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Standard Test Method for Measuring Steady-State Primary Photocurrent[1]

This standard is issued under the fixed designation F 448; 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 steady-state primary photocurrent, I_{pp}, generated in semiconductor devices when these devices are exposed to ionizing radiation. These procedures are intended for the measurement of photocurrents greater than 10^{-9} A·s/Gy(Si or Ge), in cases for which the relaxation time of the device being measured is less than 25 % of the pulse width of the ionizing source. The validity of these procedures for ionizing dose rates as great as 10^{8}Gy(Si or Ge)/s has been established. The procedures may be used for measurements at dose rates as great as 10^{10}Gy(Si or Ge)/s; however, extra care must be taken. Above 10^{8}Gy/s the package response may dominate the device response for technologies such as complementary metal-oxide semiconductor, (CMOS)/silicon-on sapphire (SOS). Additional precautions are also required when measuring photocurrents of 10^{-9} A·s/Gy(Si or Ge) or lower.

1.2 Setup, calibration, and test circuit evaluation procedures are also included in this test method.

1.3 Because of the variability between device types and in the requirements of different applications, the dose rate range over which any specific test is to be conducted is not given in this test method but must be specified separately.

1.4 The values stated in International System of Units (SI) are to be regarded as standard. No other units of measurement are included in this standard.

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.*

2. Referenced Documents

2.1 *ASTM Standards:*

E 668 Practice for the Application of Thermoluminescence-Dosimetry (TLD) Systems for Determining Absorbed Dose in Radiation-Hardness Testing of Electronic Devices[2]

F 526 Test Method for Measuring Dose for Use in Linear Accelerator Pulsed Radiation Effects Tests[3]

3. Terminology

3.1 *Definitions:*

3.1.1 *fall time*, *n*—the time required for a signal pulse to drop from 90 to 10 % of its steady-state value.

3.1.2 *primary photocurrent*, *n*—the flow of excess charge carriers across a *p-n* junction due to ionizing radiation creating electron-hole pairs throughout the device. The charges associated with this current are only those produced in the junction depletion region and in the bulk semiconductor material approximately one diffusion length on either side of the depletion region (or to the end of the semiconductor material, whichever is shorter).

3.1.3 *pulse width*, *n*—the time a pulse-amplitude remains above 50 % of its maximum value.

3.1.4 *rise time*, *n*—the time required for a signal pulse to rise from 10 to 90 % of its steady-state value.

4. Summary of Test Method

4.1 In this test method, the test device is irradiated in the primary electron beam of a linear accelerator. Both the irradiation pulse and junction current (Fig. 1) are displayed and recorded. Placement of a thin, low atomic number (Z≤13) scattering plate in the beam is recommended to improve beam uniformity; the consequences of the use of a scattering plate relating to interference from secondary electrons are described. The total dose is measured by an auxiliary dosimeter. The steady-state values of the dose rate and junction current and the relaxation time of the junction current are determined from the data trace and total dose.

4.2 In special cases, these parameters may be measured at a single dose rate under one bias condition if the test is designed to generate information for such a narrow application. The preferred approach, described in this test method, is to characterize the radiation response of a device in a way that is useful to many different applications. For this purpose, the response to pulses at a number of different dose rates is required. Because of the bias dependence of the depletion volume, it is possible that more than one bias level will be required during the photocurrent measurements.

5. Significance and Use

5.1 The steady-state photocurrent of a simple *p-n* junction

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[2] *Annual Book of ASTM Standards*, Vol 12.02.

[3] *Annual Book of ASTM Standards*, Vol 10.04.

