

FIG. 1 Schematic Circuit Arrangement for Minority Carrier Lifetime Measurement

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 ⅕of 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

large as the sum of the specimen resistance, R, and the contact resistances, R_c. There shall be provision for reversing the polarity of the current through the specimen and also provision for disconnecting the current supply from the specimen.

7.3 *Thermally Insulated Specimen Holder and Thermostat*, that permit the specimen to be held at a constant temperature of 27 ± 1°C. The specimen holder must be made so that ohmic (nonrectifying) contacts can be made over the entire end surfaces of the specimen and that at least one of the four side surfaces of the specimen can be illuminated by the light source by means of a light pipe or other optical system. Means for determining the temperature of the specimen holder must be provided.

NOTE 4—Thermostatic temperature control is recommended but not required for Test Method A.

NOTE 5—Many methods may be used for making ohmic contacts to the ends of the test specimen. It is recommended that pressure contacts of metal braid or wool be used. Thick sheets of lead or indium have also been found to be suitable.

7.4 *Filter*, polished on both sides, 1 mm thick of the same material as the test specimen. Required for Test Method A only; placed immediately above the rectangular aperture (see 7.5).

7.5 *Rectangular Aperture*, placed as closely as possible to the illuminated specimen surface. The opening of the aperture is such that the light illuminates only a part of the length of the specimen. The illuminated portion of the specimen is of length $l_I = l/2$ and width $w_I = w/2$ for Test Method A and length $l_I = 3.0 \pm 0.1$ mm and width $w_I = w$ for Test Method B. For both test methods, the illuminated portion is centered on the midpoint of the specimen.

7.6 *Electronic Signal Measuring Circuit*:

7.6.1 *Preamplifier*, with adjustable high and low bandpass limits. The low cutoff frequency should be adjustable from 0.3 to 30 Hz.

7.6.2 *Signal Conditioner*—A boxcar averager or waveform educator for improvement of the signal-to-noise ratio of small signals. Required only for Test Method B and then only if it is necessary to reduce the illumination level to ensure that the low-injection-level condition is met.

7.6.3 *Oscilloscope*, with suitable time sweep and signal sensitivity. The oscilloscope shall have a continuously calibrated time base with accuracy and linearity better than 3 % and be capable of being triggered by the signal being studied or by an external signal. It shall be fitted with a transparent screen to aid in analyzing the decay curve, as follows:

7.6.3.1 For Test Method A, the screen is ruled in centimetre squares in such a manner as to minimize parallax. The screen also contains a curve, the height of which above the base line decays exponentially with distance along the abscissa in accordance with the following equation:

$$y = 6 \exp(-x/2.5)$$

where:

x and y are in scale divisions (see Fig. 2).

7.6.3.2 For Test Method B, the screen contains an additional horizontal line at 0.37 of the maximum *y*-value.

NOTE 6—If desired, an *X-Y* or *X-t* recorder may also be used for signal recording in Test Method B.

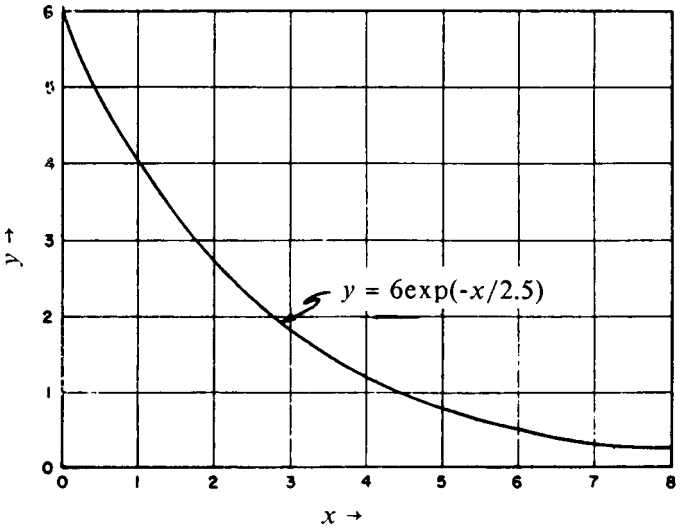

FIG. 2 Exponential Curve to be Fitted on the Oscilloscope Face for Test Method A

7.6.4 The requirements for the electronic circuit, taken as a whole, are as follows:

7.6.4.1 Calibrated vertical deflection sensitivity of 0.1 mV/cm or better.

7.6.4.2 Vertical gain and deflection linear to within 3 %.

7.6.4.3 Response time such that if the input signal changes in a step-wise fashion, the rise- or fall-time of the output signal shall be less than ⅕of the smallest filament lifetime to be measured.

