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(Revision of ANSI/IEEE Std 300-1982)

IEEE Standard Test Procedures for Semiconductor Charged-Particle Detectors

Sponsor
Nuclear Instruments and Detectors Committee of the IEEE Nuclear and Plasma Sciences Society

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IEEE Standards Board

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Foreword

(This Foreword is not a part of IEEE Std 300-1988, IEEE Standard Test Procedures for Semiconductor Charged-Particle Detectors.)

This standard provides standard test procedures for semiconductor charged-particle detectors for ionizing radiation. It supersedes the previous edition, ANSI/IEEE Std 300-1982. The standard has been modified and refined based on the experience gained in using the earlier edition over a number of years, taking into account advances in the technology. Companion documents are ANSI/IEEE Std 301-1988, Test Procedures for Amplifiers and Preamplifiers Used with Detectors of Ionizing Radiation, and ANSI/ IEEE Std 759-1984, IEEE Standard Test Procedures for Semiconductor X-ray Energy Spectrometers.

This standard was prepared by the Nuclear Instruments and Detectors Committee of the IEEE Nuclear and Plasma Sciences Society. When this standard was approved the members of the committee were:

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At the time this standard was published it was under consideration for approval as an American National Standard. The American National Standards Committee N42 on Radiation Instrumentation had the following members at the time this document was sent to letter ballot.

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IEEE Standard Test Procedures for Semiconductor Charged-Particle Detectors

1. Scope and Object

1.1 Scope

This standard applies to semiconductor radiation detectors that are used for the detection and high-resolution spectroscopy of charged particles. The measurement techniques described were selected to be readily available to all manufacturers and users of charged-particle detectors. Some superior techniques are not included because the methods are too complex or require equipment (such as particle accelerators) which may not be readily available.

Test procedures for the associated amplifiers and preamplifiers are described in ANSI/IEEE Std 301-1988 [2].[1]

1.2 Object

The object of this standard is to establish standard test procedures for semiconductor charged-particle detectors. These detectors are in widespread use for the detection and high-resolution spectroscopy of charged particles. It is desirable to maintain standard test procedures so that measurements may have the same meaning to all manufacturers and users.

Not all tests described in this standard are mandatory, but tests which are used to specify performance shall be performed in accordance with the procedures described herein.

2. References

This standard shall be used in conjunction with the following publications:

[1] ANSI ENH—Special Report SR-24B, 1982 Edition, ANSI Photo Lamp Codes.[2]

[1]The numbers in brackets correspond to those of the references in Section 2.
[2]ANSI publications are available from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018.

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[2] ANSI/IEEE Std 301-1988, IEEE Standard Test Procedures for Amplifiers and Preamplifiers Used with Detectors of Ionizing Radiation.[3]

[3] ANSI/IEEE Std 325-1986, IEEE Standard Test Procedures for Germanium Gamma-Ray Detectors.

[4] IEEE Std 194-1977, IEEE Standard Pulse Terms and Definitions.

3. Symbols and Definitions

3.1 Symbols

ADC = analogue-to-digital converter
C = electrical capacitance
C_c = calibrated capacitor used to couple a pulse generator to a preamplifier
C_f = feedback capacitor in the charge-sensitive loop of a preamplifier
E = energy of a particle or photon
ε = average energy required to form one hole-electron pair in a semiconductor detector
FWHM = full width at haft maximum
FW.1M = full width at one-tenth maximum
FW.01M = full width at one one-hundreth maximum
MCA = multichannel analyzer
q = charge of the electron, $1.602 \cdot 10^{-19}$ coulomb
Q = electric charge
R = electrical resistance
R_d = detector load resistor
S = channel number for a multichannel analyzer spectrum obtained to check the positional resolution and linearity of position-sensitive detectors
S_i = peak channel number of the ith position peak generated by a position-sensitive detector when used with a mask with slits. (The indices for i range from $i = 0$ to $i = m$.)
T = absolute temperature (K)
t = time
TAC = time-to-amplitude converter
t_c = charge collection time in a detector
t_o = observed detector rise time due to the combined effects of the charge collection time and electronic rise time
t_f = pulse fall time (90% – 10% of its peak value)
t_p = peaking time of a pulse
t_r = pulse rise time (10% – 90% of its peak value)
t_t = tailing time of a pulse
$t_{0.5}$ = width of a pulse at 50% of its peak height
$t_{.01}$ = width of a pulse at one percent of its peak height
τ = time constant
τ_d = time constant for decay of a pulse
V = electric voltage
Z_o = characteristic impedance

3.2 Specialized Definitions

Definitions that are followed with the reference IEEE Std 194-1977 [4] contain pulse-shaping terms defined in that standard.

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When the term *amplifier* is used, *preamplifier* also is implied unless otherwise stated.

active dimension (of a position-sensitive detector). A dimension (length, width) of that region of a position-sensitive detector that is depleted.

avalanche breakdown (of a semiconductor device). A breakdown caused by the cumulative multiplication of charge carriers through field-induced impact ionization.

band gap. The energy difference between the bottom of the conduction band and the top of the valence band.

baseline. The average of the levels from which a pulse departs and to which it returns in the absence of a following overlapping pulse (see IEEE Std 194-1977 [4]).

bias. (1) In a biased amplifier, the applied threshold voltage (or current) below which the gain is zero.
(2) In a detector, the polarizing electric field that causes charge to be collected.

biased amplifier. An amplifier giving zero output for input signals below an adjustable threshold and having a constant incremental gain above that threshold up to a specified maximum output.

bias resistor (detector). The resistor through which the polarizing voltage is applied to a detector.

blocking contact (of a semiconductor radiation detector). That contact from which depletion proceeds into the semiconductor material under conditions of reverse bias.

breakdown (of a semiconductor diode). A phenomenon occurring in a reverse-biased semiconductor diode, the initiation of which is observed as a transition from a region of high dynamic xresistance to a region of substantially lower dynamic resistance for increasing magnitude of reverse current.

breakdown region (of a semiconductor diode characteristic). That entire region of the voltage-current characteristic beyond the initiation of breakdown for increasing magnitude of reverse current.

breakdown voltage (of a semiconductor diode). The voltage measured at a specified current in the breakdown region.

capacitance (of a semiconductor radiation detector). The small-signal capacitance measured between terminals of the detector under specified conditions of bias and frequency.

channel, surface (of a semiconductor radiation detector). A thin region at a semiconductor surface of *p*- or *n*-type conductivity created by the action of an electric field; for example, that due to trapped surface charge.

channeling, lattice (in a semiconductor radiation detector). A phenomenon that results in a crystallographic directional dependence of the rate of energy loss of ionizing particles.

charge carrier (of a semiconductor). A mobile conduction electron or mobile hole.

charge collection time (of a semiconductor radiation detector). The time interval, after the passage of an ionizing particle, for the integrated current flowing between the terminals of the detector to increase from 10% to 90% of its final value.

clip, clipping. A limiting operation such as
1) The use of a high-pass filter (differentiator) or
2) A nonlinear operation to limit the amplitude of a pulse.

The first usage is archaic.

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constant-fraction discriminator. An amplitude discriminator in which the triggering threshold is set at a constant percentage of the input pulse amplitude independent of its size.

crest factor (ac voltmeter). The highest ratio of peak to rms voltage that can be applied to an ac voltmeter before overload sets in. The crest factor may depend upon the full-scale setting of the meter.

crossover time. The instant at which the transition between the two lobes of a bipolar pulse passes through a designated level (usually the baseline).

crossover walk. A deviation of crossover time of a bipolar pulse due to a change in peak amplitude. *See:* **walk.**

***CR-RC* shaping.** In an amplifier, the pulse shaping produced by a single-section high-pass network followed by a single-section low-pass network, with the two networks separated by an isolating stage and with both networks having the same time constant.

dead layer (of a semiconductor detector). An inactive region (layer) in which the energy absorbed from the passage of monoenergetic charged particles does not significantly contribute to the resulting full energy peak.

decay time constant. With a signal that decays with a single exponential waveform, the time required for it to fall to 1/e from any selected level on the asymptote of the last transition (see IEEE Std 194-1977 [41].

depletion region (in a semiconductor). A region in which the charge-carrier charge density is insufficient to neutralize the net fixed charge density of ionized donors and acceptors.

In a diode-type semiconductor radiation detector the depletion region is the sensitive region of the device.

depletion voltage (of a semiconductor radiation detector). The voltage at which a junction detector becomes fully depleted.

differential d*E*/d*x* Detector. A transmission detector in which the thickness is small compared to the range of the incident particle.

differentiated (pulse) (pulse amplifier jargon). A pulse is *differentiated* when it is passed through a high-pass network, such as a *CR* filter.

diffused-junction detector. A semiconductor detector in which the *p-n* or *n-p* junction is produced by diffusion of donor or acceptor impurities.

energy resolution. (1) In keV: the FWHM of a spectral line in units of keV. (2) In percent: 100 · (FWHM/*E*) where FWHM and energy *E* are expressed in the same units *See:* **FWHM.**

equivalent noise resistance (series noise). In a hypothetically noise-free amplifier, that resistance which when connected between the signal source and the amplifier will produce an output signal attributable to the observed series-noise component. This definition applies only to noise with a constant spectral density (white noise).

equivalent noise resistance (parallel noise). In a hypothetically noise-free amplifier, that resistance which when placed across the input terminals of the amplifier will produce an output signal attributable to the observed parallel-noise component. This definition applies only to noise with a constant spectral density (white noise).

fall time (of a pulse). The interval between the 90% and 10% points (unless otherwise specified) on the last transition (see IEEE Std 194-1977 [4]).

fixed fraction discriminator. *See:* **constant-fraction discriminator.**

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full width at half maximum (FWHM). The full width of a distribution measured at 50% of its peak height. If the distribution is a spectral line due to radiation, it is assumed that the background level was averaged over the base of that line and the average subtracted from the ordinates of the distribution before the FWHM was determined. For a normal distribution,

$$\text{FWHM} = 2(2 \text{ In } 2.)^{0.5} = 2.355\sigma$$

where

σ = standard deviation and also the root-mean-square value of the distribution.

full width at one-tenth maximum (FW.1M). The full width of a distribution measured at one tenth of the maximum ordinate measured above the background.