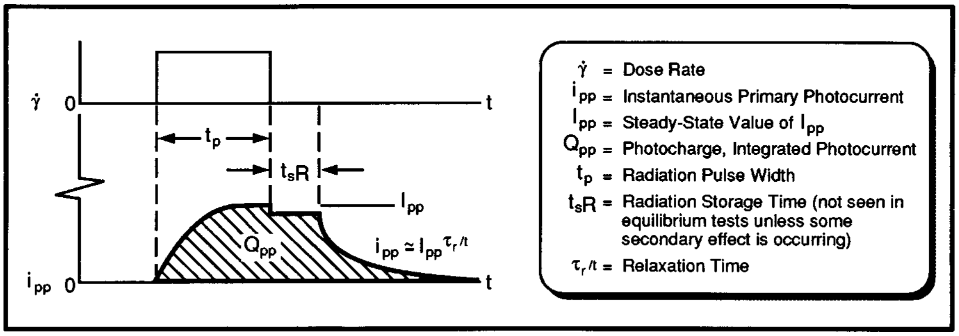

FIG. 1 Ionization Radiation Pulse and Typical Primary Photocurrent Response

diode is a directly measurable quantity that can be directly related to device response over a wide range of ionizing radiation. For more complex devices the junction photocurrent may not be directly related to device response.

5.2 *Zener Diode*— In this device, the effect of the photocurrent on the Zener voltage rather than the photocurrent itself is usually most important. The device is most appropriately tested while biased in the Zener region. In testing Zener diodes or precision voltage regulators, extra precaution must be taken to make certain the photocurrent generated in the device during irradiations does not cause the voltage across the device to change during the test.

5.3 *Bipolar Transistor*—As device geometries dictate that photocurrent from the base-collector junction be much greater than current from the base-emitter junction, measurements are usually made only on the collector-base junction with emitter open; however, sometimes, to obtain data for computer-aided circuit analysis, the emitter-base junction photocurrent is also measured.

5.4 *Junction Field-Effect Device*—A proper photocurrent measurement requires that the source be shorted (d-c) to the drain during measurement of the gate-channel photocurrent. In tetrode-connected devices, the two gate-channel junctions should be monitored separately.

5.5 *Insulated Gate Field-Effect Device*—In this type of device, the true photocurrent is between the substrate and the channel, source, and drain regions. A current which can generate voltage that will turn on the device may be measured by the technique used here, but it is due to induced conductivity in the gate insulator and thus is not a junction photocurrent.

6. Interferences

6.1 *Air Ionization*— A spurious component of the current measured during a photocurrent test can result from conduction through air ionized by the irradiation pulse. Although this is not likely to be a serious problem for photocurrents greater than 10^{-9} A·s/Gy(Si or Ge), the spurious contribution can easily be checked by measuring the current while irradiating the test fixture in the absence of a test device. Air ionization contributions to the observed signal are proportional to applied field, while those due to secondary emission effects (see 6.2) are not. The effects of air ionization external to the device may be minimized by coating exposed leads with a thick layer of paraffin, silicone rubber, or nonconductive enamel or by making the measurement in vacuum.

6.2 *Secondary Emission* [4]—Another spurious component of the measured current can result from charge emission from, or charge injection into, the test device and test circuit. This may be minimized by shielding the surrounding circuitry and irradiating only the minimum area necessary to ensure irradiation of the test device. Reasonable estimates of the magnitude to be expected of current resulting from secondary-emission effects can be made based on the area of metallic target materials irradiated. Values generally range between 10^{-11} and 10^{-9} A·s/cm^2·Gy, but the use of a scatter plate with an intense beam may increase this current.

6.3 *Orientation*— The effective dose to a semiconductor junction can be altered by changing the orientation of the test unit with respect to the irradiating electron beam. Most transistors and diodes may be considered "thin samples'' (in terms of the range of the irradiating electrons). However, high-power devices may have mounting studs or thick-walled cases that can act to scatter the incident beam, thereby reducing the dose received by the semiconductor chip. Care must be taken in the mounting of such devices.

6.4 *Bias*—As the effective volume for the generation of photocurrent in *p-n* junction devices includes the space-charge region, I_{pp} may be dependent on applied voltage. As applied voltages approach the breakdown voltage, I_{pp} increases sharply due to avalanche multiplication. If the application of the test device is known, actual bias values should be used in the test. If the application is not known, follow the methods for checking the bias dependence given in Section 10.

6.5 *Nonlinearity*— Nonlinearities in photocurrent response result from saturation effects, injection level effects on lifetimes, and, in the case of bipolar transistors, a lateral biasing effect which introduces a component of secondary photocurrent into the primary photocurrent measurement.[5] For these reasons, photocurrent measurements must generally be made over a wide range of dose rates.

