

An American National Standard

IEEE Standard Test Procedures for Semiconductor X-Ray Energy Spectrometers

Sponsor

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of the
IEEE Nuclear and Plasma Sciences Society**

Secretariat

Institute of Electrical and Electronic Engineers, Inc

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Foreword

(This Foreword is not a part of ANSI/IEEE Std 759-1984, IEEE Standard Test Procedures for Semiconductor Energy X-Ray Spectrometers.)

This document presents standard test procedures for semiconductor X-ray energy spectrometers. Such systems consist of a semiconductor radiation detector assembly and signal processing electronics interfaced to a pulse height analyzer/computer. Companion documents are ANSI/IEEE Std 300-1982, IEEE Standard Test Procedures for Semiconductor Charged-Particle Detectors, ANSI/IEEE Std 301-1976, IEEE Standard Test Procedures for Amplifiers and Preamplifiers for Semiconductor Radiation Detectors for Ionizing Radiation, and ANSI/IEEE Std 325-1971, IEEE Standard Test Procedures for Germanium Gamma-Ray Detectors.

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IEEE Standard Test Procedures for Semiconductor X-Ray Energy Spectrometers

1. Scope

This document presents standard test procedures for semiconductor X-ray energy spectrometers. Such systems consist of a semiconductor radiation detector assembly and signal processing electronics interfaced to a pulse height analyzer/computer. Test procedures for pulse-height analyzers and computers are not covered in this document. Section 5. is essentially tutorial.

This standard is not intended to imply that all tests described herein are mandatory, but only that such tests as are carried out shall be performed in accordance with the procedures described herein.

Companion documents to this standard are ANSI/IEEE Std 300-1982 [1],¹ ANSI/IEEE Std 301-1976 [2], and ANSI/IEEE Std 325-1971 [3].

The list of symbols and the glossary were derived from those in the companion documents.

Contrary to previous convention in the X-ray spectroscopy field, this document utilizes the characteristic energy E of the X-ray rather than its wavelength λ . This approach is consistent with the fact that the basic quantity measured by this type of spectrometer is the X-ray energy. A convenient conversion is provided by the relationship

$$\lambda(\text{m}) = 12.4 \cdot 10^{-10} E^{-1}(\text{keV})$$

$$\lambda(\text{\AA}) = 12.4 E^{-1}(\text{keV})$$

2. References

[1] ANSI/IEEE Std 300-1982, IEEE Standard Test Procedures for Semiconductor Charged-Particle Detectors.

[2] ANSI/IEEE Std 301-1976, IEEE Standard Test Procedures for Amplifiers and Preamplifiers for Semiconductor Radiation Detectors for Ionizing Radiation.

[3] ANSI/IEEE Std 325-1971, IEEE Standard Test Procedures for Germanium Gamma-Ray Detectors.

[4] IEC Publication 333 (1983), Test Procedures for Semiconductor Detectors.²

¹The numbers in brackets correspond to those of the references listed in Section 2.

²IEC Standards are available in the US from American National Standards Institute, 1430 Broadway, New York, NY 10018

[5] IEC Publication 340 (1979) (Second Edition), Test Procedures for Amplifiers and Peamplifiers for Semiconductor Detectors for Ionizing Radiation.

[6] IEC Publication 430 (1973), Test Procedures for Germanium Gamma-Ray Detectors.

3. Glossary

analog-to-digital converter (adc): A device whose input is information in analog form and whose output is the same information in digital form.

background (associated with a spectral peak from a semiconductor detector): Non-ideal spectral response which results from radiation which is not a part of the monoenergetic line of interest.

baseline (at pulse peak): The instantaneous value that the voltage would have had at the time of the pulse peak in the absence of that pulse.

baseline restoration (BLR): Appropriate linear or non-linear technique(s), or their combination, used to accelerate the return of a voltage to its baseline.

bias (of a semiconductor radiation detector): The voltage applied to a detector to produce the electric field to sweep out the signal charge.

biased amplifier: An amplifier giving essentially zero output for all inputs below a threshold and having constant incremental gain for all inputs above the threshold up to a specified maximum amplitude.

bias resistor (of a semiconductor radiation detector): The resistor through which bias voltage is applied to a detector.

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 resistance 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 voltagecurrent 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.