FWHM. *See:* **full width at half maximum.**

geometry, detector (detector jargon). The physical configuration of a solid-state detector.

ion implanted contact. A detector contact consisting of a junction produced by the process of ion implantation.

ion implantation. A process in which a beam of energetic ions incident upon a solid results in the implantation of those ions into the material.

inactive region (of a semiconductor radiation detector). A region of a detector in which charge created by ionizing radiation does not contribute significantly to the signal charge.

integrated (pulse) (pulse amplifier jargon). A pulse is *integrated* when it is passed through a low-pass network, such as a single *RC* network or a cascaded *RC* network.

intrinsic semiconductor. A semiconductor containing an equal number of free holes and electrons throughout its volume.

junction (of a semiconductor radiation detector). A region of transition between semiconductor regions of different electrical properties (for example, n-n^+, p-n, p-p^+ semiconductors), or between a metal and a semiconductor.

junction depth (of a *p-n* semiconductor radiation detector). The distance below the crystal surface at which the conductivity type changes.

leakage current (of a semiconductor radiation detector). The total detector current flowing at the operating bias in the absence of radiation.

lithium-drifted detector. A detector made by the lithium compensation process.

lithium drifting. A technique for compensating p-type material by causing lithium ions to move through a crystal under an applied electric field in such a way as to compensate the charge of the bound acceptor impurities.

noise linewidth. The contribution of electronic noise to the width of a spectral peak.

noninjecting contact (of a semiconductor radiation detector). A contact at which the carrier density in the adjacent semiconductor material is not changed from its equilibrium value.

ohmic contact (of a semiconductor radiation detector). A purely resistive contact, that is, one that has a linear voltage-current characteristic throughout its entire operating range.

peaking time (t_p of a pulse). The time interval between the one percent point on the first transition and the top centerline (see IEEE Std 194-1977 [4]).

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***p-i-n* detector.** A detector consisting of an intrinsic or nearly intrinsic region between a *p* and *n* region.

position-sensitive detector. A detector in which the centroid of the area of impact of ionizing radiation (at the surface of the detector) can be measured in one or two dimensions.

pulse duration. The width of a pulse measured between the first and last transitions at designated levels (see IEEE Std 194-1977 [4]).

pulse width. *See:* **pulse duration.**

quasi-Gaussian shaping. Pulse shaping in a linear amplifier in which the amplitude of the shaped pulse versus time approximates that of a normal distribution (in the case of unipolar shaping) or its mathematical derivative (in the case of bipolar shaping). Unless otherwise stated, the shaping network shall contain at least four cascaded low pass sections (integrators).

resolution, energy. *See:* **energy resolution.**

Schottky-barrier contact. A metal-semiconductor contact structure in which rectification occurs that is heavily influenced by the difference in the work functions of the materials. The contacts frequently consist of an interfacial metal/semiconductor compound such as a silicide.

Schottky-barrier radiation detector. A semiconductor radiation detector in which the blocking contact is a Schottky barrier contact.

semiconductor, compensated. A semiconductor in which one type of impurity or imperfection (for example, donor) partially cancels the electric effects of the other type of impurity or imperfection (for example, acceptor).

semiconductor radiation detector. A semiconductor device in which the production and motion of excess free charge carriers is used for detection and measurement of incident radiation.

shaping constant. An arbitrary indicator of shaped pulse width. The use of this designation is discouraged. *See:* **shaping index.**

shaping index $t_{0.5}$. The width of a unipolar pulse at 50% of its peak height.

space-charge generation (in a semiconductor radiation detector). The thermal generation of free charge carriers in the space-charge region.

space-charge region (of a semiconductor radiation detector). A region in which the net charge density is significantly different from zero. *See:* **depletion region.**

spectral line. A sharply peaked portion of the spectrum that represents a specific feature of the incident radiation, usually the full energy of a monoenergetic radiation.

spectrum (radiation). A distribution of the intensity of radiation as a function of energy, or a distribution of the amplitudes of the electrical pulses caused by the radiation.

straggling, energy. The random fluctuations in energy loss whereby those particles having the same initial energy lose different amounts when traversing a given thickness of matter (This process leads to the broadening of spectral lines).

surface-barrier contact. A metal-insulator-semiconductor (MIS) contact structure in which the rectification properties are dominated or heavily influenced by charge trapped at the interfaces and in the insulator.

surface-barrier radiation detector. A radiation detector for which the blocking contact is a surface barrier contact.

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sweep-out time, charge (of a semiconductor radiation detector). *See:* **charge collection time.**

tailing time (of an amplifier output pulse). The time interval between the top centerline of a unipolar pulse and the one percent level on the last transition (see IEEE Std 194-1977 [4]).

top centerline (of a pulse). In a peaked pulse, the ordinate that passes through the peak. In a flat-topped pulse, the ordinate that bisects the nominally flat-topped region (see IEEE Std 194-1977 [4]).

totally depleted detector. A detector in which the thickness of the depletion region is essentially equal to the thickness of the semiconductor material.

transition (pulse). The region of a pulse in which a major change in amplitude occurs, such as the leading edge (first transition) or final trailing edge (last transition) (see IEEE Std 194-1977 [4]).

transmission detector. A totally depleted detector in which the thickness, including entrance and exit windows, is sufficiently thin to permit radiation to pass completely through it.

useful active dimension (of a position-sensitive detector). A dimension (length, width) of that region of a position-sensitive detector over which the specifications of resolution and linearity are met.

walk (shaped pulse). The change in a timing point that occurs when the pulse height changes.

window (of a semiconductor radiation detector). *See:* **dead-layer thickness.**

window amplifier. *See:* **biased amplifier.**

4. Introduction

4.1 Interaction of Charged Particles with Matter

Charged particles interact with matter giving up energy through

1) Inelastic collisions with atomic electrons
2) Inelastic collisions with atomic nuclei

Other energy losses due to radiative processes and nuclear reactions are usually negligible.

For energetic charged particles (≥ 1 MeV per atomic mass unit), the energy loss is primarily due to collisions with electrons of the absorbing material. For each collision between a heavy charged particle and an electron, the amount of deflection and energy transfer is small. Many such interactions take place as the particle loses energy along a relatively straight trajectory. Under such conditions, the particles can be characterized by a definite range R and specific ionization loss (energy lost per unit path length) dE/dx within the absorbing material.

For highly ionized particles, atomic displacements can become an important part of the energy-loss process. This is the case for fission fragments, heavy ions, or lighter charged particles near the end of their range.

Energetic electrons also interact with matter through the coulomb force. Because of the small mass of the electron, no significant energy is transferred to nuclei. However, at energies of more than a few MeV, radiative processes (Bremsstrahlung) and pair production become significant in high-Z material.

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Because their mass-to-charge ratio is small, electrons are scattered along erratic tracks, and the previous concept of range cannot be used. Instead, the concept of 10% transmission range may be applied. This range is that absorber thickness that results in 10.% electron transmission at a given incident electron energy.

4.2 Semiconductor Charged-Particle Detector

4.2.1 The Basic Detector

When charged particles interact with a semiconductor crystal, electrons are scattered in lattice bonds by the processes described in 4.1, resulting in the creation of free electron-hole pairs. The average energy ε required to create a free electron-hole pair at a given temperature in a semiconductor is relatively insensitive to the type and energy of the ionizing radiation (for $E >> \varepsilon$). Values of ε are 3.6 eV at room temperature in silicon, 3.8 eV at 80 K in silicon, and 3.0 eV at 80 K in germanium. Therefore, for a given semiconductor at a given temperature, it is usual for the number of electron-hole pairs produced by the absorption of a charged particle to be directly proportional to that particle energy.

The detector consists of a semiconductor crystal between two electrical contacts. The detector may be a diode functioning in the reverse-biased mode. This is necessary to allow the attainment of sufficient electric-field strength between the detector contacts for efficient charge transport without excessive leakage current. If the resistivity of the semiconductor material is sufficiently high, rectifying contacts may not be necessary.

The application of bias voltage establishes a depletion region in which the concentration of charge carriers is greatly reduced and in which an electric field exists. Within this depletion region the free electron-hole pairs produced by a charged-particle interaction with the semiconductor material are swept to opposite contacts by the electric field. This process produces a current pulse at the input of a preamplifier. The integral of this pulse is a measure of the total signal charge and thus of the energy of the incident charged particle.

Due to a number of deleterious effects, the signal charge may be less than expected. A significant part of this reduction may be due to energy lost in nuclear collisions within the detector. Such collisions may even give rise to reaction products that are detected separately. Another part of this signal loss may be attributed to poor charge collection from within the dense plasma created along the paths of some particles. The plasma shields electrons and holes from the electric field of the detector and favors electron-hole pair recombination. Another part of this signal loss may be attributed to charge trapping, low electric field and slow charge collection. Additionally, some of the incident particle's energy may be lost in a dead layer or window thereby contributing a reduced amount of charge to the detector output signal.

4.2.2 Geometry

Charged-particle detectors are usually made in the planar configuration in which the two contacts are segments of parallel planes. The dimensions of the active region of the detector are usually determined by the dimensions of the contacts.

Detectors may be partially depleted or totally depleted. In a partially depleted detector, the depletion region extends inward from the front contact but is separated from the back contact by undepleted material. In totally depleted detectors this depletion region extends from one contact to the other. Totally depleted detectors are useful in (ΔE, E) telescopes and in timing measurements with heavy ions and fission fragments, and also in other applications requiring a very uniform sensitive depth.

