

AN-40

Heavy-Ion Spectroscopy with Silicon Surface-Barrier Detectors

1.

Introduction

Because of their large masses, heavy ions* interact with silicon surface-barrier detectors (SSBD's) in a more complex way than alphas and lighter particles. While the interactions of alphas and lighter particles with SSBD's are relatively well known at this time, many important details of the interaction of heavy ions with SSBD's are still poorly understood and are being actively investigated. Results of these investigations have been and are being published in specialized literature where great quantities of data are available.⁽¹⁻³³⁾ The sheer volume of the published data makes their use difficult. This difficulty is compounded by some disagreement between different authors when they try to describe the physical mechanism underlying some

observed data. Moreover, some phenomena typical of the interaction of heavy ions with SSBD's are normally described with terms such as "plasma effects" and "pulse-height defect" that may not be familiar to nonspecialists and are not included in detector specifications.

For these reasons, ORTEC, through this Application Note, will attempt to summarize some of the most recently published information and to recall the most important concepts that describe the interaction of heavy ions and fission fragments with SSBD's.

*The term "heavy ions" includes fission fragments.

2.

The Interaction of Heavy Ions with Silicon Surface-Barrier Detectors

2.1. General

The incoming charged particle enters the active region of the detector through a thin insensitive window. In the active region of the detector, heavy particles lose their energy essentially by Coulomb interaction with the nuclei and electrons of the absorbing material, silicon.

The interaction with electrons ultimately results in the creation of electron-hole pairs; the average energy necessary to create one electron-hole pair in silicon is 3.62 eV at 300°K and 3.72 eV at 80°K. The electron-hole pairs are swept by the electric field, created by the applied bias voltage, and the amplitude of the resulting integrated current signal represents the energy spent by the ionizing particle in electronic collisions in the detector's sensitive

region. On the other hand, the energy spent in interactions with nuclei is lost to the detection process.

The general mechanism of interaction outlined above is clearly valid, not only for "light" charged particles such as alphas, protons, etc., but also for heavy ions. However, as shown in the following discussion, because of the large mass values of the heavy ions, their interactions with SSBD's are strongly affected by some parameters that are of little or no importance when considering the interaction of lighter particles with SSBD's.

2.2. Entrance Window Effects

When any charged particle passes through the entrance window of the SSBD, it loses some of its energy. This loss, ΔE_w , reduces the total amount of energy available for creation of electron-hole pairs in the sensitive region of the SSBD. Thus the measured energy is something less than the total energy and the measurement peak is shifted to a lower energy. Also, statistical fluctuations of ΔE_w contribute degradation to the peak resolution.

Because of their large mass values, heavy ions lose greater amounts of energy in the entrance window than the lighter charged particles do. For example, an ion with a mass near 100 amu and energy near 50 MeV loses about 0.4 MeV as it passes through a gold entrance window that is 25 to 30 $\mu\text{g}/\text{cm}^2$ thick. In contrast, an alpha particle with the same energy will suffer an energy loss that is about 10^2 times less when it passes through the same window.⁽¹⁾

2.3. Nuclear Collision Effects

As stated previously, the energy spent by a charged particle in nuclear collisions is lost to the electron-hole pair creation process. Because the probability of a nuclear interaction increases with decreasing velocity of the charged particle, heavy ions lose a much larger fraction of their total energy in nuclear collisions than lighter charged particles do. For example, a 100-MeV fission fragment loses several MeV in nuclear interactions in an SSBD while, for an alpha particle of the same energy, this loss is less than 50 keV.⁽¹⁾

A complete theory for the slowing down of heavy particles has been developed by Linhard et al.⁽¹⁾ This Application Note will not report this theory in detail but will rather indicate calibration techniques that help account for energy loss due to nuclear interactions when SSBD's are used in heavy-ion spectroscopy.

2.4. Plasma Effects

Heavy charged particles create a dense "cloud" of electron-hole pairs in an SSBD. At the onset, the electric field created by the applied bias cannot penetrate this cloud. Only after the cloud has been sufficiently dispersed by ambipolar diffusion will the charge carriers begin to drift under the influence of the electric field. This phenomenon has the following effects:

1. A delay is generated between the creation of the electron-hole pairs (considered instanta-

neous) and the rising edge of the charge pulse in the detector.^(8,9,12) This delay contributes to the time jitter of the signal delivered by the detector.

