GAMMA-RAY SPECTROMETRY WITH SOLID-STATE DETECTORS
BY CURRENT PULSE-HEIGHT ANALYSIS*

by

W.M. Szymczyk, A.J. Dabrowski, J.S. Iwanczyk,
J.H. Kusmiss, and G.C. Huth
Institute for Physics and Imaging Science
University of Southern California, Marina del Rey, California 90291

and

K. Hull, A. Beyerle, and J. Markakis
EG&G, Santa Barbara Operations
Goleta, California 93116

ABSTRACT

The traditional way of doing gamma-ray spectrometry with semiconductor detectors depends on being able to collect the ionization charge. In most cases, hole trapping limits the spectrometric performance of room-temperature detectors made from compound semiconductors. Recently it has been shown for thick HgI_2 detectors that significant improvement can be produced by using a technique of unconventionally short differentiation of the detector pulses. The present paper presents the concept underlying the technique and gives its theoretical background. The method consists of measuring the amplitude of ionization current pulses before charge collection is completed rather than measuring the amount of charge collected. Hole collection is obviated, and the transport of electrons becomes the most important consideration. The conditions under which this novel method can be applied to various semiconductor materials are discussed. Two different approaches toward the electronic implementation of the technique are compared.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

*This work was performed under the auspices of the U.S. Department of Energy under Contract No. DE-AC08-76NV01183. NOTE: By acceptance of this article, the publisher and/or recipient acknowledges the U.S. Government's right to retain a nonexclusive royalty-free license in and to any copyright covering this paper.

Reference to a company or product name does not imply approval or recommendation of the product by the U.S. Department of Energy to the exclusion of others that may be suitable.

MASTER

EMB

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

1. INTRODUCTION

The classical approach to doing gamma-ray spectrometry with a solid-state detector involves integration over time of the induced current arising from the movement of electrons and holes in the detector material under the influence of an applied electric field. Another description is that the charge carriers resulting from ionization caused by the gamma-ray interaction in the crystal are "collected" at the electrodes. The essence of spectrometry lies in being able to collect the total amount of ionization charge, which is proportional to the energy of the gamma-ray interaction event. An output voltage signal is usually produced by means of a charge-sensitive preamplifier connected to the detector.

Because in gamma-ray spectrometry a detector is required which is thick enough to have a reasonable fraction of incident gamma-rays interact in it, a limitation on the classical method is set by the trapping of charge carriers. The mobility-lifetime product, μt , characterizes the charge collection properties for a given material. The drift lengths, $\lambda_e = \mu_e t_e E$ and $\lambda_h = \mu_h t_h E$ for electrons and holes, respectively, describe the mean distance a carrier will drift in an electric field, E , before it is trapped, where μ is the mobility, and t is the mean time before trapping. Roughly speaking, drift lengths of at least an order of magnitude greater than the detector thickness, L , are required in order to operate the detector satisfactorily as a spectrometer, otherwise many full-energy events are counted in the continuum rather than the full-energy peak.¹ For germanium the useful thickness of a gamma-ray detector is not limited in this way, since the μt product for both electrons and holes is usually above $1 \text{ cm}^2/\text{V}$. For wide-bandgap, room-temperature, operable compound, semiconductor detector materials such as CdTe and HgI_2 , however, the holes cannot be collected effectively except in the case of very thin devices. The rule-of-thumb condition $L < 0.1\lambda$ required for good charge collection sets rough limits of $L < 1 \text{ mm}$ for CdTe (assuming $\mu t_h = 10^{-4} \text{ cm}^2/\text{V}$ and $E = 10^4 \text{ V/cm}$) and $L < 0.5 \text{ mm}$ for HgI_2 (assuming $\mu t_h = 10^{-5} \text{ cm}^2/\text{V}$ and

$E = 5 \times 10^4$ V/cm; a higher electric field strength is possible for HgI_2 because it has a larger bandgap than does CdTe, resulting in less leakage current and noise). On the other hand, the linear attenuation coefficient for gamma radiation in the energy range from a few hundred keV to a few MeV is about 0.2 to 0.5 cm^{-1} (primarily Compton scattering). This means that to be reasonably efficient ($L \sim 1/\mu$) a spectrometer detector should be in the range of 2 to 5 cm thick.