Although planar detectors are usually made as disks, other shapes are sometimes used. Annular detectors may be employed to measure backscattering of a beam that passes through a hole in the detector. Detectors of the position-sensitive type are often made in a rectangular configuration. A coaxial cylinder geometry can be used to maximize detector active volume for a given depletion-layer thickness. This is primarily of importance for high-energy γ-ray detectors and for high-range particles.

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4.2.3 Material

Charged-particle detectors are usually made of silicon, but germanium and other materials may also be used. The higher density of germanium results in a reduced range for energetic particles. Therefore, for a given detector thickness particles of significantly higher energy may be studied with a germanium detector than may be studied with a silicon detector. However, silicon detectors are often more convenient to use because they may be operated at room temperature while germanium detectors must be operated at cryogenic temperature. In addition, silicon detectors typically have thinner dead layers than germanium detectors.

The thickness of the depletion region, which may be obtained with a given material, is dependent on the purity of the material and the applied bias voltage. For silicon, the room-temperature resistivity is often used as a measure of the purity of the material. As an example, a silicon detector with an electrically active impurity concentration of $1.1 \cdot 10^{12}$ cm^{-3} (resistivity of 4500 Ω·cm for *n*-type or 12 000 Ω·cm for *p*-type) requires a bias of 70 V to achieve a depletion region 300 μm thick. Impurity concentrations in the $5 \cdot 10^{11}$ to $2 \cdot 10^{11}$ cm^{-3} range (~ 10 000 Ω·cm to 20 000 Ω·cm, *n*-type) allow depletion layers of 1 mm to 1.5 mm to be obtained at several hundred volts bias. Silicon of sufficient purity (in the range of 1.10^{11} cm^{-3} or less) provides depletion layers of 3 mm to 5 mm with bias of 1000 V or more. However, silicon material of this purity has been difficult to obtain.

The lithium-compensation technique was developed to allow fabrication of Si (Li) detectors with depletion layers many millimeters thick starting with readily available material of relatively low resistivity. In this process lithium ions are drifted deep into the detector under the influence of an electric field in such a way that the lithium compensates the acceptor impurities in *p*-type silicon. This produces a region of nearly intrinsic material. Such devices are sometimes referred to as a *p-i-n* diodes.

Much work has been directed towards developing detectors for ionizing radiation from compound semiconductors such as mercuric iodide, cadmium telluride, and gallium arsenide. Although the main advantages of such materials are probably in γ-ray and X-ray applications, they may also prove useful for charged particles.

4.2.4 Fabrication

After suitable semiconductor material is obtained, a detector shape is produced by slicing, dicing, or other techniques. For thin ΔE detectors, special shaping techniques are required to ensure that the detector thickness is sufficiently uniform. Treatments involving the bulk of the material, for example lithium compensation, may also be performed.

Noninjecting detector contacts must be fabricated. One of the contacts is usually a reverse-biased rectifying junction, which can be a surface barrier, a Schottky barrier, or a diffused, alloyed, or ion implanted junction.

Since one of the detector contacts serves as the entrance window, a dead layer associated with this contact directly affects the detector performance. One effect is a pulse-height reduction due to the absorption of part of the energy of incident particles in the dead layer. Any variation in the angle of incidence of the particles or any nonuniformity in the dead-layer thickness will cause variations in the amount of energy absorbed and result in spectral broadening. Even if the dead layer is uniform and the angle of incidence is constant, the energy loss in the dead layer undergoes fluctuations (which increase in magnitude with dead-layer thickness) that contribute to spectral broadening. Depending on the nature of the dead layer and the ionizing radiation, some nonlinearity in energy response may also result.

Detector contacts have special significance for the position-sensitive detector in which both energy and position of impact are measured. One configuration of this detector utilizes a resistive contact that acts as a current divider. The output pulse height is representative of the impact position along the length of the detector. However, the resistive contact is a source of noise that reduces both the energy and spatial resolution of the device. In some applications this is overcome by the use of an array of separate detectors with individual outputs.

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The fabrication of silicon or germanium detectors also requires the achievement of critical surface conditions through such techniques as etching and other chemical treatments. This is necessary to produce surfaces that can withstand high electric fields without producing excessive leakage current or electrical noise.

4.3 Bias Resistor

Depending upon the type and size of detector, leakage current can vary over a wide range. This factor influences the choice of detector bias resistor (which is usually located in the preamplifier). For the best SNR, it is desirable to make the bias resistance 100 MΩ or more, but the resistance shall not be so high that leakage current flowing through it causes a voltage drop greater than 10% of the bias-supply voltage at the operating temperature. It should also be recognized that leakage current approximately doubles for every 8 °C increase in temperature.

4.4 Pulse Shaping

To optimize the SNR and count-rate performance obtainable from any given semiconductor detector and amplifier combination, it is necessary to use some form of electrical filtering procedure. This is carried out by suitable electrical networks associated with the amplifying system. One pulse is produced for each event registered in the detector. The shape of the pulse can be unipolar or bipolar. A unipolar pulse is one with a single lobe. A bipolar pulse contains two lobes, one above and the other below the baseline, with the areas of the two lobes equal to each other. Because unipolar pulses yield a better SNR and a shorter resolving time than bipolar ones, the former are used almost exclusively in high-resolution spectrometers.

While the pulse shape yielding the best SNR is known to be a symmetrical cusp, it is not used because its extended skirts result in poor count-rate performance, and the sharp point at the top causes a large change in pulse height for a small change in detector collection time. Instead, it is usual to use *quasi-Gaussian* or *quasi-triangular* shaping. Both forms are produced by a single *CR* differentiator followed by up to six *RC* integrators. More than six integrators can be used, but the improvement in performance does not justify the added cost and complexity.

4.4.1 Quasi-Gaussian Shaping

One form of quasi-Gaussian shaping is produced by a CR-$(RC)^n$ network with all time constants alike. Its response to a detected event is of the form

$$V_A = K(t/\tau)^n e^{-t/\tau}$$

where

K = numerical constant
n = number of integrating sections (the order of the network)
τ = time constant of the differentiator

Another form is known as sine^n shaping, characterized by

$$V_A = K e^{-3t/\tau} \text{sine}^n t/\tau$$

In this network the integrating time constants are all different and follow a particular pattern. This form yields a better SNR and shorter resolving time for the same number of *RC* sections than the CR- $(RC)^n$ network.

4.4.2 Quasi-Triangular Shaping

This form of shaping is derived from either of the preceding quasi-Gaussian networks by summing the signals of early integrating sections with that of the last. The waveform has a nearly linear rate of rise.

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4.4.3 Waveform Features

A comparison between quasi-Gaussian (solid lines) and quasi-triangular (dotted lines) waveforms normalized to $t_{0.5}$ is shown in Fig 1. The parameters of interest are the FWHM of the pulse $t_{0.5}$, the peaking time t_p measured from one percent amplitude on the leading edge (first transition) to the top centerline, the trailing time t_t measured from the top centerline to one percent amplitude on the trailing edge (last transition), and the total width at one percent amplitude $t_{.01}$, which is the sum of t_p and t_t.

4.4.4 Effect of Pulse Shape on SNR and Energy Resolution

The rms parallel noise transmitted through the system is directly proportional to the square root of the shaping index $t_{0.5}$; the rms series noise is inversely proportional to its square root. The total noise is minimized when the two components are equal and also when the waveform is symmetrical, that is, when t_p/t_t is near unity.

This last condition is approached asymptotically by adding integrating sections. The count-rate performance is inversely proportional to $t_{.01}$. It can be seen from Fig 1 that the quasi-triangular waveform is both narrower at $t_{.01}$ and more symmetrical than its quasi-Gaussian counterpart, and, as expected, results in better SNR and count-rate performance. However, the contrast in Fig 1 is exaggerated because the quasi-triangular network was derived from a 6th order sine^n shaper whereas the quasi-Gaussian waveform is that due to a 4th order network. If the comparison were made with both shapers obtained from a 6th order sine^n network, the quasi-triangular rms noise and the $t_{.01}$ width would be, respectively, 0.3% and 8% less than the CR-$(RC)^n$ counterparts, with the noise improvement occurring solely in the parallel component.

A noise minimum exists at a particular $t_{0.5}$. Depending upon detector characteristics and needed count-rate performance, the optimum operating point may be at or on either side of the minimum. High detector leakage current drives the minimum towards lower $t_{0.5}$ and degrades the SNR regardless of where the minimum occurs. The degradation is exacerbated by the necessity of using a smaller detector-bias resistor than would otherwise be necessary. As partial compensation, a lower $t_{0.5}$ allows a higher counting rate for a given loss in energy resolution. It should be noted that the rms noise performance and the resolving time of the most complex shaping network, 6th order quasi-triangular, are, respectively, 17% and 29.5% better than that of the simplest and worst-performing network, CR-$(RC)^1$.

In the energy range of most α particles (3.5 MeV – 8 MeV), straggling dominates the energy resolution unless the detector capacitance or leakage current, or both, are high. At lower energies, electronic noise dominates, including the component due to leakage current. At low energy and at low counting rates, it is worthwhile finding the shaping index that results in minimum electronic noise; at higher counting rates, optimum energy resolution will occur at shaping times less than that resulting in minimum electronic noise.