2. The charge signal rise time slows down⁽⁴⁻¹²⁾ thus also increasing the time jitter value.

3. Because of the existence of a dense cloud of charge, creating a zero initial electric-field region, a recombination of charge carriers can occur with consequent loss of pulse amplitude.^(19,20) This effect, combined with the energy loss in the window (Section 2.2) and in nuclear collisions (Section 2.3), results in an overall energy loss which causes a "pulse-height defect." It should be noted that carrier recombination depends strongly on the lifetime of the carriers in the crystal used to fabricate the SSBD, and also that carrier recombination is unimportant in the detection of light particles or gamma- or x-rays because the probability of carrier recombination in a semiconductor region with a high electric field is negligible.

These three effects are difficult to quantize. The delay can be measured only with respect to a time reference signal and at a predetermined fraction of the pulse from the detector, and is therefore dependent on its definition.^(8,9) The slowing down of the pulse (normally called "plasma time") must somehow be extracted from the total signal rise time. The total rise time includes the carriers' transit time due to their drift in the electric field and, possibly, detector equivalent circuit and electronics effects.⁽⁴⁾ Usually the plasma time is experimentally defined by subtracting in quadrature the carriers' drift time and the equivalent circuit and electronics rise time components from the measured 10% to 90% rise time (see Refs. 4, 8, 9, and references quoted therein). However, other definitions have been used.^(10,11) Finally, the amount of charge lost by recombination must be extracted from the pulse-height defect and this also includes the effects of nuclear collisions and losses in the entrance window, as previously indicated.

All the plasma effects decrease with increasing values of the electric field on the centroid of the track (some authors simply use the maximum value of the electric field, which is easier to determine). The dependence of delay and plasma time on the electric field is described in the literature as KE^{-m} , where K is a constant and m is a value between 1 and 2. The fraction of charge lost by recombination

depends on the quality of the crystal and on the electric field through the carriers' lifetime to plasma lifetime ratio.⁽¹⁰⁾ Delay time and plasma time decrease as the detector temperature is decreased; this is due to an increased carrier mobility.⁽⁵⁾ We will try to give some semiquantitative information on the order of magnitude of the above mentioned effects.

The information on the "delay effect" in the literature is very incomplete and relates only to alpha particles. It is expected that this effect for alphas is several times smaller than for fission fragments. The results reported in Ref. 9 indicate that if the maximum electric field in the detector is of the order of 10^4 V/cm, a delay of about 1 nanosecond is expected.

Much more information is available on "plasma time." With an electric field of the order of 1 to 1.5×10^4 V/cm, a typical value of plasma time for heavy ions and fission fragments is around 5 to 15 nanoseconds; the same parameter for alpha particles is about 1 to 2 ns. These numbers will decrease by a factor of 2 at CO₂ temperature and by a factor of 4 at LN₂ temperature.

An indication of the order of magnitude of recombination effects in plasma is given in Ref. 19. Both heavy and light ²⁵²Cf fragments showed a total pulse-height defect of 16 MeV and mass dependence of 0.4 MeV/amu in a detector with a maximum field value of 1.45×10^4 V/cm. The estimated carrier lifetime in the silicon crystal was 20 to 30 μ s. Nuclear collision losses were estimated to contribute 2 MeV for light fragments to 4 MeV for heavy fragments with a mass dependence of about 0.04 MeV/amu for both light and heavy fragments. The loss in the entrance window of about 0.4 MeV is negligible when compared with the losses due to nuclear collisions and recombination in this case.

2.5. Channeling Effects

It is well known that if a beam of charged particles enters a crystalline solid along a well-defined crystallographic axis, the incoming particles are "steered" by the atoms of the lattice. When this condition occurs, the charged particles suffer fewer nuclear collisions than particles that enter the solid from a "random" direction.

For heavy ions and fission fragments, significant channeling is obtained only when the particles enter the detector within the critical angle of 0.5° to

the chosen crystalline axis [normally (110), the most "open" direction]. Channeling has been used to improve the energy resolution of SSBD's when used in heavy-ion spectroscopy.^(14,26) The energy resolution is better because there are fewer nuclear collisions and a larger range, resulting in a less dense plasma cloud and consequently in a lower recombination rate.