Compound semiconductor detectors are not limited by carrier trapping for low-energy x-rays,^{2,4} because in that case all of the ionization charge is produced close to the entrance electrode; if that electrode is negatively biased and the thickness of the crystal is appreciably less than the drift length for electrons, the energy resolution is primarily limited by the noise linewidth of the electronics. With high-energy gamma-rays the continuum part of the pulse height spectrum is often much larger than what would be expected from Compton scattering. Incomplete charge collection (particularly of holes) shifts a significant number of full-energy events from the full-energy peak to the continuum part of the spectrum. Figure 1 is a ^{137}Cs spectrum taken with the classical setup involving the use of a charge-sensitive preamplifier; the detector was made of a 0.5-mm-thick HgI_2 crystal with relatively good hole transport parameters. The ratio of integration time, T_{int} , to electron transit time, T_{et} , was more than 500. The energy resolution is still limited by trapping, despite the thinness of the crystal which makes it unsatisfactory from the point of view of efficiency; note the unfavorable ratio of the number of counts in the full-energy peak to the number of counts in the continuum, as well as the pronounced HgK x-ray escape peak at $(662 - 70.8) \text{ keV}$. Figure 2 is a ^{137}Cs spectrum taken with a 1-cm-thick HgI_2 detector with an integration time still longer than the electron transit time ($T_{\text{int}}/T_{\text{et}} \sim 1.5$). In such a thick detector the holes are practically not collected at all, and the spectrum exhibits an even worse ratio of the areas under the continuum and under the full-energy peak. Figure 3 is a sketch of the voltage pulse at the output of a charge-sensitive preamplifier resulting from time integration of the detector current pulse. The electric field is assumed

uniform inside the detector. The maximum value of the voltage at the output is proportional to the total charge flowing into the input, Q_i , rather than the total ionization charge from an event, Q_0 . What that charge Q_i is depends on where a gamma-ray interacts in the crystal.

Since large boules of single-crystal HgI_2 have become available, making possible the fabrication of thick detectors, much effort has been expended (especially by the group at EG&G, Santa Barbara, California) in trying to improve the hole collection capability of this material.^{5,6} This has generally been considered to be the key problem in the use of HgI_2 for high-energy gamma-ray spectroscopy. The level of detector performance based on this approach to date has been far from satisfactory. Probably at least two orders of magnitude improvement in the $\mu\tau$ product for holes would have to be attained in order to really change the situation. However, it has been observed that considerable improvement in gamma-ray spectra can be obtained by using unconventionally short differentiation of the pulses with thick HgI_2 detectors. Experimental results concerning the application of this technique to mercuric iodide detectors are presented in a separate paper in this same volume.⁷ This paper presents the concept behind the technique and gives its theoretical background.

2. PRESENTATION OF THE CONCEPT: CURRENT PULSE HEIGHT ANALYSIS

In order to be able to disregard the collection of holes, which is incomplete in a thick detector with poor hole transport properties, one must abandon the idea of measuring the total charge collected on the electrodes of a gamma-ray spectrometer, because the holes unavoidably contribute to the total. Instead it is proposed to measure a signal which is proportional to the number of charge carriers generated inside the detector by an incoming gamma-ray, before the carriers are completely collected.

Assuming the ionization event takes place at time $t = 0$, the instantaneous current through the detector can be expressed as

$$i(t) = (-en_o/L) \left\{ \exp(-t/t_e) \mu_e E \{x_e(t)\} + \exp(-t/t_h) \mu_h E \{x_h(t)\} \right\} \quad (1)$$

where:

e = magnitude of the electron charge

n_o = number of electron-hole pairs produced in the event

$x_e(t)$ = position of drifting holes at time t

$E(x_e)$ and $E(x_h)$ = the values of the electric field intensity at those two position, respectively.