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 (jargon): A limiting operation such as 1) use of a high-pass filter (see **differentiated**), or 2) a nonlinear operation such as diode limiting of pulse amplitude.

crest factor (semiconductor radiation detectors) (of an average reading or root-mean-square voltmeter): The ratio of the peak voltage value that an average reading or root-mean-square voltmeter will accept without overloading to the full-scale value of the range being used for measurement.

cr-rc shaping: The pulse shaping present in an amplifier that has a simple high-pass filter consisting of a capacitor and a resistor together with a simple, low-pass filter, separated by impedance isolation. Pulse shaping in such an amplifier cuts off at 6 decibels per octave at both ends of the band.

dc level: See **baseline**.

dead layer thickness (of a semiconductor radiation detector): The thickness of an inactive region (in the form of a layer) through which incident radiation must pass to reach the sensitive volume.

decay time constant: The time for a true single exponential waveform to decay to a value of $1/e$ of the original height.

depletion layer (region) (in a semiconductor): A region in which the charge-carrier charge density is insufficient to neutralize the net fixed charge density of donors and acceptors. In a diode-type semiconductor radiation detector the depletion region is the sensitive region of the device.

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

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

efficiency (of a semiconductor radiation detector for a monoenergetic radiation source): The ratio of the number of events in the spectral distribution to the total number of photons incident on the active detector volume during the same time interval.

energy resolution (FWHM) (of a semiconductor radiation detector): The detector's contribution (including detector leakage current noise), expressed in units of energy, to the FWHM of a pulse-height distribution corresponding to an energy spectrum.

energy resolution (percent) (of a semiconductor radiation detector): One hundred times the energy resolution divided by the energy for which the resolution is specified.

equivalent noise referred to input (of a linear amplifier): The value of noise at the input that would produce the same value of noise at the output as does the actual noise source.

full energy peak (for a monoenergetic photon spectrum for a semiconductor spectrometer system): The distribution of events within the peak of the pulse-height distribution spectrum representing response to the monoenergetic photon source.

NOTE — Notwithstanding other definitions or procedures for subtracting background and other distortions, the full energy peak intensity is defined as not including any events which exceed a Gaussian distribution by more than a factor of two σ .

full energy peak efficiency (of a semiconductor radiation detector): The ratio of the number of events in the full energy peak of the spectral distribution to the total number of photons incident on the active detector volume during the same time interval.

full width at fiftieth maximum: Same as FWHM except that measurement is made at one fiftieth of the maximum ordinate rather than one half.

full width at half maximum: The full width of a distribution measured at half the maximum ordinate. For a normal distribution, it is equal to $2(2 \ln 2)^{1/2}$ times the standard deviation σ .

full width at tenth maximum: Same as FWHM except measurement is made at one tenth of the maximum ordinate rather than one half.

FWFM: (See **full width at fiftieth maximum**.)

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

FWTM: (See **full width at tenth maximum**.)

gate: A device or element that, depending upon one or more specified inputs, has the ability to permit or inhibit the passage of a signal.

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.

integral nonlinearity (INL) (of a pulse amplifying system): The maximum nonlinearity (deviation) over the specified operating range of a system, usually expressed as a percentage of the maximum of the specified range.

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.

integrating preamplifier: A pulse preamplifier in which individual pulses are intentionally integrated by passive or active circuits.

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.

linear gate: A gate whose presence does not affect the linearity of the gated signal.

line-to-background ratio (of a spectral line): The ratio of the intensity of a monoenergetic line to the intensity of the background immediately adjacent to the line.

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.

load impedance (of a semiconductor radiation detector): The impedance shunting the detector, and across which the detector output voltage signal is developed.

load resistance (of a semiconductor radiation detector): The resistive component of the load impedance.

MCA: Multichannel analyzer.

modal channel: The modal channel is that channel in the distribution containing the largest number of counts.

multichannel analyzer (MCA): An instrument which digitizes analog amplitude signal pulses and stores them in a memory as a function of the analog amplitude.

noise linewidth: The contribution of 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.

nonlinearity (of a pulse amplifying system): Distortion caused by a deviation from a desired linear relationship between specified measures of the output and input pulse amplitudes of a system or device.