2.6. Charge Multiplication Effects

A high-electric field under the entrance window (greater than 10^4 V/cm) is important for heavy-ion detectors because all the effects due to the formation of a plasma will decrease as the electric field increases. However, if the detector is improperly manufactured, the high-electric field can create charge multiplication effects due to tunneling.⁽²⁷⁾ The charge multiplication phenomenon results in abnormally large pulses with consequent high-energy tailing of the peak, poor energy resolution, or even double peaking.⁽²⁷⁾

2.7. Radiation Damage

Normally SSBD's can withstand heavy-ion doses of approximately 10^8 ions/cm² without severe deterioration of energy resolution. However, it was observed⁽⁷⁾ that timing performance can deteriorate noticeably at doses of the order of only 10^7 ions/cm² or less. The reasons are not clearly understood but, following in part the discussion in Ref. 7, the following explanation is proposed. The energy resolution of SSBD's used for heavy ions is determined by both the phenomena that are independent of the electric field (window loss, nuclear collisions) and by carrier recombination, which depends on the electric field through the plasma time. Damage due to heavy ions can create deep electrically-active defects in the lattice with consequent local variations of the electric field value. At "low" doses these variations can be such that recombination is not a noticeable factor in the overall energy resolution. However, the detector's timing performance is affected directly by any local variation of the electric field through both the plasma time and the delay time.

One final consideration is that the creation of deep active centers increases the leakage current of the detector. Sometimes, following radiation damage caused by heavy ions, it is possible to prolong the lifetime of the detector by merely cooling it to 0°C to reduce the leakage current.

3.

Use of Silicon Surface-Barrier Detectors in Heavy-Ion Spectroscopy

3.1. Calibration Techniques

The energy calibration of an SSBD for heavy-ion spectroscopy is not as straightforward as it is for light ions such as alpha particles. Some of the reasons are the existence of a pulse-height defect due to energy loss in the entrance window, nuclear collisions, and recombination effects. The most widely used calibration technique was proposed by Schmitt et al.⁽²⁾ and uses the following equation:

$$E(X,M) = (a + a_1M)X + b + b_1M, \quad (1)$$

where

E is the energy of the fragment,
 X is the pulse height, and
 M is the mass.

The coefficients a , a_1 , and b_1 in Eq. (1) are determined experimentally by measuring the pulse-height spectrum of a standard fission-fragment source such as ²⁵²Cf.

More recently, S. B. Kaufman et al.⁽²¹⁾ have proposed a more sophisticated calibration technique of more general validity. According to Ref. 2, Eq. (1) can be used successfully for ions heavier than mass 80 and energies in the range of 30 to 120 MeV. Outside that range the method of Kaufman et al. is recommended. [See the original work⁽²¹⁾ for a description of this method, which cannot be summarized as simply as the Schmitt et al. method.⁽²⁾] No matter which method is used, measurement accuracy increases as pulse-height defect decreases. Of the two methods known for use to decrease pulse-height defect (channeling and high-electric field), only the high-electric field is feasible without special facilities for beam collimation and special detectors. A high-electric field in the SSBD reduces the portion of pulse-height defect due to carrier recombination and improves

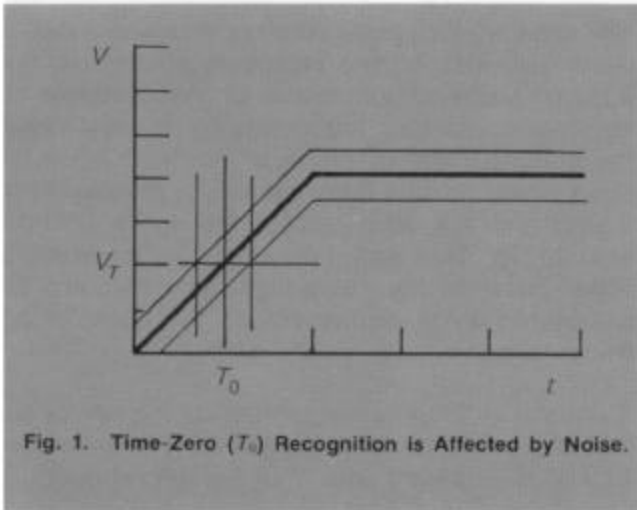
the timing performance by shortening the plasma time. As explained in Section 2.4, especially with relatively low-lifetime material, the fraction of pulse-height defect due to carrier recombination may be larger than the fractions that are due to window loss and nuclear collisions.

Normally, a high-electric field over the relatively short range of a heavy ion is best achieved by using low-resistivity Si as starting material; the typical value is a few hundred ohm-cm. All ORTEC heavy-ion detectors are made from silicon crystals with resistivities in this range and operate with a minimum electric-field value of 1.5×10^4 V/cm under the front contact. In addition, all the silicon crystals used to make ORTEC heavy-ion detectors have carrier lifetimes greater than 1 millisecond. According to the data of Refs. 19 and 20, these values of the electric field and the carrier lifetime should reduce to practically zero the portion of the pulse-height defect that is due to plasma recombination.