7.6.4.4 No visible pulse deterioration such as overshoot or damping effects.

7.7 *Lapping Facilities*, to provide flat, parallel, abraded surfaces on all sides of the test specimen.

7.8 *Facilities for Cleaning and Drying the Test Specimen*—Cleaning may require ultrasonic agitation in water; drying should be done with dry nitrogen.

7.9 *Micrometer or Vernier Caliper*, to determine the dimensions of the test specimen to ±0.1 mm or better.

8. Reagents and Materials

8.1 *Purity of Water*—Reference to water shall be understood to mean deionized water having a resistivity >2 MΩ·cm at 25°C as determined by the nonreferee method of Test Methods D 1125.

8.2 *Lapping Abrasive*—Aluminum oxide powder commercially specified as having a size in the range from 5 to 12 µm.

8.3 *Materials for Forming Ohmic Contacts*—Nickel, rhodium, or gold plating baths, uncontaminated by copper, may be required for forming ohmic contacts on the ends of the specimens. For silicon specimens a droplet of gallium on an emery cloth may be required. If gallium is used, a hot plate for heating the specimen to 35°C is also required.

9. Hazards

9.1 The high voltages used in the power supply for the pulsed light source are dangerous; suitable care should be taken in connecting and operating them. In particular, the associated capacitor may remain charged for some time after turning off

the power supply; it should be discharged completely before making any changes or adjustments to the circuit.

9.2 Constant current supplies are capable of producing high output voltages if not connected to an external circuit. Therefore, any changes of circuits connected to the constant current supply should be made either with the current supply turned off or with its output short circuit.

9.3 Mechanical choppers can be hazardous to fingers and loose clothing. Any mechanical chopper used in the apparatus setup should be suitably shielded.

10. Sampling and Test Specimens

10.1 Because the concentration of recombination centers in a crystal may be nonuniform, select samples carefully so that they are representative of the characteristics of the crystal to be evaluated.

10.2 Cut test specimens from the desired region of the crystal in the form of rectangular parallelepipeds of length *l*, thickness *t*, and width *w* , as listed in Table 1; for Test Method B, only Types B and C are recommended. Measure and record all dimensions to the nearest 0.1 mm.

NOTE 7—Smaller size specimens are suitable for testing materials with lower values of lifetime. Type B is suitable for measurements on most Czochralski silicon while Type C is recommended for measurements on float zone silicon.

10.3 Immediately prior to the measurement, lap all six faces of the test specimen to produce a smooth matte finish using aluminum oxide of size from 5 to 12 µm.

10.4 After lapping, rinse the specimen in a vigorous stream of water or in an ultrasonic water bath and dry by blowing off with dry nitrogen. Make certain that all lapping residues are removed from the end surfaces of the specimen so that good contact may be achieved over the entire area of each end surface.

10.5 Make ohmic (nonrectifying) contacts over the entire surfaces of the two ends of the specimen.

NOTE 8—It is recommended that the ends of germanium specimens shall be plated with either nickel, rhodium, or gold. Copper shall be avoided in the plating operation. The preferred method for achieving ohmic contacts on silicon is to heat the specimen to 35°C and rub the end against a gallium droplet on an emery cloth to form a gallium smear. Nickel plating on the ends of *n*-type silicon specimens and rhodium plating on the ends of *p*-type silicon specimens are also satisfactory.

10.6 If not known, determine the conductivity type of the test specimen in accordance with Test Method F 42.

10.7 Test the contacts.

10.7.1 Place the specimen in the specimen holder and pass current through it in one direction to produce a voltage between 2 and 5 V. Record the voltage drop across the specimen as V_1.

10.7.2 Reverse the current and record the voltage drop across the specimen as V_2.

10.7.3 Accept the specimen as having ohmic contacts if V_1 and V_2 are equal to within 5 %.

10.8 Measure and record the resistivity of the specimen corrected to 27°C in accordance with the Two-Probe Method of Test Method F 43.