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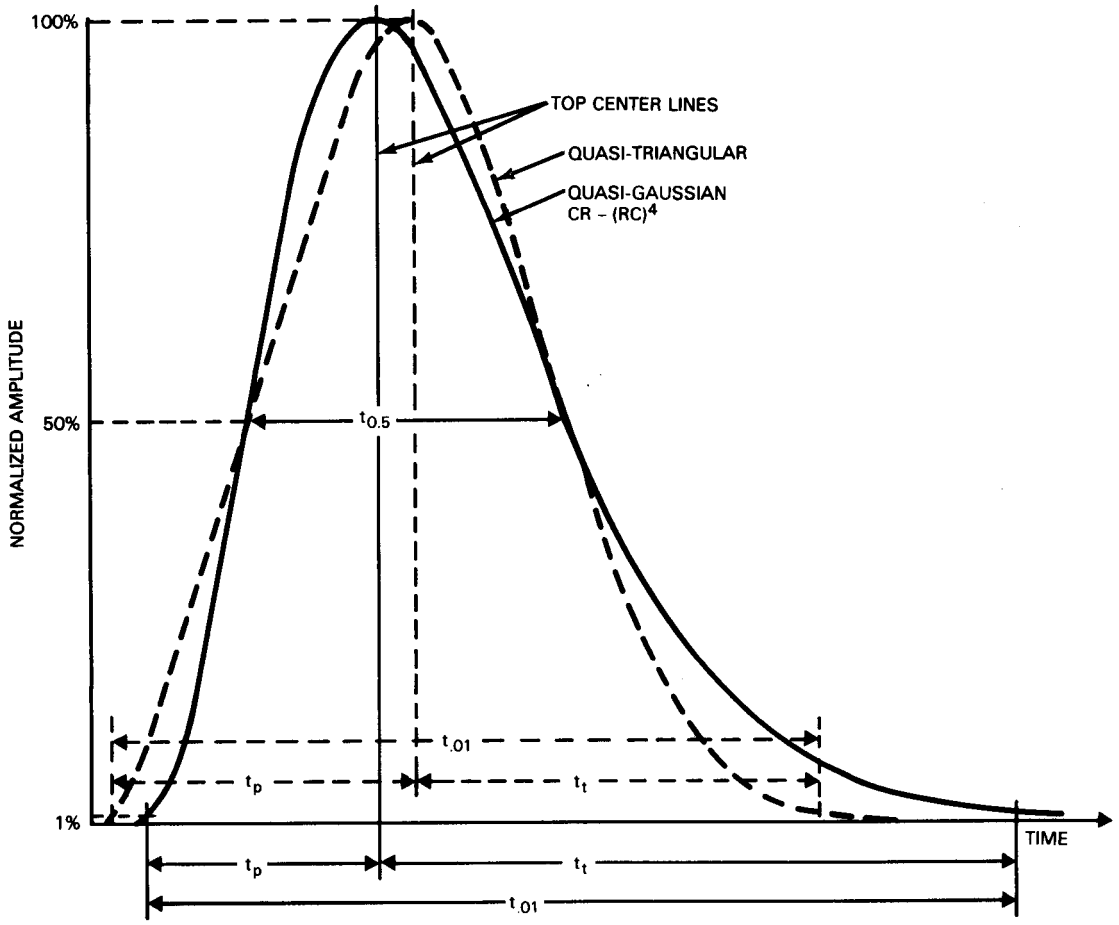


Figure 1—Quasi-Gaussian (solid line) and Quasi-Triangular (dotted line) Pulse Shapes

4.4.5 Standard Test Conditions

From the foregoing, it is clear that not all measuring conditions can be anticipated and a reasonable choice must be made: When specifying particle-detector performance, the tests shall be made with an amplifier system containing a 4th order or higher quasi-Gaussian shaping network with $t_{0.5}$ = 1 μs and a detector bias resistor such that the voltage drop due to detector leakage current does not exceed 10% of the supply voltage at 20 °C. All tests shall be performed at 20 °C and all test parameters shall be included as part of the specifications. It should be noted that with a sine^6 shaping network, $t_{0.5}$ and t_p differ by 2.3%. With a quasi-triangular network derived from a sine^6 network, the difference is 6%. The discrepancy widens to 17% for a CR-$(RC)^4$ network.

5. General Requirements

The following requirements apply for all of the tests and measurements described herein.

5.1

All measurements shall be performed with the device itself in total darkness unless otherwise specified.

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5.2

The ambient conditions shall be 20 °C and a pressure of less than 10^{-6} torr, unless otherwise specified. Precautions should be taken when working in the pressure region (~ 0.1 μmHg - 100 μmHg) because of corona discharge. Also, some detectors that work satisfactorily at higher pressures may show degradation at pressures lower than 10^{-6} torr.

5.3

The values of the parameters measured shall be reproducible within the specified precision after any and all of the tests have been performed.

5.4

The detector bias supply and other test equipment (amplifier, multichannel analyzer, etc) shall not significantly influence the detector parameter measurements.

5.5

Maximum diode voltage, current, radiation flux ratings, and other manufacturer specified limits should not be exceeded or permanent changes of the device characteristics may result.

5.6

It must be confirmed that the radioactive sources that are used do not contribute to the resolution broadening (This may occur especially with alpha-particle sources due to self attenuation and aging effects).

5.7

All data reported should correspond to equilibrium conditions unless clearly noted otherwise.

5.8

All measurements must be made and reported in accordance with proper scientific practice. Changes in test system components (for example, substituting a different preamplifier or detector) or changes in system parameters (for example, changing gain or equivalent detector capacitance) may not be made without complete system recalibration. Results that contain the effects of changing more than one parameter must explicitly show the effects of each parameter on the measurement.

5.9

The detector bias resistor shall be such that leakage current through the detector at the operating temperature of the tests causes no more than 10% of the applied bias voltage to be lost in the resistor.

5.10

When performance data are presented, no more significant figures shall be given than fit the context of the measurements or the use to which they will be put. Usually, two or three significant figures are adequate. In the absence of a ± tolerance it is implied that the last figure is meaningful to ±0.5 in the next place, for example, 1.35 implies 1.35 ±0.005, or the range from 1.345 to 1.355.

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6. Resolution Measurements

6.1 Energy Resolution

The resolution of a detector system at a specific energy is determined by measuring the full width at half maximum (FWHM) of a spectral peak. A source of ionizing radiation emitting one or more prominent lines is used.

The detector is connected to an integrating (charge sensitive) preamplifier, main amplifier, and multichannel analyzer as in Fig 2. The amplifier pulse shaping shall be quasi-Gaussian with a $t_{0.5}$ of 1 μs. Alternatively, other shaping may be used, but the shaping characteristics must then be clearly stated. The precision pulse generator should be turned to OFF when measuring the resolution for ionizing radiation.

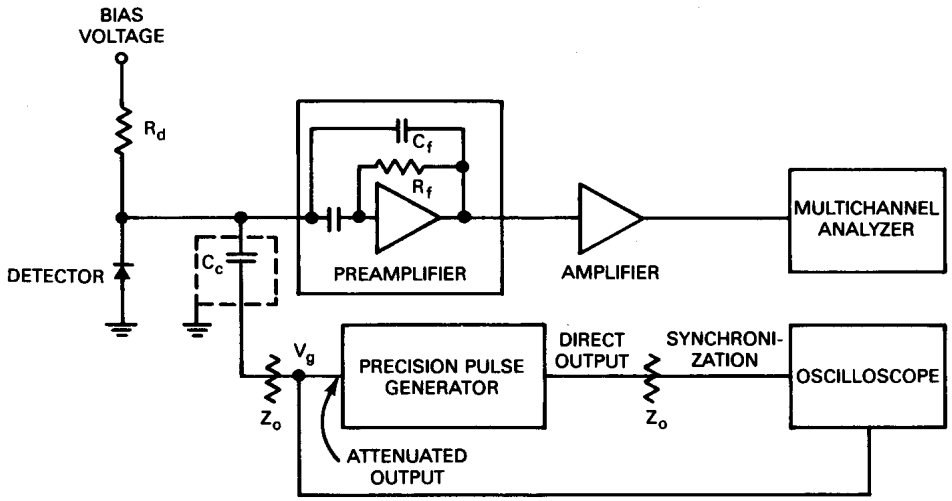


Figure 2—System Configuration for Spectral Measurements

A spectrum shall be acquired in which the peak to be measured has a FWHM of at least six channels and a peak channel count of at least 4000 counts. At least one other peak should be located in the spectrum for the purpose of energy calibration. This may be a line of known energy from a source of ionizing radiation. Alternatively, it may be a line produced by a precision pulse generator. A typical spectrum for this measurement is shown in Fig 3.

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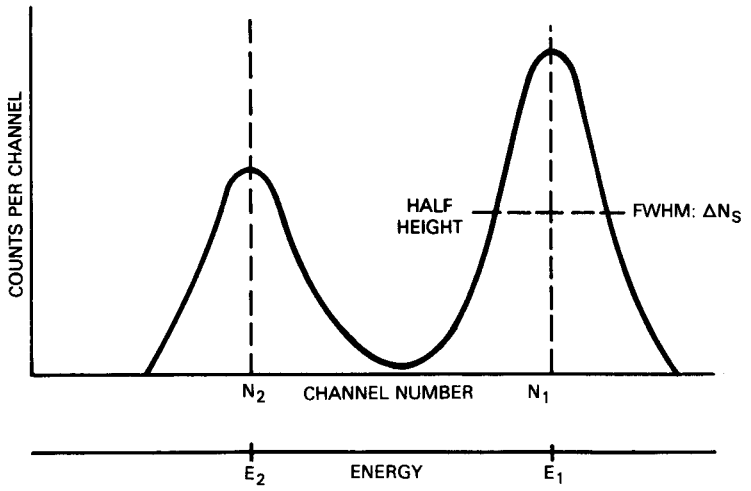


Figure 3—A Typical Spectrum

The FWHM of the peak is measured in channels ΔN_s (interpolated). The channel location of the peak center can be determined by the method described in ANSI/IEEE Std 325-1986 [3], 8.4. The energy E_1 of the peak should be known and its channel location N_1 noted. If a second peak corresponding to energy E_2 with channel location N_2 is known, then the FWHM in energy units is given by Eq 1.

$$\mathrm{FWHM_S} = \frac{E_1 - E_2}{N_1 - N_2}\Delta N_s \tag{1}$$

If the peak corresponding to energy E_2 is produced by a precision pulse generator, then the pulse generator is calibrated by adjusting the attenuation of the output until pulses of voltage V_{p1} are shown to produce a peak of channel location N_1 on the multichannel analyzer. This is the same location as that of the peak of known energy E_1. Then a second peak is generated using pulses of voltage V_{p2}. The energy corresponding to this peak is given by

$$E_2 = V_{p2}\left(\frac{E_1}{V_{p1}}\right) \tag{2}$$

The value of E_2 can then be used in Eq 1 to find the FWHM in energy units.