3.2. Timing

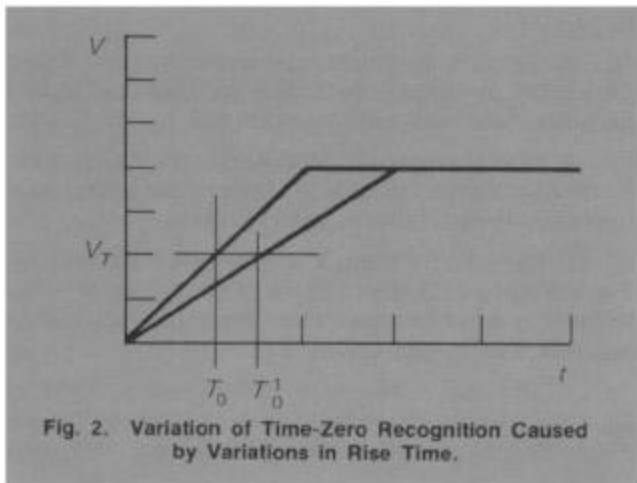
Timing measurements with heavy ions and SSBD's are of great importance because the time-of-flight (T.O.F.) technique is a primary tool for heavy-ion mass identification (see Refs. 13–18). In every T.O.F. experimental setup a zero time detector and a stop detector are used. The stop detector is usually an SSBD, while semiconductor and other detector types have been used for the zero time signals. In general, the time variance obtainable from an SSBD system used with heavy ions is affected by the following four parameters:

1. The variance, σ_n^2 , due to electronic noise. This variance is determined by the ratio of the system rise time (detector plus preamplifier) to the electronic noise. The system rise time is obtained by the convolution of the detector's own rise time and the rise time of the preamplifier. This variance is briefly illustrated in Fig. 1, showing a signal of fixed amplitude crossing a threshold, V_T , at time instant T_0 . If a "ribbon" of noise is superimposed on the signal, a "jitter" is generated on the determination of time T_0 .



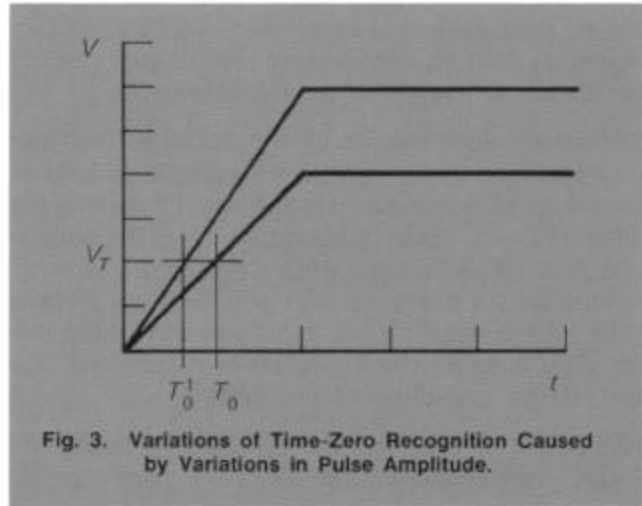
2. The variance of σ_T^2 of the rate of rise, dV/dt , of the signals generated by the detector for pulses of a given amplitude (see Fig.2). A contribution to this variance is provided by disuniformities in the electric field corresponding to nonuniform resistivity of the starting material. The slowdown in rise time due to the plasma effect enhances this problem because of the strong dependence on the electric field value.

3. The variance, σ_A^2 , generated when a given threshold voltage is crossed by signals that have



different amplitudes (e.g., because of pulse-height defect) even though they have the same rise time (see Fig. 3). A contribution to this variance in the case of "transmission type" detectors can be provided by any thickness variations across the active detector area.