11. Procedure for Test Method A—Pulsed Light Method

11.1 Clamp the specimen in the specimen holder and position the aperture so that the central portion of the specimen is exposed to the illumination. Measure and record the temperature of the specimen holder to ± 1°C.

11.2 Switch on the light source, and connect the preamplifier and oscilloscope.

11.3 Connect the current supply and adjust the current so that a voltage of 2 to 5 V appears across the specimen.

11.4 Make the observed decay curve coincident with the reference exponential curve drawn on the transparent screen of the oscilloscope (see 7.6.3.1) by the following procedure:

11.4.1 Adjust the vertical shift control to bring the base line of the observed decay curve together with the base line of the reference exponential curve. Adjust the time-base-sweep-speed to a slow value so that the screen width encompasses many lifetimes and thus facilitate the adjustment.

11.4.2 Expand the time base to produce a single-cycle trace. Adjust the horizontal shift, vertical amplification, and time-base-sweep-speed controls until the observed decay curve matches the reference exponential curve as closely as possible with the peak value of the pulse amplitude, ΔV_0, aligned with the upper left point on the reference curve.

11.5 Verify that the specimen does not have inhomogeneities that cause a photovoltage. Switch off the current source, leaving the light source on and the other controls unchanged. Observe whether a photovoltage signal can be detected on the oscilloscope. If a signal greater than 1 % of the peak value of the pulse can be detected, record the specimen as being unsuitable for testing by this test method because of the presence of inhomogeneities.

11.6 If no photovoltage signal is observed and if the decay is purely exponential, then determine the filament lifetime, τ_F, inµ s by the following equation:

$$\tau_F = 2.5 \cdot S_1$$

where:

S_1 = time-base-sweep speed in µs/cm.

NOTE 9—If an oscilloscope with a continuously calibrated time base is not available, the reference exponential decay curve cannot be utilized, but the filament lifetime may be found as follows: Turn the time-base-sweep speed to a convenient calibrated value, S_2 µs/cm, measure the horizontal distance, M, in centimetres, between any two points on the decay curve whose amplitudes are in the ratio of 2:1, and calculate the filament lifetime from the following equation:

$$\tau_F = 1.44\ M S_2$$

This procedure may also be used if the transparent screen (see 7.6.3.1) is not available.

11.7 When the observed decay curve is not purely exponential, but approaches this condition, determine the filament lifetime from several pairs of points at the lower end of the decay curve.

11.7.1 If half or less of the specimen width is illuminated, determine the filament lifetime from the portion of the curve after the photoconductivity voltage signal has decayed to 60 % of its peak value.

11.7.2 If more than half of the specimen width is illuminated, determine the filament lifetime for the portion of the curve after the photoconductivity voltage signal has decayed to 25 % of its peak value.

11.7.3 In either case, increase the vertical gain control to expand the decay curve so that the desired portion fills the entire vertical scale of the screen. Adjust the time-base-sweep speed to a convenient calibrated value, S_2 μs/cm, for which the desired portion of the decay curve fills as much as possible of the horizontal scale of the screen, measure the horizontal distance, M, in centimetres, between two points on the decay curve whose amplitudes are in the ratio of 2:1, and calculate the filament lifetime from the following equation:

$$\tau_{F1} = 1.44\, M\, S_2$$

Repeat this procedure at least two more times to obtain τ_{F2}, τ_{F3}, etc.

11.7.4 Determine and record the average filament lifetime τ_F as the average of the τ_{Fi}. If the values τ_{Fi} differ by more than 10 %, do not record an average value but report the specimen as being unsuitable for measurement by this test method.

NOTE 10—In the case of *p*-type silicon, in particular, the lifetime can be a very rapid function of the injected carrier density and the error involved in taking a wide-range average may be large.

11.8 Check for the existence of trapping by noting any variation in filament lifetime values as determined from points on the portion of the decay curve below 25 % of its peak value,ΔV_0. If the lifetime values increase as the measurement is made farther down the curve, trapping is present; eliminate the effect of trapping by heating the specimen to 50 to 70°C or by flooding it with a steady background light. If trapping contributes more than 5 % to the total amplitude of the decay curve, report the specimen as unsuitable for measurement by this method because of trapping effects.