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.

overload pulse: Any signal that drives a section of the amplifying chain into saturation.

paralyzable system: Any system or device whose response characteristics contain a region where the ratio of output-to-input count rate decreases with increasing input count rate.

partially dead region or layer (of a semiconductor detector): Any region or layer on or in the detector which contributes an output pulse which is less than the full energy peak for that incident radiation.

percent energy resolution: (See energy resolution.)

pile-up (of signal pulses): Two pulses (signals) are said to be piled-up when a second pulse occurs before the transient response of the preceding pulse has decayed to a negligible value.

pile-up rejection: A technique used to identify and reject pulses (signals) that are piled up.

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

pole-zero cancellation (PZ): A technique used to cancel out the effects of a singularity in an amplifiers' transfer function in order to affect a monotonic return of signal pulses to the baseline.

pulse decay time (t_d): The interval between the instants at which the instantaneous value last reaches specified upper and lower limits, namely, 90% and 10% of the peak pulse value unless otherwise stated. (In the case of a step function applied to an amplifier that has simple CR - RC shaping, the decay time is given by $t_d = 3.36 CR$.)

pulse rise time (t_r): The interval between the instants at which the instantaneous value first reaches specified lower and upper limits, namely, 10% and 90% of the peak pulse value unless otherwise specified. (In the case of a step function applied to an RC low-pass filter, the rise time is given by $t_r = 2.2 RC$. In the case of a step function applied to an amplifier that has simple CR - RC shaping, that is, one high-pass and one low-pass RC filter of equal time constants, the rise time is given by $t_r = 0.57 RC$.)

punch-through voltage (of a semiconductor radiation detector): The voltage at which a junction detector becomes fully depleted.

resolution, energy (percent): (See **energy resolution [percent]**.)

SCA: Single-channel analyzer,

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 that utilizes the production and motion of excess free charge carriers for the detection and measurement of incident radiation.

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 also 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 its equivalent electric analog (such as charge or voltage) at the output of a radiation detector.

standard source diameter: The diameter of the X-ray emission source which is used to measure the response characteristics of the spectrometer. Unless otherwise specified, this is assumed to be a point source.

standard working axis (of a semiconductor X-ray energy spectrometer): A straight line drawn between the center of the entrance window on the detector and the specified location of the source of X-rays.

surface barrier contact: A rectifying contact that is characterized by a potential barrier associated with an inversion or accumulation layer; said inversion or accumulation layer being caused by surface charge resulting from the presence of surface states and work function differences, or both.

surface barrier radiation detector: A radiation detector for which the principal rectifying junction is a surface barrier contact.

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

tail or tailing (on a monoenergetic peak): Any peak shape distortion that does not comply with the limits defining the full energy peak intensity and that does not come from a source of radiation other than the monoenergetic source in question.

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

transmission detector: A totally depleted detector whose thickness including its entrance and exit windows is sufficiently small to permit radiation to pass completely through the detector.

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

window amplifier: (See **biased amplifier**.)

working distance: The distance, measured along the working axis, between the source of X-rays and the outermost window on the detector.

4. Symbols

Symbol	Term Denoted
A	Intensity of full energy monoenergetic peak; total number of counts in a full energy peak.
A_b	number of counts in the background under a peak.
A_E	intensity of spectral peak at energy E ; the total number of counts in the full energy peak of energy E .
A_{Mn}	intensity of backscattered Mn K_α peak.
A_t	Total peak area, number of counts in the full energy peak, plus background.
a, b	constants characterizing noise.
B	bandwidth.
BLR	baseline restorer
C	electrical capacitance.
C_d	detector capacitance.
C_c	calibrated capacitor used to couple a pulse generator to a circuit under test.
C_{eff}	effective input capacitance of a preamplifier.
C_f	feedback capacitance in the integrating loop of a charge-sensitive preamplifier.
C_t	total capacitance at a preamplifier input.
C_1	the average number of counts per channel in five contiguous channels centered around the energy of 5.4 keV in the tail of a Mn K_α X-ray energy spectrum.
C_2	same as C_1 except 4.5 keV.
C_3	same as C_1 except 1 keV.
Δ	FWHM of a monoenergetic spectral peak.
Δ^A_E	FWHM expressed in units of energy, due to amplifier noise.
Δ^A_N	FWHM expressed in channels, due to amplifier noise.
Δ^A_Q	FWHM expressed in units of charge, due to amplifier noise.
Δ^D_E	FWHM expressed in units of energy, due to detector noise.
Δ^D_N	FWHM expressed in channels, due to detector noise.