4. The variance, σ_D^2 , due to the delay generated by the plasma effect.



Finally, note that this brief discussion is somewhat simplified because the threshold circuits are charge-sensitive rather than voltage-sensitive.⁽⁴⁾

The problem faced by the experimental physicist is how to minimize the time variance and to thus optimize the precision of the T.O.F. measurement. To start with, the electronic noise must be minimized. ORTEC offers three fast preamplifiers to be used with different detectors and experiment configurations. The Model 140 is a charge preamplifier with a separate ultra-fast timing signal obtained in the voltage mode.⁽²⁸⁾ The front end of the preamplifier is mounted integrally with the SSBD in the head assembly. This minimizes noise pickup and timing losses in an input cable. Models 142A and 142B are very fast low-noise preamplifiers that feature a separate timing output that is derived from the energy (charge) signal. These preamplifiers are connected to the detectors in the usual manner with coaxial cables. The Model 142A is the optimum choice for detector capacitances below 50 pF and for lower energies. The Model 142B is the optimum choice when the detector capacitance is 100 pF or more and the cable connection to the preamplifier is short. The Model 140 is the optimum choice for detector capacitances of 100 pF or more and for all situations where there

is a long distance between the detector and the walls of the vacuum chamber. More information on timing with these preamplifiers is available in Refs. 32 and 33.

The contributions of the variances, σ_T and σ_A , can be significantly reduced through the use of either the constant fraction (CF)⁽²⁹⁾ or the amplitude and rise time compensated (ARC)⁽³⁰⁾ discrimination technique. The ORTEC Models 454, 473A, and 574 are all modular instruments that can be used in a timing system to obtain optimum timing characteristics with heavy-ion measurements.⁽³¹⁾

The timing jitter caused by the detector itself can be minimized by using as high an electric field as possible and, whenever it is feasible, by cooling the detector below room temperature. All of the plasma effects in SSBD's (rise time slowdown, recombination, delay) decrease with an increased electric field in the detector so a high-electric field will not only improve the timing performance but also the energy resolution of the system.

Probably the best results obtained in heavy-ion T.O.F. measurements with a ΔE - E telescope of

SSBD's are reported in Ref. 15. The SSBD's, made by ORTEC, were both cooled to 0°C and biased at a voltage as high as practicable. The active thicknesses and areas were 16 μm X 25 mm² for the ΔE detector and 200 μm X 200 mm² for the E detector. The detectors were separated by a 28-cm flight path. The time resolution, measured with 56-MeV ¹⁶O ions was 89 ps FWHM, and the energy resolution was 149 keV FWHM.

The exceptionally good results described in Ref. 15 were due also to the relatively small size and superb thickness uniformity of the detectors. In larger-area devices, the variations in resistivity of the starting material result in electric field variations which, in turn, vary the values of the plasma timing and the delay across the active detector area. In Ref. 12, a well-defined correlation is established between the mean-flight-time shift and the silicon-resistivity profile across the detector entrance window.

Typically in T.O.F. arrangements using one or two SSBD's, a 200 to 300 picosecond time resolution FWHM is achieved with ²⁵²Cf fission products.

Bibliography

1. G. Bertolini and A. Coche, Eds., *Semiconductor Detectors*, Sections 4.1.1 and 4.2.1 to 4.2.4, American Elsevier Publishing Co., New York (1968).
2. H. W. Schmitt, W. M. Gibson, J. H. Neiler, F. J. Walter, and T. D. Thomas, Absolute Energy Calibration of Solid State Detectors for Fission Fragments and Heavy Ions, *Phys. and Chem. of Fission, IAEA, Vienna*, p. 531 (1965).
3. J. B. England, A Note on the Detection of Heavy Ions by Over-Biased Totally Depleted Thin Surface Barrier Detectors, *Nucl. Instrum. Methods* **102**, p. 365 (1972).
4. A. Alberigi Quaranta, M. Martini, and G. Ottaviani, The Pulse Shape and the Timing Problem in Solid State Detectors — a Review Paper, *IEEE Trans. Nucl. Sci.* **NS-16**(2), 35 (1969).
5. A. Alberigi Quaranta, A. Taroni, and G. Zanarini, Plasma Time in Semiconductor Detectors, *IEEE Trans. Nucl. Sci.* **NS-15**(3), 373 (1968).
6. A. Taroni and G. Zanarini, Plasma Effects and Charge Collection Time in Solid State Detectors, *Nucl. Instrum. Methods* **67**, 277 (1969).
7. P. Mulást and E. I. Haines, Degradation of the Time Characteristics of Surface Barrier Detectors with Fission Fragment Dose, *Rev. Sci. Instrum.* **40**, p. 507 (1969).
8. A. Alberigi Quaranta, A. Taroni, and G. Zanarini, Plasma Time and Related Delay Effects in Solid State Detectors, *Nucl. Instrum. Methods* **72**, p. 72 (1969).
9. M. Moszynski and B. Bengtson, Plasma Delay and Plasma Time Jitter in Subnanosecond Timing with a Surface Barrier Detector, *Nucl. Instrum. Methods* **91**, p. 73 (1971).
10. W. Seibt, K. E. Sundstrom, and P. A. Tove, Charge Collection in Silicon Detectors for Strongly Ionizing Particles, *Nucl. Instrum. Methods* **113**, p. 317 (1973).
11. R. N. Williams and E. M. Lawson, The Plasma Effect in Silicon Semiconductor Radiation Detectors, *Nucl. Instrum. Methods* **120**, p. 261 (1974).
12. H. Henschel, H. Hipp, A. Kohnle, and F. Gonnwein, The Influence of Plasma Effects on the Timing of Fission Fragments with Semiconductor Detectors, *Nucl. Instrum. Methods* **125**, p. 365 (1975).
13. E. Andrade, D. Rendic, V. A. Otte, and G. C. Phillips, Charged Particle Mass Identification by Energy-Time-of-Flight Technique, *Nucl. Instrum. Methods* **113**, p. 93 (1973).