11.9 Verify that carriers are not being swept out at the ends of the specimen.

11.9.1 Switch off or block the light source and measure the direct current voltage, V_{dc}, across the specimen.

11.9.2 Calculate the product of V_{dc} and $\sqrt{\tau_F}$. If this product is greater than or equal to the constant given in Table 4 for the material and specimen type being tested, proceed to 11.10; the sweep-out condition is met.

NOTE 11—The constants given in Table 4 are for specimens of recommended length. If specimens of other lengths are used, the condition is given by the following:

$$V_{dc} \cdot \sqrt{\tau_F} \leq 30l/\sqrt{\mu},$$

where:

l = length of specimen in mm,
μ = mobility of minority carrier in $cm^2/V \cdot s$ (see Table 4), and
τ_F = filament lifetime in μs.

11.9.3 If the sweep-out condition is not met, reduce V_{dc} by decreasing the current through the specimen.

11.9.4 Since this changes the shape of the decay curve, and therefore the value of τ_F, repeat the procedure from 11.4 through 11.9.3 until the value of τ_F is constant and the sweep-out condition is met.

TABLE 4 Minority Carrier Mobilities, $cm^2 \cdot V \cdot s$, and Test Method A Sweep-Out Condition Constants for Recommended Specimen Lengths

Material	Mobility	Type A	Types B and C
p-type germanium	3800	7.3	12
n-type germanium	1800	11	18
p-type silicon	1400	12	20
n-type silicon	470	20	35

11.10 Establish whether the low-injection-level condition is met.

11.10.1 With the same current used to establish that the sweep-out condition is met, switch on the light and measure the peak value of the pulse amplitude, ΔV_0.

11.10.2 If $\Delta V_0/V_{dc} \leq 0.01$, proceed to the calculations section; the injection level is low enough for this test method.

11.10.3 If $\Delta V_0/V_{dc} > 0.01$, correct the filament lifetime in accordance with the following equation:

$$\tau_F = \tau_{F\,meas}\,[1 - (\Delta V_0/V_{dc})]$$

where:

$\tau_{F\,meas}$ = the value of filament lifetime as measured in 11.6 or as calculated in 11.7.4, and
τ_F = the corrected value of filament lifetime.

12. Procedure for Test Method B—Chopped Light Method

12.1 Clamp the specimen in the specimen holder and position the aperture so that the central portion of the specimen is exposed to the illumination. Verify that the temperature of the specimen holder is 27± 1°C; record the temperature.

12.2 Switch on the light source, and connect the preamplifier and oscilloscope.

12.3 Connect the current supply and adjust the current so that a voltage of 2 to 5 V appears across the specimen. Adjust the amplitude of the pulse and the oscilloscope vertical gain and time-base-sweep-speed controls so that a signal with several periods is seen on the oscilloscope.

12.4 Adjust the pulse duration so that the pulse amplitude reaches its saturation value, ΔV_0, before switching off and adjust the pulse off-time so that the signal reaches the base line (direct current voltage value) between the pulses.

12.5 Adjust the oscilloscope time-base-sweep-speed control and the current and pulse amplitude so that the trace of a single period with large amplitude is seen on the oscilloscope. Do not allow the direct current voltage to exceed 5 V. Adjust the oscilloscope vertical-shift control to bring the base line in coincidence with the desired scale marking on the oscilloscope screen. Readjust the other controls as needed until the trace fills the screen (see Fig. 3).

12.6 Switch off the current source, leaving the light source on and the other controls unchanged. Observe whether a photovoltage signal can be detected on the oscilloscope. If a signal greater than 1 % of the saturation value of the pulse can be detected, record the specimen as being unsuitable for testing by this test method because of the presence of inhomogeneities.

12.7 If no photovoltage signal is observed, determine a first approximation to the filament lifetime, τ_F, as the time between the beginning of the decay of the photoconductivity signal and the point on the decay curve where the photoconductivity signal is 0.37 of the saturation value.

12.8 Increase the low frequency cutoff of the preamplifier (up to a value $10/\tau_F$) so that low frequency noise is eliminated. Do not increase the low frequency cutoff to the point that the decay curve shows a positive increase.