Energy calibration may also be accomplished by appropriate normalization of pulser output. First, the linear attenuator output of the pulser is set to a multiple of the numerical value of the peak energy E_1. Then a second (normalization) attenuator is adjusted until the output voltage is V_{p1}. This voltage is achieved when the output pulses produce a peak at channel location N_1 corresponding to energy E_1. The linear attenuator may then be set to the desired value of E_2, and the output voltage will be V_{p2}. The actual values of V_{p1} and V_{p2} do not need to be known since their relative values are given by the attenuator setting. When this method is employed, the precision pulse generator shall have an integral nonlinearity of $< 0.1\%$.

In recording information on energy resolution, the following conditions shall be noted:

1) Incident particle type and energy
2) Amplifier pulse shaping parameters ($t_{0.5}$, t_p, t_t, $t_{.01}$ and type of pulse shaping utilized)
3) Detailed description of the detector including active area and sensitive depth
4) System total noise FWHM with the detector connected and operating
5) Detector operating conditions (bias, temperature, ambient atmosphere)

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6) Detector bias resistor
7) Detector-source geometry including identification of the detector face on which the radiation is incident
8) Count rate

6.2 Time Resolution

The measurement technique given here is recommended for its convenience and reproducibility. Instead of charged particles, which is the usual signal source for measurements of this type, a light pulse from a laser diode pulser (LDP) is used (Plasma effects accompanying charged particles and the spatial dispersion of long tracks will degrade the time resolution).

A coincidence measuring system is shown in Fig 4. The LDP furnishes the start pulse for the TAC, and the output signal initiated by the detector triggers the stop signal. A spectrum of time dispersion is accumulated in the MCA. In the chain between the detector and the TAC is a fast preamplifier, a fast shaping amplifier, and a constant-fraction discriminator in which the fraction is set at 20% and the delay at 1.1 t_r (10%-90%). Shaping times should be adjusted to optimize the timing performance. Usually, the optimum occurs when no integration is used and when the differentiation time constant is somewhat greater than the rise time of the signal from the preamplifier. Also in the system is a shaping amplifier that gates the MCA, allowing the selection of energy bands.

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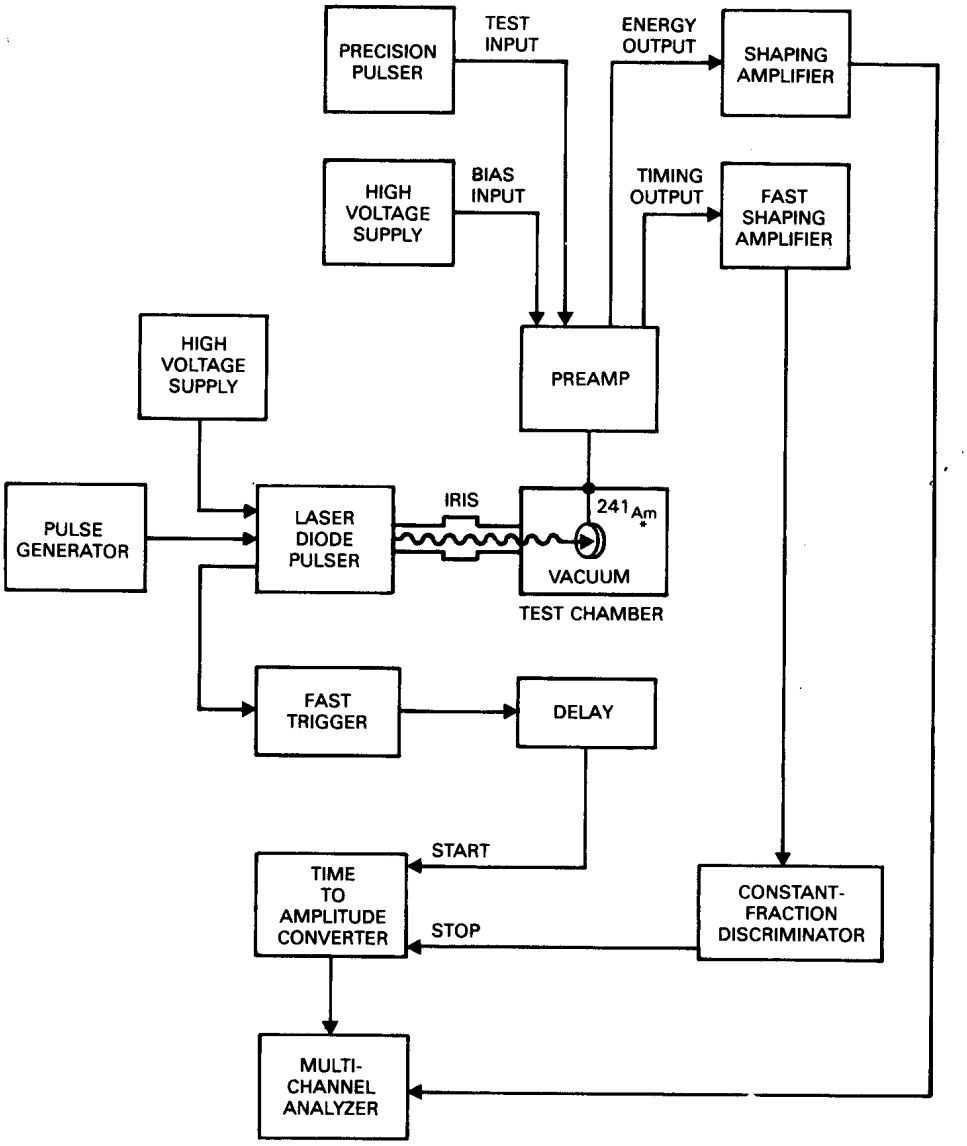


Figure 4—Time Resolution Measurement System

The FWHM and FW. 1M of the time-distribution peaks at several energies shall be stated. The energies selected should cover the operating range and should be separated by approximately equal intervals.

The equivalent energy of the light pulses from the LDP must be known. A vacuum chamber is used in which the detector may be rotated to face either the LDP or a ^{241}Am source. The precision pulse generator is first calibrated for the 5.486 MeV α line of ^{241}Am. Then the desired energy is selected with the pulser, and the LDP adjusted to produce the same signal amplitude. Typically, several timing measurements are made at energies ranging from ~ 1 MeV to ~ 100 MeV. The precision pulser output should be turned to OFF while the timing measurement is being made.

Using this method, a timing peak should be obtained with a FWHM of at least six channels, and with at least 4000 counts contained in the peak channel. Alternatively, if computer fitting is used, determination of the FWHM within ±5% (90% confidence level) is adequate.

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After calibrating the time axis with at least two calibrated delays, the FWHM and FW.1M shall be measured and stated in units of nanoseconds. Measurements at three or more energies ranging from ~ 1 MeV to ~ 100 MeV, as obtained by adjustment of the iris diaphragm (Fig 4), are recommended (Quadrature subtraction can be used to determine the time resolution of the detector itself from the system time resolution that is measured). The following parameters shall be stated for each measurement:

1) Spectral characteristics of the pulsed light
2) Detector bias voltage
3) Constant-fraction discriminator setting and shaping time delay
4) Differentiation time and rise time of the fast shaping amplifier

6.2.1 Detector Electrical Rise Time

Using the apparatus of Fig 5, a step of $|V_p|$ volts is applied in series with the detector. The value of V_p shall not exceed one tenth of the band-gap voltage, or one tenth of the bias voltage, whichever is the smaller. The quadrature difference between the rise time of the preamplifier output signal with the detector connected and the preamplifier rise time is defined as the electrical risetime.

6.2.2 Charge Collection Time

Direct measurement of charge collection time t_c for one sign of charge carrier in relatively *slow* detectors can be made by using a monoenergetic source of short-range particles and observing the signal pulse directly at the output of a charge-sensitive preamplifier. If the observed 10% to 90% output pulse rise time is t_o, while the rise time observed by injecting pulses into the preamplifier input from a precision pulse generator is t_r, then the detector charge collection time is given by Eq 3.

$$t_c = \sqrt{t_o^2 - t_r^2} \tag{3}$$

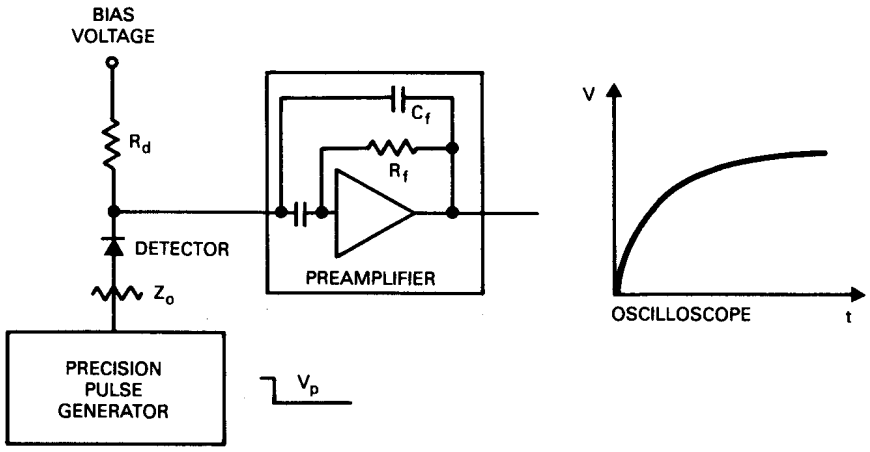


Figure 5—Detector Electrical Rise Time Measurement

For this measurement to be significant, t_o and t_r must differ by at least 20%.