Equation (1) assumes that the velocity of carriers in the detector is far below the saturation value, which is usually true in the case of relatively low-mobility compound semiconductors. At the fixed time of measurement $t = t_m$ (less than the time of charge carrier collection) the current is given by

$$i(t_m) = n_o \left\{ c_1 E \{x_e(t_m)\} + c_2 E \{x_h(t_m)\} \right\} \quad (2)$$

where c_1 and c_2 are constants; $i(t_m)$ does not depend on the location of the event in the detector if the electric field is uniform throughout the volume of the detector, that is, $E(x) = \text{constant}$ for $0 < x < L$. Since $i(t_m)$ is proportional to n_o , and n_o in turn is proportional to the energy of the incident gamma-ray, it can be seen that in principle gamma-ray spectrometry can be done by measuring the current in the detector.

Compound semiconductor materials are particularly well suited to the method of high-energy gamma-ray spectrometry by means of current pulse height analysis. First, the detector volume required for efficiency automatically produces long transit times because of the relatively low electron mobility at room temperature, as compared to the very high values attained at cryogenic temperatures in germanium

devices. Second, the noise is usually only a minor factor in the energy resolution of a trapping-limited high-energy gamma-ray spectrometer.

The crucial conditions on the solid state detector material for the applicability of current pulse analysis to gamma-ray spectrometry are that:

1. The mobility of at least one type of charge carrier be large enough to give an appreciable current pulse for a realistic value of electric field strength.
2. The mean time before trapping of the higher-mobility charge carrier be significantly greater than the observation time required for making the current measurement.
3. The material be homogeneous enough to allow fabrication of detectors with a sufficiently uniform electric field distribution, i.e., sufficiently constant $E(x)$ throughout the active volume of the detector.

Specifically, the proposed method is completely insensitive to the efficiency of collection of the slower-moving carriers, namely holes in the case of compound semiconductors used in room-temperature, gamma-ray spectrometry.

3. CONCEPT IMPLEMENTATION

There are two approaches to implementing the measurement of current pulses in the detector. Figure 4a shows the first approach schematically. A low resistance, R , is put in parallel with the detector, and the combination is followed by a fast voltage-sensing preamplifier with its bandwidth limited by an integrating time constant, for considerations of noise. The value of the resistance must be small in order to have a short RC time constant due to capacitance at the input. In the second approach, shown in Figure 4b, a charge-sensitive preamplifier of the type normally used is followed by differentiation of its

output pulse. The method difference with respect to electronic noise is that in the more direct approach the major contribution to the noise is the low resistance in parallel with the detector, whereas in the second approach the input FET of the charge-sensitive preamplifier is the major source of noise; usually the latter is a more favorable situation. A more detailed discussion of noise in the two cases is given in the Appendix.

In connection with the second approach to measuring the instantaneous detector current, i.e., differentiation of the output of a charge-sensitive preamplifier, it should be pointed out that it is standard procedure in traditional current-integration spectrometry to filter the output signal as a means of obtaining a better signal-to-noise ratio. However, the time constants for integration and differentiation in the (usually Gaussian) pulse shaping network are typically several times the charge carrier transit time in the detector. In contrast, the time constant for differentiation in the proposed scheme to measure the detector current would be a small fraction of the electron transit time. All the integrating time constants in the stages following the differentiation must also be kept short (a small fraction of T_{et}) to preserve proportionality to current rather than charge. The chosen magnitude of the time constant will be a compromise between obtaining a more faithful representation of the original current pulse for shorter times versus more noise accompanying the increased bandwidth.

Figure 5 is a drawing of the pulses from several different full-energy peak events which would result from either of the two approaches to the proposed measurement of instantaneous detector current. The pulses have differing lengths depending on where the ionization event occurs in the crystal. Since the pulse height is what the spectrometric action is based on, being proportional to the energy of the detected gamma-ray, the analogue-to-digital conversion technique used must not be sensitive to pulse length.

4. DISCUSSION

The information about the amount of charge deposited inside the detector is theoretically available right after the ionization process is completed and all the charge carriers produced start to move. In principle, the measurement could be completed in a few picoseconds. However, the noise associated with such a quickly responding system would obscure the signal. Therefore, the response is intentionally slowed (the bandwidth decreased) to suppress the noise. This means that in order to be able to measure the original current amplitude one has to wait for the waveform to reach its full amplitude in a time, t_m , equal to a few integrating time constants. The selection of the t_m time will be dictated by a tradeoff between noise level and the fraction of full-energy events which will be shifted downward in energy from the full-energy peak position in the spectrum. The longer the time until the measurement is made, the larger will be the fraction of the detector volume (comprised of the region close to the positively-biased electrode) producing pulses part of whose amplitude has been lost because of electron collection at the electrode.