Symbol	Term Denoted
Δ_Q^D	FWHM expressed in units of charge, due to detector noise.
ΔE_{Max}	the maximum deviation, in units of energy, between the measured linearity curve and the ideal linear response curve.
Δ_N	a shift (expressed in channels) of the peak center (modal) channel.
Δ_E^O	FWHM, expressed in units of energy, due to all factors other than electrical noise.
Δ_N^O	FWHM, expressed in channels, due to all factors other than electrical noise.
Δ_E^S	FWHM for monoenergetic incident radiation, expressed in units of energy, including all spectral broadening effects.
Δ_N^S	FWHM for monoenergetic incident radiation, expressed in channels, including all spectral broadening effects.
Δ_E^T	FWHM, expressed in units of energy, due to the combined effect of detector and amplifier noise.
Δ_N^T	FWHM, expressed in channels, due to the combined effect of detector and amplifier noise.
Δ_Q^T	FWHM, expressed in units of charge, due to the combined effect of detector and amplifier noise.
E	energy of a particle or photon.
ε	average energy required to form one hole-electron pair in a semiconductor.
e	electron charge or natural log base (2.71828).
E_F	the energy corresponding to the maximum linear output of a spectrometer.
e_{ni}	equivalent root-mean-square noise voltage referred to the preamplifier input.
e_{no}	root-mean-square noise voltage.
e_{qi}	root-mean-square noise in units of charge at the amplifier input.
F	Fano Factor, an empirical coefficient that corrects for the fact that Poisson statistics are not obeyed.
G_B	gain of a biased amplifier.
ψ	noise spectral power density.
i	detector noise current.
I	electric current.
I_d	detector leakage current.
I_o	diode equivalent Gaussian noise current in a specified frequency band.

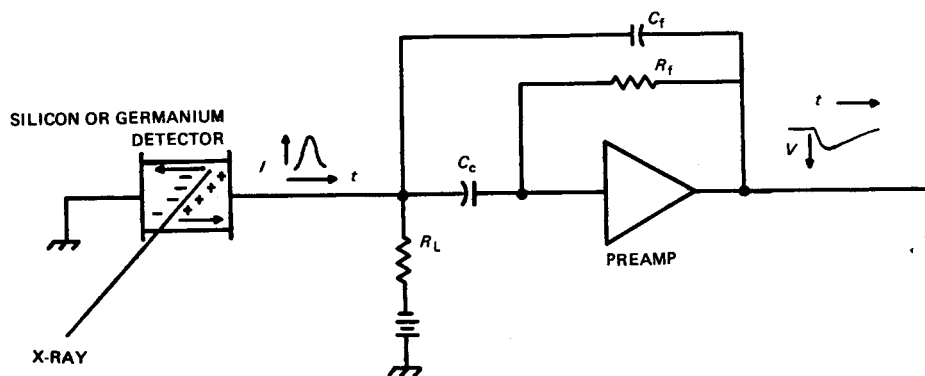
Symbol	Term Denoted
INL	integral nonlinearity; the maximum deviation from linearity expressed as a percentage of the maximum linear output.
k	Boltzmann's constant.
K	constant relating FWHM in units of energy to FWHM in units of charge.
MCA	multichannel analyzer.
L_D	differential nonlinearity of an amplifier.
L_i	integral nonlinearity of a biased amplifier.
L_1	integral nonlinearity of an amplifier.
N	channel number corresponding to the maximum of a monoenergetic spectral peak.
N_{avg}	average number of counts in all channels of a multichannel pulse-height analyzer spectrum.
N_B	equivalent number of channels suppressed by a biased amplifier.
N_p	the total number of counts in the modal (peak center) channel of the Mn full energy peak from a Mn K X-ray energy spectrum.
N_x	number of counts in channel X of a multichannel pulse-height analyzer spectrum.
P_1	the peak-to-tail ratio at 5.4 keV for a Mn K X-ray energy spectrum.
P_2	the peak-to-tail ratio at 4.5 keV for a Mn K X-ray energy spectrum.
P_3	the peak-to-tail ratio at 1 keV for a Mn K X-ray energy spectrum.
PZ	pole-zero cancellation.
Q	electric charge.
R	electrical resistance.
R_c	resistor used in parallel with C_c to effect pole-zero cancellation.
R_f	a resistor in parallel with C_f (used to stabilize the operating point of the first active element in a preamplifier).
r_i	input data rate to a system or device.
R_L	detector load resistor.
r_o	output data rate of a system or device.
S_L	output pulse height stability.
S_M	sensitivity of mca or adc/computer system expressed in energy units of eV/channel.
T	absolute temperature.