6.6 *Electrical Noise*— Since linear accelerator facilities are inherent sources of r-f electrical noise, good noise-minimizing techniques such as single-point ground, filtered d-c supply lines, etc., must be used in photocurrent measurements.

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[4] Sawyer, J. A., and van Lint, V. A. J., "Calculations of High-Energy Secondary Electron Emission," *Journal of Applied Physics*, JAPIA, Vol 35, No 6, June 1964, pp. 1706–1711.

[5] Habing, D. H., and Wirth, J. L., "Anomalous Photocurrent Generation in Transistor Structures," *IEEE Transactions on Nuclear Science*, IETNA, Vol NS-13, No 6, December 1966, pp. 86–94.

6.7 *Temperature*— Device characteristics are dependent on junction temperature; hence, the temperature of the test should be controlled. Unless otherwise agreed upon by the parties to the test, measurements will be made at room temperature (23 ± 5°C).

6.8 *Beam Homogeneity and Pulse-to-Pulse Repeatability*— The intensity of a beam from a linear accelerator is likely to vary across its cross section. Since the pulse-shape monitor is placed at a different location from the device under test, the measured dose rate may be different from the dose rate to which the device was exposed. The spatial distribution and intensity of the beam may also vary from pulse to pulse. The beam homogeneity and pulse-to-pulse repeatability associated with a particular linear accelerator should be established by a thorough characterization of its electron beam prior to performing a photocurrent measurement.

6.9 *Ionizing Dose*— Each pulse of the linear accelerator imparts a dose of radiation to both the device under test and the device used for dosimetry. The ionizing dose deposited in a semiconductor device can change its operating characteristics. As a result, the photocurrent that is measured after several pulses may be different from the photocurrent that is characteristic of an unirradiated device. Care should be exercised to ensure that the ionizing dose delivered to the device under test is as low as possible consistent with the requirements for a given dose rate and steady-state conditions. Generally, this is done by minimizing the number of pulses the device receives. The dose must not exceed 10 % of the failure dose for the device.

6.10 The test must be considered destructive if the photocurrent exceeds the manufacturer's absolute limit.

7. Apparatus

7.1 *Regulated d-c Power Supply*, with floating output to produce the voltages required to bias the junction.

7.2 *Oscilloscopes*— Either a single dual-beam, or two single-beam oscilloscopes that have adequate bandwidth capability of both main frames and plug-ins to ensure that radiation response and peak steady-state values are accurately displayed.

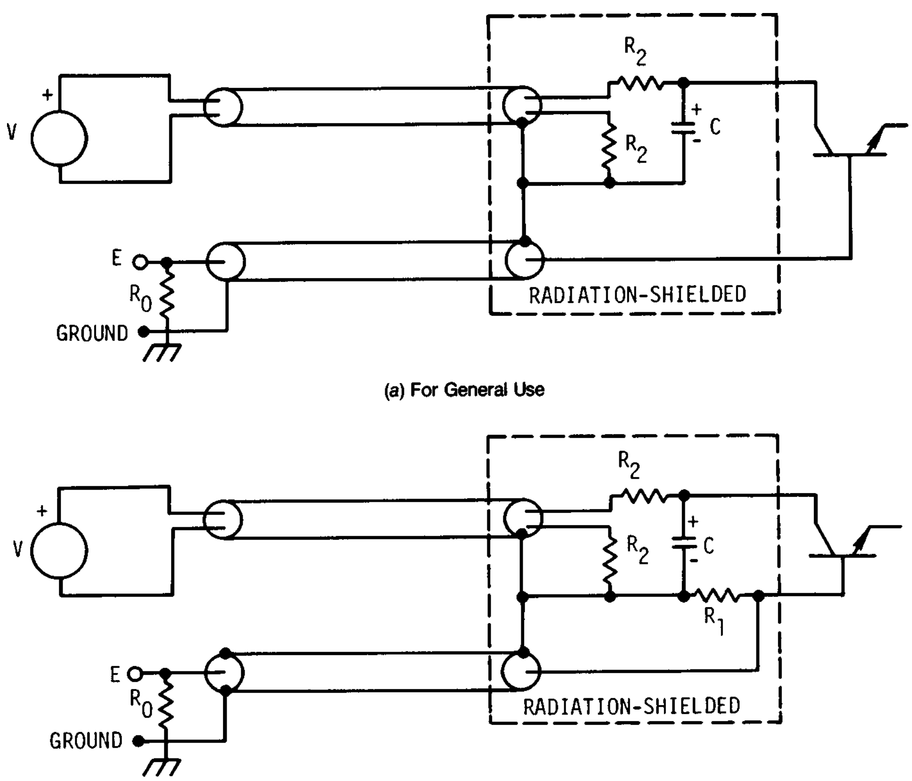
7.2.1 *Oscilloscope Camera(s) and Film*, capable of recording single transient traces at a sweep rate consistent with good resolution at the pulse widths used in the test.