The response of a fast detector is most easily measured by using a pulsed accelerator or fast light source to generate a large number of hole-electron pairs in a detector. The resulting current pulse is directly monitored with a sampling oscilloscope. In either case, it is essential to determine the detector electrical rise time (see 6.2.1) by separate measurements and to distinguish its effect from that due to carrier motion in the depletion layer.

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Charge-collection-time data shall include details of the nature of the incident radiation, track orientation and position, and amplifier rise time.

6.3 Position Resolution and Linearity of a Position-Sensitive Detector

One common type of position-sensitive detector is shown in Fig 6. This detector has one contact of relatively high resistivity that has one end grounded and the other end connected to a preamplifier input. The resistive contact acts as a current divider, and as a result, the output pulse height is proportional to the distance of the position of impact from the grounded end of the detector. Bias voltage is applied to the contact on the rear surface.

Both position and energy measurements for this type of detector should be made using the system shown in Fig 7 (preferred method) or an equivalent system. As an alternative, commercially available analog pulse dividers may be used.

Shaping indexes and other settings should be optimized. The system as used must be capable of measuring simultaneously position and energy. This is required since a system configured only for energy measurements may have measurably better resolution than a system configured for the simultaneous measurement of energy and position. An energy-only system may provide a useful measurement of the detector quality but it is not fully representative of the detector performance in other applications.

Position resolution and linearity measurements are performed with a mask having slits in it placed in front of the detector face as shown in Fig 8. The slits are perpendicular to the direction along which position is measured. A minimum of 5 slits shall be used, and they should be approximately uniformly distributed across the mask in front of the active region of the detector. A slit image shall be located at each end and near the middle of the useful active length of the detector because the deviation from linearity is usually largest at the ends. Sources of monoenergetic ionizing radiation shall be located in front of the mask in such a way that an image of each slit is formed on the surface of the detector by the beam of radiation impinging on that slit.

The details of collimation, source location, and geometry shall be such that the following conditions are met:

1) There is a one-to-one correspondence between the slits on the mask and the slit images on the detector.
2) The width of the image of each slit is small enough that it does not introduce any significant error into the position resolution measurements. If any corrections are made for finite slit width, a simple quadrature subtraction is inadequate. Any correction must not exceed 10% of the reported result.
3) The error in determining distances between the slit imges is small enough that it does not introduce any significant error into the position linearity measurement.. This usually requires placing the slits as close to the detector surface as possible.
4) The image of each outermost slit shall be located within two slit widths of the ends of the useful active length of the detector.

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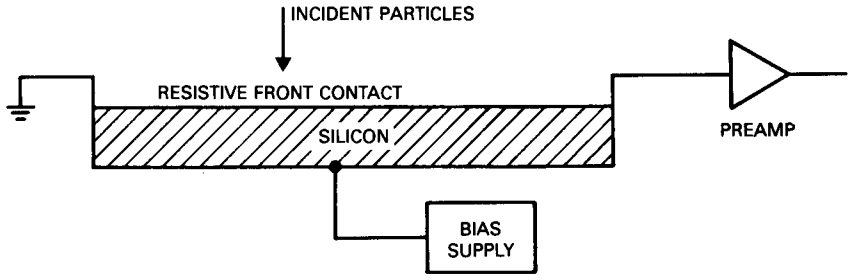


Figure 6—Position-Sensitive Detector

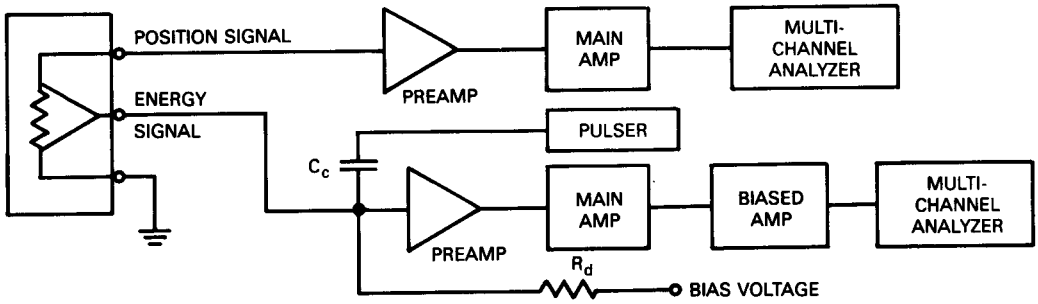


Figure 7—Position-Sensitive Detector Measurements

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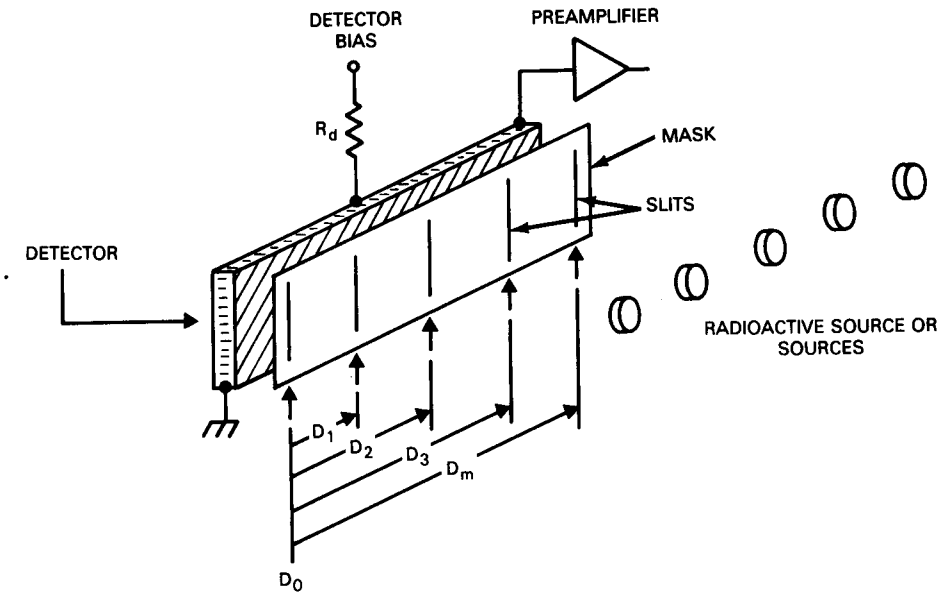


Figure 8—Apparatus for Position Measurements

A spectrum shall be acquired using the described methods. Each peak must have a FWHM of at least six channels with a minimum of 4000 counts in the peak channel. Position linearity and resolution are determined from this spectrum.

The integral nonlinearity (in position) of a position-sensitive detector is defined as the maximum positional deviation from linearity expressed as a percentage of the total length over which the measurement is made. The deviation from linearity shall be measured for each slit image, and the integral nonlinearity of the detector shall be determined from the largest of these values.

Let the peak-count channel numbers be S_0, S_1, S_2,… S_i, … S_m where S_0 and S_m are the smallest and largest count respectively. Let the distances from the first slit image to successive slit images be represented by $D_1, D_2,\ldots D_1,\ldots D_m$. Set $D_0 = 0$, and let D_m be the distance between the two outermost slits. A straight line is then fitted to the set of points (D_0, S_0), (D_1, S_1), (D_2, S_2), … (D_i, S_i),… (D_m, S_m) by the method of least squares. Let ΔD_{max} be the maximum difference between any value of D_i and the corresponding value of D on the fitted line at the point where $S = S_i$. The integral nonlinearity L_p of the detector is given by Eq 4.

$$L_p = \frac{\Delta D_{max}}{D_m} \tag{4}$$

Position resolution is calculated for each slit image. Given the FWHM of a peak in channels, the position resolution in units of length ΔD_p is given by Eq 5.

$$\Delta D_p = \frac{D_m}{S_m - S_o} \text{ FWHM} \tag{5}$$

If one value of positional resolution is given to characterize the entire detector, it shall be the largest FWHM value obtained for any slit image. Record the same information with this measurement as requested for the energy measurement in 6.1.

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The following information shall be supplied with the results of this linearity measurement.

1) Total active length of the detector
2) useful active length of the detector
3) Shaping indexes (shaping time characteristics) used for energy and position measurements
4) Detailed description of the detector including sensitive depth and detector geometry
5) Operating conditions
6) Incident particle type and energy

7. Noise Measurement

7.1 Noise Measurement by Pulse Height Distribution

7.1.1 Measurement with Radioactive Source Calibration

The total noise contribution to spectral broadening (including detector leakage current) can be measured by determining the FWHM of a peak produced with a precision pulse generator.

The equipment shall be configured as shown in Fig 2. The amplifier pulse shaping shall be quasi-Gaussian with a $t_{0.5}$ of 1 μs. Alternatively, other shaping suitable for the detector may be used, but the shaping characteristics must then be clearly stated and the same as that used to specify energy resolution. A simple method for system calibration is similar to that described in 6.1 using a source of monoenergetic ionizing radiation and a precision pulse generator. However, the radiation (of known energy E_1) need only be counted until the peak location N_1 is accurately known. The source is then removed, and the pulser is adjusted to generate a peak at this same location. A second peak, equivalent to energy E_2 at location N_2 is generated with E_2 determined from the calibration as in 6.1.