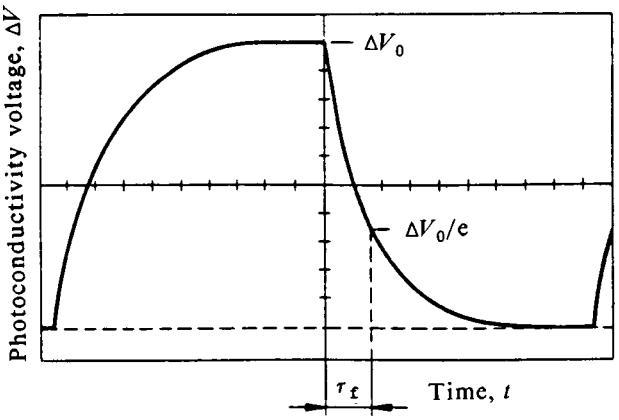

FIG. 3 Oscillogram of One Period of the Photoconductivity Voltage for Test Method B

12.9 Establish that carriers are not being swept out at the ends of the specimen **(5)**.

12.9.1 Switch off or block the light source and measure the direct current voltage, V_{dc}, across the specimen.

12.9.2 If the sweep-out condition is met (that is, $V_{dc} \leq 1170/\tau_F$ for *n*-type silicon or $V_{dc} \leq 390/\tau_F$ for *p*-type silicon), proceed to 12.10.

NOTE 12—The constants given in 12.9.2 are for specimen sizes B and C and the illumination length (3.0 mm) specified in 7.5. If specimens of other dimensions are employed the condition is given by the following equation:

$$V_{dc} \leq (10^6 \cdot l_c \cdot l)/(500 \cdot \mu \cdot \tau_F)$$

where:

l_c = distance between the illuminated probe area and the negative contact (for n-type silicon) or the positive contact (for p-type silicon), mm,
l = length of specimen, mm,
μ = mobility of minority carrier, $cm^2/V \cdot s$ (see Table 4), and
τ_F = filament lifetime, μs.

12.9.3 If the sweep-out condition is not met, reduce V_{dc} by decreasing the current through the specimen.

12.9.4 Since this changes the shape of the decay curve, and therefore the value of τ_F, repeat the procedure from 12.7 through 12.9.3 until the value of τ_F is constant and the sweep-out condition is met.

NOTE 13—If the illuminated portion of the length of the specimen is located asymmetrically with respect to the center (for example, with one end of the illuminated region located at the center of the specimen), the sweep-out condition is met if the measured value of τ_F is not changed by more than 5 % when the polarity of the current through the specimen is reversed.

12.10 Establish that the low-injection-level condition is met.

12.10.1 With the same current used to establish that the sweep-out condition is met, switch on the light and measure the saturation value of the photoconductivity voltage, ΔV_0.

12.10.2 If the low-injection-level condition is met (that is, $\Delta V_0/V_{dc} \leq 1.6 \times 10^{-4}$ for *n*-type silicon and $\Delta V_0/V_{dc} \leq 4.8 \times 10^{-4}$ for *p*-type silicon), proceed to 12.11.

NOTE 14—The constants given in 12.10.2 are for specimen sizes B and C and the illumination length (3.0 mm) specified in 7.5. If specimens of other dimensions are employed, the low-injection-level condition is given by the following equation:

$$(\Delta V_0/V_{dc}) \leq 10^{-3} \cdot [1 + (\mu_{min}/\mu_{maj})] \cdot (l_l/l)$$

where:

μ_{min} = the mobility of the minority carrier, $cm^2/V \cdot s$, and
μ_{maj} = the mobility of the majority carrier, $cm^2/V \cdot s$.

12.10.3 If the low-injection-level condition is not met, reduce the intensity of the light.

12.10.4 Repeat the procedure from 12.8 through 12.10.3 until the low-injection-level condition is met.

NOTE 15—When the intensity of the light must be reduced, it is recommended to use the signal conditioner (see 7.6.2) to improve the signal-to-noise ratio.

12.11 When both the sweep-out and low-injection-level conditions have been met, adjust the oscilloscope time-base-sweep-speed control so that end of the light pulse is seen on the screen.

NOTE 16—The time-base-sweep required for this is about 5 to 10 times the initial estimate of τ_F.