7.3 *Digitizers with Bandwidth, Sampling Interval, and Time-base Capabilities*, adequate for handling the transient signals with good resolution for all pulse widths utilized in the test may be used. Hard copy printouts of the recorded signal may be a part of the capability of this apparatus.

7.4 *Cabling*, to complete adequately the connection of the test circuit in the exposure area with the power supply and oscilloscopes in the data area. Any type of ungrounded wiring may be used to connect the power supply to the bias points of the test circuit; however, coaxial cables properly terminated at the oscilloscope input are required for the signal leads.

7.5 *Test Circuits*— One of the following test circuits:

7.5.1 *Resistor-Sampling Circuit (Fig. 2)*—For most tests, the configuration of Fig. 2*(a)* is appropriate. The resistors R_2 serve as high-frequency isolation and must be at least 20 Ω.



(*a*) For General Use

(*b*) For Large Photocurrents

FIG. 2 Resistor-Sampling Test Circuits

The capacitor *C* supplies the charge during the current transient; its value must be large enough that the decrease in voltage during a current pulse is less than 10 %. Capacitor *C* should be paralleled by a small (approximately 0.01 µF) low-inductance capacitor to ensure that possible inductive effects of the large capacitor are offset. The resistor R_0 is to provide the proper termination (within ±2 %) for the coaxial cable used for the signal lead. When the photocurrents are large, it is necessary to use a small-value resistor, R_1, in the configuration of Fig. 2*(b)* to keep the signal small so as to maintain the bias across the junction within 10 % of its nominal value during the test. The response characteristics of this circuit must be adequate to ensure that the current signal is accurately displayed (see 9.4).

7.5.2 *Current Transformer Circuit (Fig. 3)*—In this circuit, R_2 and *C* have the same significance as in the resistor-sampling circuit, but it may be required that the signal cable monitoring the current transformer be matched to the characteristic impedance of the transformer, in which case R_0 would have this impedance (within± 2 %), which is specified by the manufacturer of the current transformer. The current transformer must have a bandwidth sufficient to ensure that the current signal is accurately displayed. Rise time must be less than 10 % of the pulse width of the radiation pulse being used. The low frequency cutoff of some commercial current transformers is such that significant droop may occur for pulse widths greater than 1 µs. Do not use a transformer for which this droop is greater than 5 % for the radiation pulse width used. When monitoring large photocurrents, care must be taken that the ampere-microsecond saturation of the current transformer is not exceeded.

7.6 *Irradiation Pulse-Shape Monitor*—One of the following to develop a signal proportional to the dose rate delivered to the test device:

7.6.1 *Fast Signal-Diode*, in the circuit configuration of Fig. 2 *(a)* as described in 7.5.1. The response of the diode must be linear (within ±2 %) with dose rate over the range of interest. This is the preferred apparatus for this purpose.

7.6.2 *P-I-N Diode*, in the circuit configuration of Fig. 2*(a)* as described in 7.5.1. Because of the great sensitivity of this diode, it must be mounted at the fringe of the radiation field to avoid saturation effects.

NOTE 1—A PIN diode is a semiconductor diode in which the *p*-type and *n*-type regions are separated by an intrinsic region.

7.6.3 *Current Transformer*, as described in 7.5.2, mounted on a collimator at the output window of the linear accelerator so that the primary electron beam passes through the opening of the transformer after passing through the collimator.

7.6.4 *Secondary-Emission Monitor*, consisting of a thin foil, biased negatively with respect to ground, mounted in an evacuated chamber with thin windows through which the primary electron beam passes after passing through a collimator. A resistor in series with the foil and bias supply is used to sense the current.