The spectrum of the second pulse generator peak shall be accumulated until it reaches 4000 counts in one channel. The width shall be at least six channels at FWHM. However, a lesser number of counts may suffice if computer fitting that determines the FWHM to within ±5% (90% confidence level) is employed. The total noise resolution is determined from the width of this peak in channels ΔN_T by Eq 6. The separation of the peaks shall be at least three times the FWHM.

$$\mathrm{FWHM_T} = \left[\frac{E_1 - E_2}{N_1 - N_2}\right]\Delta N_T \tag{6}$$

7.1.2 Measurement with Capacitor and Pulse Generator Calibration

An alternative to the method of 7.1.1 uses a pulse generator with a calibrated capacitor to introduce a known quantity of charge with each pulse to the preamplifier input. This leads directly to the determination of noise linewidth in units of charge.

If this method is to be used, a calibrated capacitor C_c is connected to the preamplifier input in series with a precision pulse generator. The capacitor C_c shall be contained in a shield enclosure; the capacitance is measured between its ends and the shield enclosure is grounded. A highly accurate measurement of the capacitance between the two insulated terminals can be obtained with a capacitance bridge in which the capacitance to ground does not influence the measurement between the ends.

The pulse generator should provide signals of the form shown in Fig 9, where the rise time t_r is no more than 5% of the main amplifier differentiating time constant and the decay time constant τ_d is such that the pulse V_p does not droop more than 2% in a time equal to the differentiating time constant of the system pulse-shaping network.

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Under these conditions the charge injected per pulse from the pulse generator is $V \cdot C_c$ coulombs to within approximately one percent. With all elements of the system operating within their linear range, two settings of the pulse generator, corresponding to voltages V_{p1} and V_{p2}, should result in a spectrum consisting of two separated peaks centered at channels N_1 and N_2 as shown in Fig 3. The system gain and pulse amplitudes must be such that the FWHM ΔN_T peak is at least six channels.

The system total noise linewidth FWHM, in coulombs, is given by Eq 7

$$\Delta Q_T = \frac{V_{p1} - V_{p2}}{N_1 - N_2} C_c \Delta N_T \tag{7}$$

with ΔN_T being determined from the wider of the two peaks.

The units of charge can be converted to units of energy by dividing ΔQ_T by the electronic charge $q = 1.60 \cdot 10^{-19}$, then multiplying by $\varepsilon = 3.60$ eV per hole-electron pair, which is the energy necessary to produce one hole-electron pair in silicon.

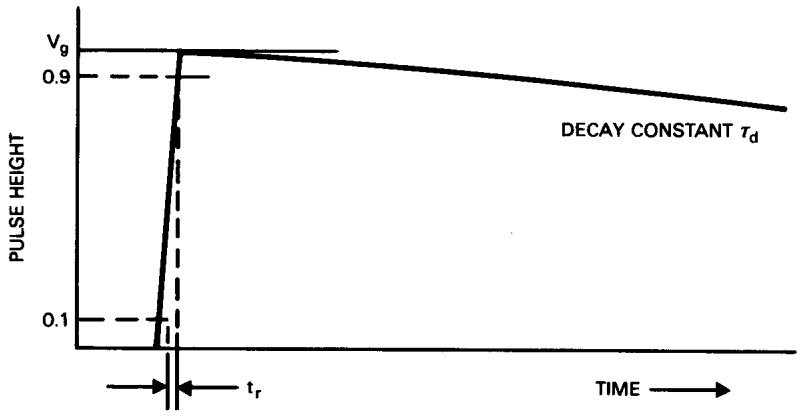


Figure 9—Precision Pulse Generator Waveform

7.2 Noise Measurement by Oscilloscope and True Root-Mean-Square Voltmeter

An alternative method of measuring noise employs the system shown in Fig 10. It is similar to that system used for pulse-height distribution measurements (Fig 2), but it differs in that a voltmeter replaces the multichannel analyzer (MCA).

The voltmeter response must be proportional to the rms value of the noise. A true rms meter is preferred, but a meter that contains a full-wave rectifier that responds to the average value of the input waveform and is calibrated for sine-wave response may be used, but its indications must be multiplied by 1.128 to convert its dial calibration to the rms value of a random-noise signal.

This method may utilize either a radioactive source or capacitor and pulse generator calibration.

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If this method is to be accurate, two conditions must be fulfilled.

1) The voltmeter must have a flat frequency response over the entire amplifier bandwidth. A suggested minimum 3 dB bandwidth is 10 MHz.
2) The amplifier incremental gain must be constant to well below the noise level. Neither a biased amplifier nor a baseline restorer may be used, because these force the amplifier into a region of extreme nonlinearity when the signal drops below their threshold levels.

7.2.1 Measurement with Radioactive Source Calibration

The detector is exposed to a source that has a prominent, easily resolvable line of known energy E. After the system gain is set to a convenient level, the output pulse amplitude V_o is read from the oscilloscope for pulses corresponding to energy E. The source is then removed, and the rms voltage $e_{n\,o}$ is read from the voltmeter. The total system noise FWHM is given by Eq 8.

$$\Delta E_T = 2.355 \frac{E}{V_o} e_{no} \tag{8}$$

7.2.2 Measurement with Capacitor and Pulse Generator Calibration

A pulse generator is used with a calibrated capacitor C_c, as in 7.1.2, to introduce a known quantity of charge with each pulse into the preamplifier input. After the system gain is set to a convenient level, pulses of amplitude V_p are applied to the calibrated capacitor. The system output pulse amplitude V_o is read from the oscilloscope. The pulse generator output is switched OFF, and the rms noise voltage $e_{n\,o}$ is read from the voltmeter. The total system noise FWHM (in units of charge) is given by Eq 9.

$$\Delta Q_T = 2.355 V_g C_c \frac{E_{no}}{V_o} \tag{9}$$

The FWHM in units of charge can be converted to units of energy as described in 7.1.2.

7.3 Measurement of Electronic Noise with Detector Removed

The electronic noise linewidth FWHM can be determined by the methods of 7.1 and 7.2 after disconnecting the detector from the circuit and substituting for it a suitable capacitor that has been shown not to contribute noise and which is of capacitance substantially equal to that which the detector exhibited under test conditions (see 9.2).

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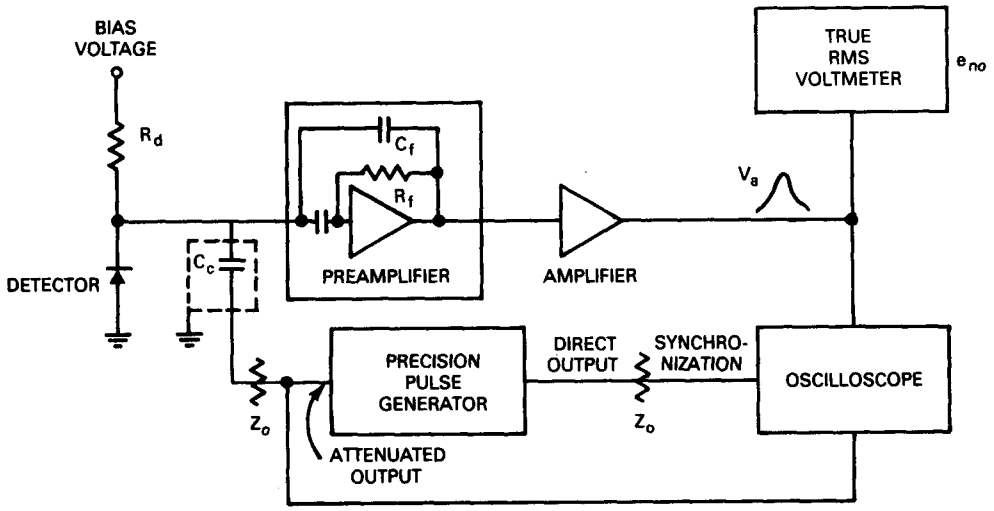


Figure 10—Noise Measurement by Oscilloscope and True RMS Voltmeter

If the radioactive source calibration is used, then it must be performed before the detector is removed. Care must be taken not to change the system gain before the measurement is made. The capacitor and pulse generator calibration may be performed with either the detector or the substituted capacitor in place.

The noise FWHM is determined in number of channels, units of charge, or in units of energy according to the methods of 7.1 and 7.2, and the symbols used are ΔN_E, ΔQ_E, or ΔE_E respectively. These values represent the electronic noise without the detector noise contribution.

7.4 Determination of Detector Contribution to Noise and Resolution

In Sections 6. and 7., methods are given to determine energy resolution ΔN_s, ΔE_s, total system noise ΔN_T, ΔQ_T, ΔE_T, and electronic noise other than detector noise ΔN_E, ΔQ_E, ΔE_E. These quantities are expressed in channels ΔN, in units of charge ΔQ, and in units of energy ΔE, respectively.

Since all of these spectral broadening effects add in quadrature, the following quantities of interest may be calculated for Gaussian or quasi-Gaussian distributions:

1) The detector contribution to spectral broadening attributable to factors other than noise, ΔN_o or ΔE_o.

$$\Delta N_O = \sqrt{\Delta N_S^2 - \Delta N_T^2} \tag{10}$$

$$\Delta E_O = \sqrt{\Delta E_S^2 - \Delta E_T^2} \tag{11}$$

2) The contribution to spectral broadening of detector noise alone ΔN_D, ΔQ_D, or ΔE_D.

$$\Delta N_D = \sqrt{\Delta N_T^2 - \Delta N_E^2} \tag{12}$$

$$\Delta Q_D = \sqrt{\Delta Q_T^2 - \Delta Q_E^2} \tag{13}$$

$$\Delta E_D = \sqrt{\Delta E_T^2 - \Delta E_E^2} \tag{14}$$

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7.5 Noise Linewidth (FWHM) as a Function of Amplifier Shaping Index

Information related to the detector noise spectrum can be obtained from the noise linewidth FWHM as a function of the amplifier shaping index. The method of 6.1 is employed with quasi-Gaussian pulse shaping. The noise linewidth FWHM should be plotted versus $t_{0.5}$ for a number of values of detector bias voltage. In quoting the results, the electronic noise referred to the input of the preamplifier should be given (see ANSI/IEEE Std 301-1988 [2] or ANSI/IEEE Std 325-1986 [3].