12.12 Measure and record the amplitudes and associated decay times of at least five points on the decay curve at equidistant intervals between $0.9 \cdot \Delta V_0$ and $0.1 \cdot \Delta V_0$.

12.13 Rotate the specimen by 90° and allow the specimen to reach temperature equilibrium at 27 ± 1°C.

12.14 Under the same measurement conditions as before but in the new position, measure the amplitudes and associated decay times of at least five points on the decay curve at equidistant intervals between $0.9 \cdot \Delta V_0$ and $0.1 \cdot \Delta V_0$.

12.15 For each position of the specimen, plot the amplitudes against the corresponding times on a semi-logarithmic scale ($\log \Delta V = f(t)$).

12.16 If the resulting graph shows a linear decay, proceed to 12.17. Otherwise report the specimen as not being suitable for determination of carrier lifetime by this test method.

12.17 If a linear decay is obtained, determine the filament lifetime, τ_F, for each specimen position from the slope as the time difference read on the abscissa between the values corresponding to ΔV_0 and $0.37 \cdot \Delta V_0$.

12.18 Average the two values of τ_F.

13. Calculation

13.1 Calculate the low-injection-level bulk minority carrier lifetime, τ_0, as follows:

$$\tau_0 = (\tau_F^{-1} - R_s)^{-1}$$

where:

R_s, the surface recombination rate, is given in Table 3 for standard specimen types.

NOTE 17—**Caution:** Observe the recommendation in 6.2.1 and Table 2 regarding the maximum bulk lifetime that can be determined.

NOTE 18—If specimens of other dimensions are measured, R_s may be found for rectangular specimens of length l, width w, and thickness t, as follows:

$$R_s = \pi^2 D (l^{-2} + w^{-2} + t^{-2})$$

.

For right circular specimens of length l and radius r:

$$R_s = \pi^2 D[l^{-2} + (9/16r^{2})].$$

In these equations, D is the diffusion coefficient of the minority carrier.

14. Report

14.1 Report the following information:

14.1.1 Date and place of testing,

14.1.2 Name of operator,

14.1.3 Test method used (A or B) and any deviations from the standard procedures employed, and

14.1.4 Kind of light source used.

14.2 For each specimen measured, report the following information:

14.2.1 Specimen dimensions (or sample type),

14.2.2 Conductivity type and resistivity of the specimen,

14.2.3 Measurement point on specimen and length and width of the illuminated area, l_I and w_I, in millimetres,

14.2.4 Direct current voltage drop, V_{dc}, in V, and peak (Test Method A) or saturation (Test Method B) value of the voltage modulation, ΔV_0, in millivolt,

14.2.5 Whether or not a signal conditioning unit was used (Test Method B only),

14.2.6 Whether or not the modulation correction was applied (Test Method A only),

14.2.7 Measured (and if a modulation correction was used in Test Method A, corrected) value of filament lifetime, τ_F, in µs, and

14.2.8 Calculated bulk minority carrier lifetime, τ_B, in µs.

15. Precision and Bias

15.1 *Precision*:

15.1.1 *Test Method A*—In the 1975 edition of this test method it was stated that the precision expected when this test method is used by competent operators in a number of laboratories is estimated to be ±50 % (two relative standard deviations) for measurements on germanium and ±135 % (2 relative standard deviations) for measurements on silicon. No basis for these estimates was provided. Because certain aspects of the method have been more completely defined, the precision of the present version can be expected to be improved over these estimates. However, for more precise measurements on silicon, Test Method B is recommended.

15.1.2 *Test Method B*—DIN 50440/1 [3] states that the relative uncertainty in the low-injection-level minority carrier lifetime, when determined in accordance with the conditions of this test method, does not exceed ±10 %. No data to support this statement is provided.

15.2 *Bias*—A full statement regarding bias cannot be made because there are no absolute standards from which to determine the true value. However, DIN 50440/1 [3] states that, when the lifetime is controlled by certain recombination centers in silicon, the systematic error that occurs because the low-injection-level condition given in the method is not stringent enough for these centers, does not exceed + 10 %.

16. Keywords

16.1 carrier lifetime; germanium; minority carriers; photoconductivity decay; silicon; single crystal silicon

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