7.7 *Dosimeter*—One of the following types of dosimeter to calibrate the output of the pulse-shape monitor in terms of dose rate:

7.7.1 *Thermoluminescent Dosimeter (TLD)*, and readout system as specified in Practice E 668.

7.7.2 *Thin Calorimeter*, and associated equipment, including instructions for use.

NOTE 2—For a discussion of calorimeter design considerations, see the calorimeter of the Apparatus Section, and Appendix X1 of Test Method F 526.

7.8 *Electron Linear Accelerator (Linac)*, to produce the ionizing pulse. It must produce relatively flat (current variations within ±10 %) pulses of electrons (as measured with the apparatus of 7.6) of greater than 10 MeV, in pulses with a length at least four times the relaxation time of the device under test. The primary electron beam is used as the ionizing source. A thin scatter plate of a material with low atomic number, such as aluminum, 0.15 to 0.65 cm thick, may be placed at the exit window of the linear accelerator to spread the beam and somewhat homogenize it so that positioning of the test device is not as critical as it would be if the beam were unscattered.

NOTE 3—**Caution: There is approximately 5 MeV/cm energy attenuation of the beam passing through aluminum.**

NOTE 4—Another primary source of ionizing radiation for photocurrent measurements is a flash X-ray machine (FXR). However, the FXR is not qualified to provide radiation for steady-state photocurrent measurements since its short, almost triangular pulse does not provide the equilibrium conditions necessary.

7.9 *Pulser*, capable of supplying current pulses of magnitude 10^{-4} to 0.1 A, rise time of 10 ns or less, and source voltage 5 V into the test circuit selected. If the circuit of Fig. 2*(b)* is used, an additional resistor may be placed in series with R_1 to maintain the required load impedance. Both sides of

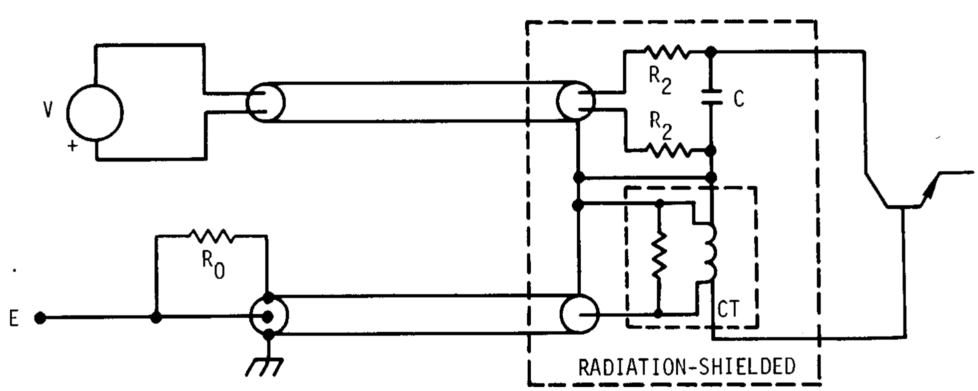


FIG. 3 Current Transformer Test Circuit

output must be isolated from ground.

7.10 *Thermometer*, to measure ambient temperature in the vicinity of the device under test to ±1°C.

8. Sampling

8.1 This may be a destructive test. Hence, for purposes of lot testing or lot qualification, a representative sample should be drawn from the lot in accordance with a plan agreed upon by the parties to the test.

8.2 The sampling plan should also include a selection of devices for which the relaxation time is to be calculated (see 11.2).

9. Preparation of Apparatus

9.1 Select an appropriate test circuit and align it with the exit port of the linear accelerator. Position the scatter plate and appropriate shielding, collimation, and pulse-shape monitor.

9.2 Use one of the following methods to determine the dose-rate factor:

9.2.1 *Thermoluminescent Dosimeter (TLD)*—Mount the TLD in the position to be occupied by the test device. Pulse the linear accelerator and record the pulse-shape monitor signal. Remove the TLD and determine the dose following the manufacturer's instructions. Graphically integrate the irradiation pulse-shape monitor signal and calculate a dose-rate factor as follows:

$$F = \gamma/\Sigma \tag{1}$$

where:
F = dose-rate factor, Gy(Si)/V·s,
γ = dose, Gy(Si), and
Σ = integrated pulse-shape monitor signal, V·s.