8. Sensitivity to Ambient Conditions

In performing the following measurements, the manufacturer's specifications should not be exceeded or permanent damage to the device may result.

For certain tests it may be appropriate to test the detector before and after exposure to specified conditions rather than during exposure. Other tests may be performed during exposure. When test results are quoted, it should be clearly stated whether they were obtained during exposure or before and after exposure. The limits of reproducibility of the measurements should be stated with the results.

8.1 Atmospheric Sensitivity

The detector shall be mounted in a chamber in which it can be tested while exposed to vacuum or to various gases under specific conditions of pressure, temperature, and humidity. Such conditions may include, for example, dry oxygen at standard temperature and pressure. Other appropriate conditions may be specified for particular applications.

In each environment, sufficient time must be allowed to enable the detector characteristics to reach equilibrium. Alternatively, the time spent in each ambient shall be recorded. Under each set of ambient conditions, the appropriate tests described in 6.1, 6.3, and 6.4 may be repeated.

As a caution, it should be noted that certain environments may be very harmful to many detectors. Bottled gas has been known to become contaminated with harmful substances such as certain acids. Some desiccants may give off a residual acid. Various solvents and cleaning compounds may evolve harmful vapors. Ammonia vapor and other reducing atmospheres may be harmful.

8.2 Vacuum Thermal Cycle Test

The ability of a device to withstand vacuum thermal cycling without degradation is important for certain applications. A temperature cycle over a specified range with a vacuum of 10^{-6} Torr is suggested.

The noise of a detector should first be measured at 20 °C. Then the detector should be taken through the required thermal cycle. Noise values at 20 °C, at maximum temperature, and at minimum temperature should be recorded. Finally, the temperature of the detector should be returned to 20 °C and the noise measured again. The final measured noise value should not differ from the initial noise value at 20 °C by more than the stated limits of reproducibility for the detector to pass this test.

The detector may be taken through a thermal cycle while under vacuum with no applied bias voltage. The detector should have a noise measurement at 20 °C with the same bias voltage before and after such a thermal cycle. Again, the two noise measurements should not differ by more than the stated limits of reproducibility for the detector to pass this test.

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8.3 Mechanical and Environmental Test

Detectors may be tested before, during, and after any specified mechanical, thermal, or other environmental exposure. All of the tests indicated in 6.1, 6.3, 6.4, and 7.6 may be performed. As a minimum the noise and leakage current should be measured before and after such exposure. Unless other specifications suitable for the particular application are stated, the measured characteristics of the detector should not change by more than the stated limits of reproducibility for it to pass such a test.

In certain cases, such as long term exposure to a vacuum ambient, it may be necessary to perform electrical tests during the exposure period and also before and after it.

8.4 Light Sensitivity

Most detectors are light sensitive and should be used and tested in the dark. Some detectors are constructed in such a way that they are relatively insensitive to light. The light sensitivity of a detector should be specified as that percentage increase in system noise that results from moving the detector from total darkness to specific conditions of light exposure.

The recommended condition of light exposure shall be achieved by placing the detector 45.0 cm away from the standard lamp with the face of the detector perpendicular to a line connecting the lamp and the detector. The standard lamp shall be a 250 W tungsten filament quartz-halogen bulb with a color temperature of 3000 K. It shall have bulb and filament configurations and meet all other specifications of ANSI ENH (Special Report SR-24B, 1982 Edition of ANSI Photo Lamp Codes [1]. A filament current of 2.08 A ±0.05 A dc shall be maintained. Test conditions should be provided in which reflected light and contribution of light from other sources are minimized.

It should be noted that the noise increase observed for a detector with some light sensitivity can be much greater if the light is modulated rather than constant in intensity. This is particulary relevant for detectors exposed to flourescent lighting. Detectors to be used under conditions of modulated light should be tested for sensitivity to such light.

Other conditions of light exposure may be used as required for certain applications. Such conditions must be stated if a value of light sensitivity is given. Note that light intensity above some level will significantly heat the detector and result in thermal effects.

8.5 Radiation Damage Measurements

Following irradiation, properties of the detector may be affected and each test may have to be repeated. To obtain meaningful data, it is important to record:

1) Test data obtained before irradiation
2) Type and energy of radiation, flux, and fluence
3) Detector temperature, bias voltage, and ambient conditions during irradiation
4) Time between termination of irradiation and commencement of tests, and detector conditions in the intervening period

9. Other Measurements

9.1 Current-Voltage Characteristics

A point-by-point measurement is made of the reverse bias leakage current as a fuction of the detector voltage V_b at a constant temperature (see Fig 11). Both the points corresponding to successively increasing and successively decreasing voltage should be recorded. The voltage changes should be made slowly enough to exhibit any hysteresis effects.

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9.2 Dead-Layer Energy Loss

A beam of mono-energetic heavy ionizing particles is caused to impinge upon a detector in which the dead layer is to be measured. The amount of energy lost in the dead-layer region shall not exceed 5% of the total energy of the particle. The particles shall be collimated to a semiangle not exceeding 5° and oriented so that the incident particles enter the detector normal to the surface. A spectrum is then obtained. The detector is subsequently rotated by an angle Θ and another spectrum is obtained. Using the reference pulse generator, the energy origin of the multichannel analyzer and hence the energy difference δE between the two spectra can be determined. From this difference, the effective energy loss for the particles used in the test may be determined. The 5.486 MeV α particles emitted by ^{241}Am are suggested as a standard, although other particle types and energies may be used.

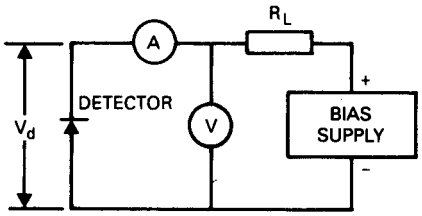


Figure 11—Detector Current-Voltage Characteristic Measurement

If the specific energy loss within the dead layer is essentially constant, the energy lost in the dead layer by particles at normal incidence is given by Eq 15.

$$\text{Dead-layer energy loss (normal incidence)} = \delta E \frac{\cos \Theta}{1 - \cos \Theta} \tag{15}$$

where

E = energy difference in megaelectronvolt (MeV) between measurements at normal incidence and after a rotation through angle Θ

Θ = angle of rotation of detector for non-normal incidence of particles (45° is a recommended value for Θ)

Since the dead-layer energy loss may depend on the detector bias voltage, this voltage should be stated.

Because of the change in line broadening that occurs when Θ is changed, the center of the peak is not a reliable indicator of energy. Instead, the asymptote of the high-energy side of the peak where it intersects the energy axis shall be used.

For transmission detectors, the measurement should be performed for the entrance and exit faces. The method is applicable only to charged-particle detectors with a depletion depth exceeding the incident particle range and if the energy resolution permits.

9.3 Sensitive Area

While monitoring the detector leakage current, the surface is explored with a small light spot. The edge of the sensitive region can be defined as that boundary beyond which the photocurrent decreases by approximately 10%. The light-spot diameter must be small compared with the dimensions of the sensitive area and the light intensity such that the photocurrent is large compared to the leakage current. For detectors having an opaque front window the edge of the

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sensitive region can be found by using a collimated beam of monoenergetic, heavy charged particles and defining the boundary as that region beyond which the FWHM of the spectral peak doubles in value.

The sensitive area, without regard to delineation, may be measured by exposing the detector to a known flux of heavy charged particles and measuring the counting rate with and without a collimator of known dimensions.

9.4 Detector Thickness (Transmission Detectors)

A radioactive source is used to provide a narrow collimated beam of monoenergetic photons (X rays or low-energy γ rays). Provision must be made to determine the location of the charged-particle detector in this beam. The beam must also be incident upon a detector that is part of a low-energy photon spectroscopy system. A high-resolution detector is needed to minimize the effect of scattered radiation on this measurement. The intensity of the radiation, from the line of interest, incident on the photon detector is measured with and without the presence of the charged-particle detector.

Thickness is then determined from the attenuation of the charged-particle detector for the specific photon energy employed. This technique may be used to measure thickness uniformity by using a highly collimated beam. The matching of photon energy to charged-particle detector thickness should be such that at least 15% but not more than 85% attentuation is achieved. The 6.4 keV, 14.4 keV, and 122 keV lines from ^{57}Co are frequently useful for this measurement. It must be noted that the X-ray attentuation technique measures the total effective detector thickness and not the detector sensitive thickness.

This thickness measurement can be performed nondestructively on finished devices. During the manufacturing process, simpler techniques are feasible.

9.5 Capacitance-Voltage Characteristics

The capacitance of a detector as a function of detector bias can be measured by using an ac bridge. The bridge should operate in the range 10^3 Hz-10^5 Hz. At each value of applied bias the peak-to-peak ac signal amplitude to the detector shall not exceed 10% of the dc bias voltage or 10% of the band-gap voltage, whichever is the smaller. The detector temperature, bias voltage, and environment must be recorded. A log-log plot may be used to display the capacitance-voltage characteristics. Series resistance, possibly resulting from undepleted base material in the diode, can lead to significant errors in the capacitance values obtained by this technique. This measurement tends to be more susceptible to error from surface effects at low bridge frequencies. Errors caused by stray capacitance can be minimized by using a three-terminal measurement.

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