In the case of HgI_2 , for example, a detector fabricated from a 2-cm-thick crystal would have an electron transit time T_{et} of about 14 μs , taking values of $\mu = 70 \text{ cm}^2/\text{Vs}$ and $E = 2 \times 10^3 \text{ V/cm}$. For CdTe a similar calculation gives a transit time of 2 μs , using $1000 \text{ cm}^2/\text{Vs}$ for the mobility and 10^3 V/cm for the electric field intensity. In order not to shift more than, say, 10% of the total number of events from the full-energy peak to the low-energy side tail of the peak would require choosing t_m to be not more than $T_{et}/10$ in the first approximation. It follows that the integrating time constant, t_i , must not be larger than about $7_{et}/30$, assuming that the integrated waveform is close enough to its final form after a time equal to three time constants. In the example calculation above, t_i would have to be not greater than 500 ns in the case of HgI_2 and not greater than about 65 ns in the case of CdTe . These values are about 8 to 15 times lower

than the ones usually used to optimize the signal-to-noise ratio; hence one can expect an approximate increase of between 2 and 3 times the electronic noise level. Such an increase seems to be tolerable in most cases of trapping-limited spectrometry.

The electron mobility in most compound semiconductors is usually much better than the hole mobility,^{1,8} a fact which is instrumental in making the proposed method possible. The trapping time is strongly dependent on the quality of individual crystals rather than being a characteristic of a given semiconductor. For CdTe and HgI₂ values of the mean time before trapping of electrons of several microseconds are often found,^{1,9-11} which is enough to make the proposed method feasible for these materials. The potential for improvement in the case of HgI₂ can be illustrated by noting recently that a value of the mean time before trapping of electrons of not less than several hundred microseconds was observed. Details of the measurement of these extremely long electron lifetimes (which would be considered very good even in silicon) in HgI₂ will be reported elsewhere.

Figure 6 is a pulse height spectrum from ¹³⁷Cs taken by means of the new method of gamma-ray spectrometry with the same mercuric iodide (HgI₂) detector which produced the spectrum of Figure 2. The detector had a 2000 V bias applied and exhibited a transit time for electrons of about 6 μs. The integration time constant was kept below 0.3 μs ($T_{\text{int}}/T_{\text{et}} < 0.05$). Note the vastly decreased background in the spectrum because the effects of incomplete collection of holes are eliminated. Over 40% of all the counts is registered in the full-energy peak. Noise practically does not contribute to the width of the peak. For a detailed presentation of experimental results see Reference 7.

5. CONCLUSION

It has been shown that a new method for doing gamma-ray spectrometry with a solid state detector can be applied in the case of compound semiconductors with

much better results than are achieved with the conventional current-integration technique. Application of this novel method to gamma-ray spectroscopy with room-temperature HgI_2 is reported in a companion paper in this volume.⁷ The new method consists of measuring the spectrum of current pulses from the detector, and depends on 1) having a large enough mobility and lifetime of at least one type of charge carrier in the material to be able to make the measurement above the noise, and 2) a sufficiently uniform electric field in the detector so that the spectrum is not too distorted. In the traditional current-integration technique, the effective useful thickness of a detector (the thickness producing counts in the full-energy peak) can be very small, despite the much larger total thickness of the crystal. The limitation comes from the inadequate hole collection capabilities of compound semiconductors in the present stage of materials development. The new method of doing gamma-ray spectrometry which has been presented circumvents the problem and concentrates completely on electrons, which are sufficiently well collected. It is hoped that the new method will allow materials such as HgI_2 and CdTe to be used for high-energy gamma-ray spectrometry in spite of their poor hole transport properties.