Repeat the measurement five times and average. Use this value for the dose-rate factor.

9.2.2 *Thin Calorimeter*— Mount the calorimeter in the position to be occupied by the test device. Provide thermal isolation for the calorimeter foil. Pulse the linear accelerator, record the pulse-shape monitor signal and the temperature rise of the calorimeter. Calculate the dose delivered in accordance with the instructions provided for the calorimeter. Graphically integrate the irradiation pulse-shape monitor signal and calculate a dose-rate factor in accordance with Eq 1. Repeat the measurement five times and calculate the average for the five measurements. Record the average value as the dose-rate factor.

9.3 *Measure the Test Circuit with Device Removed*—With no device in the test circuit, apply the bias to be used (see 10.3) and pulse the linear accelerator to deliver a dose rate of 10^5 Gy(Si or Ge)/s or greater. Record both the irradiation pulse-shape monitor signal and the current signal from the test circuit. The measured current should be less than or equal to one-tenth the anticipated steady-state photocurrent. If it is, proceed with the test (see Section 10). If it is not, change the bias and repeat. If the signal changes (indicating air-ionization problems), pot the exposed leads of the test circuit (see 6.1). If the signal is still large and affected little by the applied bias, restrict still further the exposure area and increase the shielding of the test circuit, or remove the scatter plate, or both, and repeat the measurement. Continue in this manner until a current of one tenth the anticipated steady-state photocurrent or less is obtained. Record the actual values measured and the changes made.

9.4 *Verify the Response Characteristics of the Test Circuit and Cables*—Connect the pulse generator to the test circuit across the input terminals in place of the device under test. Pulse the circuit with a current between 10^{-4} and 0.1 A and display the response. Observe and measure the rise and fall times and the steady-state amplitude of the displayed pulse. Calculate the current from Eq 2, Eq 3, or Eq 4 (see 11.1) as appropriate for the test circuit. The calculated current must be within 5 % of the driving current, and the rise and fall times must be less than 10 % of the width of the radiation pulse.

10. Procedure

10.1 Mount the test device in the test circuit.

10.2 Measure and record the ambient temperature in the vicinity of the test device.

10.3 Apply bias to the test device equal to one half the manufacturer's rated breakdown voltage for the junction under test.

10.4 Adjust the linear accelerator beam current until a dose rate is obtained that is within ±20 % of the lowest value specified for the particular set of tests.

10.4.1 Determine the dose rate by multiplying the dose-rate factor (see 9.2) by the voltage of the irradiation pulse-shape monitor (see 7.6).

NOTE 5—**Caution: If the control of the linear accelerator is such that adjustment of beam current can be accomplished with the discharge of no more than ten pulses, leave the test device in place during current adjustment. However, if the current adjustment requires the use of more than ten pulses, remove the test device or shield it from the beam during the adjustment.**

10.5 Pulse the linear accelerator and record both the irradiation pulse-shape monitor signal and the photocurrent signal.

10.6 Increase the dose rate by a factor of 3 to 10 (see 10.4.2) as agreed by the parties to the test.

10.7 Repeat 10.5 and 10.6 until measurements have been made over the specified range of dose rates.

10.8 Reduce the dose rate to one of the mid-range values used (see 10.4.2), change the bias to 1 V, and repeat 10.5.

10.9 Compare the data of 10.8 with those taken at the same dose rate with a bias of one-half the manufacturer's rated breakdown voltage. If they are within ±20 % of the earlier values, proceed to the calculations (Section 11). If they differ by 20 % or more, repeat 10.4-10.7, first for a bias of 1 V and then for a bias of 0.8 times the manufacturer's rated breakdown voltage.

11. Calculation

11.1 For each data set, calculate the steady-state photocurrent, I_{pp}, from the formula appropriate to the test circuit selected.

11.1.1 Resistor-sampling test circuit for general use (see Fig. 2*(a)*):

$$I_{pp} = E/R_0 \tag{2}$$

where:

I_{pp} = steady-state photocurrent, A,
E = steady-state signal voltage, V, and
R_0 = cable termination resistance, Ω.