Symbol	Term Denoted
t_c	charge collection time in a detector.
t_d	dead time in a device or system.
t_e	observed detector rise time due to the combined effects of the charge collection time and detector electrical rise time.
t_p	detector electrical rise time.
t_r	rise time (10% to 90%).
τ	time constant.
τ_c	time constant of a CR network used to simulate the rise of a pulse from a radiation detector.
τ_d	decay time constant.
t_w	width of a pulse, in time units, at the baseline established by the discriminator threshold level.
V	electric voltage.
V_a	amplitude of amplifier output voltage.
V_d	detector bias voltage.
V_D	depletion voltage
V_P	amplitude of the voltage step impressed on C_c by the pulse generator.
W_E	window attenuation index at energy E as determined by spectrum from NBS-SRM 477 excited with ^{55}Fe .
X	channel number in an inca or computer display of a photon energy spectrum.
Z	atomic number
Z_0	characteristic impedance
λ	the characteristic wavelength associated with an X-ray photon.
δ_E^S	FWTM for monoenergetic incident radiation, expressed in units of energy, including all spectral broadening effects.
δ_N^S	FWTM for monoenergetic incident radiation, expressed in channels, including all spectral broadening effects.
δ_E^T	FWTM, expressed in units of energy, due to the combined effect of detector and amplifier noise.
δ_E^O	FWTM, expressed in units of energy, due to all factors other than electrical noise.
δ_N^T	FWTM, expressed in channels, due to the combined effects of detector and amplifier noise.

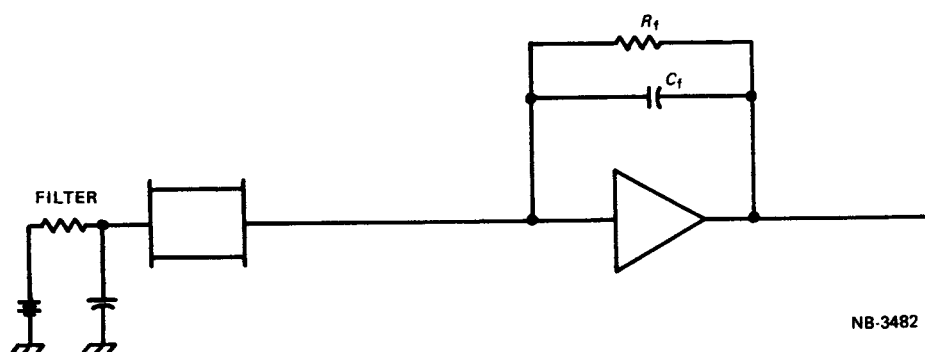
5. Introduction

5.1 Detector System

A semiconductor detector is analogous to a gas ion chamber in which the gas has been replaced by a solid. Figure 1 illustrates this type of detector and its preamplifier configuration. The detector consists of a semiconducting crystal between two conducting electrodes. A potential difference is established between the electrodes thereby producing an electric field in the semiconductor. When an X-ray photon enters the semiconductor it produces free charge carriers in the crystal, the number of which is proportional to the energy lost by the X-ray photon. The charge motion resulting from the influence of the electric field produces an induced current pulse in the external circuit. This current represents the basic signal information, and the integrated current pulse is proportional to the energy lost by the X-ray. The pulses are routed to a multichannel pulse-height analyzer (MCA) where they are sorted and stored according to the amplitude distribution to produce a pulse-height spectrum that corresponds to the X-ray energy spectrum. The MCA may be a dedicated instrument or an analog-to-digital converter (adc) interfaced to a computer.



(a) ac-Coupled Configuration



(b) dc-Coupled Configuration

Figure 1—Schematic of Semiconductor Detector and Preamplifier

The semiconductor materials most frequently used for X-ray spectrometers, silicon and germanium, do not have sufficiently high resistivity to withstand large electric fields without excessive leakage currents. It is therefore necessary to use special techniques to limit the current flow through the semiconductor device. This is usually accomplished by utilizing the space charge region of a reverse biased diode junction as the detector-sensitive volume. Silicon and germanium are the only semiconductor materials presently available with sufficient crystalline perfection