REFERENCES

1. G.A. Armantrout, S.P. Swierkowski, J.W. Sherohman, and J.H. Yee, IEEE Trans. on Nucl. Sci. NS-24 (1977) 121.
2. J.S. Iwanczyk, J.H. Kusmiss, A.J. Dabrowski, J.B. Barton, G.C. Huth, T.E. Economou, and A.L. Turkevich, Nucl. Instr. and Meth. 193 (1982) 73.
3. A.J. Dabrowski, *Advances in X-ray Analysis*, Vol. 25, Edited by John C. Russ, Charles S. Barrett, Paul K. Predecki and Donald E. Leyden (Plenum Publishing Corporation, New York, 1982).

4. A.J. Dabrowski, J. Iwanczyk, W.M. Szymczyk, P. Kokoschinegg, J. Stelzhammer, and R. Triboulet, Nucl. Instr. and Meth. 150 (1978) 25.
5. M. Schieber, Nucl. Instr. and Meth. 144 (1977) 469.
6. M. Schieber, W.F. Schnepple, and L. van den Berg, J. Crystal Growth 33 (1976) 125.
7. K. Hull, A. Beyerle, J. Markakis, and W.M. Szymczyk, Nucl. Instr. and Meth., this issue.
8. R. H. Bube, *"Photoconductivity of Solids,"* Robert E. Krieger Publishing Co., Huntington, N.Y. (1978) 268.
9. R.C. Whited and M.M. Schieber, Nucl. Instr. and Meth. 162 (1979) 113.
10. C. Sharager, P. Siffert, A. Holzer, and M. Schieber, IEEE Trans. on Nucl. Sci. NS-27 (1980) 276.
11. M. Sapa, P.A. Tove, and G. Boberg, Nucl. Instr. and Meth. 150 (1978) 55.

FIGURE CAPTIONS

- Figure 1. Typical ^{137}Cs spectrum taken with 0.5 mm-thick- HgI_2 detector with relatively good hole transport parameters.
- Figure 2. ^{137}Cs spectrum taken with 10-mm-thick HgI_2 detector with a charge integration time constant longer than the electron transit time, i.e., $(T_{\text{int}}/T_{\text{et}}) \sim 1.5$.
- Figure 3. Illustration of usual charge-sensitive measurement setup. Voltage pulse amplitude at the output of the charge-sensitive amplifier is proportional to the charge induced at the input of the amplifier, Q_1 , rather than the total charge liberated in the detector, Q_0 . If holes are preferentially trapped, Q_1 depends on the distance $L - x_1$ that the electrons move before collection.
- Figure 4. (a) Direct and (b) indirect approaches to measuring the detector current pulses. The indirect approach (b) makes use of the charge-sensitive integrating loop Q followed by a short differentiation time constant τ_d , resulting in lower noise.
- Figure 5. Illustration of current-sensitive measurement setup. Voltage pulse amplitude at the output of a current-sensitive amplifier is proportional to the detector current I_0 ; it does not depend on the location of the ionization event. The current amplitude I_i carries the spectrometric information ($I_i \sim Q_0 \sim \text{gamma-ray energy}$). The thin curved lines represent the waveform after passing through the noise-limiting integrator. The amplitude of the shortest pulse (3) is influenced by the limited bandwidth, and would give rise to a count which is shifted downwards in energy in the spectrum.

Figure 6. ^{137}Cs spectrum taken with the same HgI_2 detector which produced the Figure 2 spectrum. The noise-integrating time constant is much shorter than the electron transit time ($T_{\text{int}}/T_{\text{et}} \sim 0.05$), thus the displayed spectrum is actually a spectrum of current pulse heights.

APPENDIX

Herein are considered the following two approaches to measuring the amplitude of current pulses from semiconductor detectors:

- A. Placing a low resistance in parallel at the input and following it with a fast voltage amplifier with bandwidth limited to τ .
- B. Using a high-resistance charge-sensitive preamplifier followed by differentiation with time constant τ_d and voltage amplification with bandwidth limited to τ_i .

The two different approaches will be evaluated and compared from the noise point of view.

A.1 APPROACH A

(Insert drawing A here)

where R is a low input resistance dominating parallel noise sources. C is the total input capacitance, and R_{eq} is the noise-equivalent resistance of the preamplifier series noise.