11.1.2 Resistor-sampling test circuit for large photocurrents (see Fig. 2*(b)*):

$$I_{pp} = E\,(R_0 + R_1)/R_0R_1 \tag{3}$$

where:

I_{pp} = steady-state photocurrent, A,
E = steady-state signal voltage, V,
R_0 = cable termination resistance, Ω, and
R_1 = load resistance, Ω.

11.1.3 Current transformer test circuit (see Fig. 3):

$$I_{pp} = E/\,S \tag{4}$$

where:

I_{pp} = steady-state photocurrent, A,
E = steady-state signal voltage, V, and
S = sensitivity of current transformer, V/A.

11.2 Calculate the relaxation time for a representative sample of the data sets, selected by a method agreed to in advance by the parties to the test.

11.2.1 Plot the $\log_{10}$ of I_{pp} against time for the tail of the photocurrent pulse, and visually fit this plot with the best straight line. Because the tail of the pulse is a complementary error function rather than an exponential, the fit may be rather poor.

11.2.2 Calculate the measured relaxation time from the slope of the straight line as follows:

$$\tau_m = \Delta t/2.3(\Delta \log_{10} I_{pp}) \tag{5}$$

where:

τ_m = measured relaxation time, s,
Δt = interval along the time axis, s, and
$\Delta \log_{10} I_{pp}$ = interval along the $\log_{10} I_{pp}$ axis.

11.2.3 If τ_m calculated in this way is more than four times the rise time of the measuring equipment, this value of τ_m may be reported as the relaxation time, τ_r. If τ_m calculated in this way is less than 10 % greater than the rise time of the measuring equipment, report the relaxation time as "less than τ_e, test circuit limited," where τ_e is the rise time of the test equipment. For any τ_m between these limits, τ_r may be calculated as follows:

$$\tau_r = \sqrt{\tau_m{}^2 - \tau_e{}^2} \tag{6}$$

where:

τ_r = relaxation time, s,
$\tau_m{}^2$ = measured relaxation time, s, and
τ_e = rise time.

12. Report

12.1 Report the following information:

12.1.1 Device identification,

12.1.2 Date of test and test operator,

12.1.3 Identification of linear accelerator facility and test port,

12.1.4 Description of scatter plate, if used,

12.1.5 Description of test circuit,

12.1.6 Description of irradiation pulse-shape monitor,

12.1.7 Dosimetry technique,

12.1.8 Test-circuit current with device removed (see 9.3),

12.1.9 Test-circuit response data (see 9.4),

12.1.10 Ambient temperature,

12.1.11 Values of I_{pp} and dose rate for each data set,

12.1.12 Records of typical signals, and

12.1.13 Relaxation time, if calculated.

13. Precision

13.1 A round-robin evaluation of the reproducibility of this test method was conducted with five laboratories participating. Each laboratory measured the photocurrent from five devices: two *pnp* transistors, two *npn* transistors, and one *n*-channel field-effect transistor (FET). To eliminate possible variations introduced by different dosimetry techniques, all device photocurrents were measured as a function of the output of a dosimeter PIN diode which was to be mounted adjacent to the part under test. Only the specimen parts and the PIN dosimeter were circulated; each laboratory fabricated its own test fixture.

13.2 Individual data points could not be compared directly, as all data were taken at arbitrary points over three orders of magnitude in output of the PIN dosimeter. Instead, comparison was made of the best linear fits to the log I_{PP}-versus-log PIN data; the results are given in Table 1.

13.3 For the five devices, maximum laboratory-to-laboratory scatter in the fitted results ranges from 25 to 51 % above the mean value and from 20 to 51 % below the mean value. Individual measurements may lie outside the range described.

14. Keywords

14.1 hardness assurance; ionizing radiation; photocurrent; primary photocurrent; semiconductor testing

TABLE 1 Round-Robin Results

Device	Type	Mean I_{PP}/I_{PIN}	Standard Deviation	High Extreme Mean	Low Extreme Mean
2N2222	*npn*	0.024	0.0079	1.43	0.68
2N5939	*npn*	0.51	0.14	1.31	0.75
2N3972	*pnp*	0.085	0.026	1.55	0.49
2N2907	*pnp*	0.027	0.0052	1.29	0.80
2N3504	FET	0.042	0.014	1.51	0.62