An amplifier with bandwidth limited by an integrating time constant t has an output noise given by

$$\overline{U_{out}^2} = \int_0^{\infty} \overline{U_{in}^2} \cdot \frac{d\omega}{2\pi (1 + \omega^2 \tau^2)}$$

The densities of noise sources giving rise to $\overline{U_{in}^2}$ are.

$$\overline{U_{in}^2} = \overline{U_{n_2}^2} + \overline{i_{n_1}^2} \left[\frac{R}{1 + j\omega RC} \right]^2 = 4kT \left(R_{eq} + \frac{R}{1 + \omega^2 R^2 C^2} \right)$$

Hence the output noise is equal to

$$\overline{U_{out}^2} = kT (R_{eq}/\tau + R/(\tau + RC))$$

or

$$NOISE = \sqrt{kT} \cdot \sqrt{R_{eq}/\tau + R/(\tau + RC)}$$

The signal in the time of interest region given by RC and $\tau \ll$ time of interest < time of collection is equal to

$$SIGNAL = i_{sig} \cdot R = QR/T_{et}$$

Hence

$$SN = \frac{QR}{T_{et} \sqrt{kT} \sqrt{R_{eq}/\tau + R/(\tau + RC)}}$$

The more integration, the lower the noise, but τ and RC will have to be kept less than fT_{et} to preserve current proportionality rather than charge proportionality of the output signal; $f \ll 1$ defines the arbitrarily chosen "fidelity factor."

If $\tau = fT$ and $RC = fT_{et}$ (i.e., if R is kept equal to $R_{max} = fT_{et}/C$), then

$$S/N = \frac{Qf}{\sqrt{kTC}} \cdot \sqrt{\frac{\tau}{\tau + 2 CR_{eq}}}$$

A.2 APPROACH B

(Insert drawing B here)

where C and R_{eq} have the same meaning as in Approach A., and all parallel sources (leakages, resistors at input) are assumed to be negligible compared to series noise sources at the short time constants employed. As before, τ_i will have to be

kept less than fT_{et} . The larger the differentiation time constant τ_d , the larger the signal U'' , but τ_d will have to be kept less than fT_{et} to ensure sufficient proportionality of U'' to current signal i_{sig} rather than to its integral U' ; $f \ll 1$ defines the arbitrarily chosen "fidelity factor."

So

$$\tau_i = \tau_d \equiv \tau = fT_{et}, \quad f \ll 1$$

The combination of amplifiers with bandwidth limited by integration and differentiation time constants equal to τ results in output noise of

$$\overline{U_{out}^2} = \int_0^{\infty} \overline{U_{in}^2} \cdot \frac{\omega^2 \tau^2}{(1 + \omega^2 \tau^2)^2} \cdot \frac{d\omega}{2\pi}$$

The density of noise at the input is equal to

$$\overline{U_{in}^2} = \overline{U_{n1}^2} \quad (\text{all parallel sources disregarded in view of short shaping times})$$

Hence the output noise is equal to

$$\overline{U_{out}^2} = kT R_{eq}/2\tau$$

or

$$\text{NOISE} = \sqrt{kT R_{eq}/2\tau}$$

$$\text{SIGNAL} = i_{sig} \cdot \tau_d/C = Q\tau_d/CT_{et} = fQ/C$$

Therefore

$$S/N = \frac{Qf}{\sqrt{kTC}} \cdot \sqrt{\frac{2\tau}{CR_{eq}}}$$

A.3 COMPARISON

Removing the low resistance from the input and employing the more sophisticated integration-differentiation approach can result in improving the signal-to-noise ratio (in comparison to the direct approach) by a factor of

$$(4 + 2\tau/CR_{eq})^{1/2}$$

where C is the total "cold" capacitance at the input, R_{eq} is the noise-equivalent resistance of the series noise in the preamplifier, and τ is the bandwidth shaping time constant.

Figure 1

FIG 1
S-213

Figure 2

Fig 2
S-213

Fig 3

Figure 3

Fig 3
S-213

Figure 4

Figure 5

S-215-TP 11/85

Figure 6

FIG A

S-213

Figure A

Figure B

S-213-TP

FIG B
S-213