14. W. J. Sullivan and B. W. Wehring, Study of the Use of Particle Channeling in Time-of-Flight Fission-Fragment Mass-Yield Measurements, *Nucl. Instrum. Methods* **123**, p. 29 (1975).
15. B. Zeidman, W. Henning, and D. G. Kovar, A High-Resolution Mass-Identification System for Heavy Ions, *Nucl. Instrum. Methods* **118**, p. 361 (1974).
16. T. M. Cormier, R. S. Galik, E. R. Cosman, and A. J. Lazzarini, Performance of a Heavy-Ion Time-of-Flight Spectrometer, *Nucl. Instrum. Methods* **119**, p. 145 (1974).
17. W. F. W. Schneider, B. Kohlmeyer, W. Pfeffer, F. Pohlhofer, and R. Bock, Properties of a Time-of-Flight Telescope for Heavy Ions in the $A = 100$ Range, *Nucl. Instrum. Methods* **123**, p. 93 (1975).
18. W. Lang and H. G. Clerc, A Fast Zero-Time Detector for Time-of-Flight Measurements with Heavy Ions, *Nucl. Instrum. Methods* **126**, p. 535 (1975).
19. E. C. Finch and A. L. Rodgers, Measurements of the Pulse Height Defect and its Mass Dependence for Heavy-Ion Silicon Detectors, *Nucl. Instrum. Methods* **113**, p. 29 (1973).
20. E. C. Finch, An Analysis of the Causes of the Pulse Height Defect and its Mass Dependence for Heavy-Ion Silicon Detectors, *Nucl. Instrum. Methods* **113**, p. 41 (1973).
21. S. B. Kaufman, E. P. Steinberg, B. D. Wilkins, J. Unik, and A. J. Gorski, A Calibration Procedure for the Response of Silicon Surface-Barrier Detectors to Heavy Ions, *Nucl. Instrum. Methods* **115**, p. 47 (1974).
22. C. Cottini, E. Gatti, and V. Svelto, Instrumentation Techniques in Nuclear Pulse Analysis, Publication 1184, National Academy of Science, National Research Council, Washington, DC, p. 53 (1964).
23. O. Meyer and H. J. Langmann, Die Beweglichkeit "Heisser" Elektronen und Ihr Einfluss auf die Anstiegszeit der Impulse von Halbleiterzählern aus n-Silizium, *Nucl. Instrum. Methods* **34**, p. 77 (1965).
24. H. Meyer, Studies of the Response Speed of Silicon Surface Barrier Detectors, when Irradiated with Different Particles, *IEEE Trans. Nucl. Sci.* **NS-13**(3), 180 (1966).
25. A. H. Krulish and R. C. Axmann, Transient Response of Surface Barrier Detectors as a Function of Fission Fragment Energy, *IEEE Trans. Nucl. Sci.* **NS-14**(4), 58 (1967).
26. C. D. Moak, J. W. T. Dobbs, and W. W. Walker, Response of Silicon Fission Detectors to Channeled ^{127}I and ^{40}Ar Ions, *Rev. Sci. Instrum.* **37**(9), 1131 (1966).
27. F. J. Walter, Multiplication in the Fission Fragment Pulse Height Response of Silicon Surface Barrier Detectors, *IEEE Trans. Nucl. Sci.* **NS-11**(3), 232 (1964).
28. I. S. Sherman and R. G. Roddick, Low Noise Preamplifiers for Simultaneous High Resolution Energy & Time Measurement with Semiconductor Detectors, *IEEE Trans. Nucl. Sci.* **NS-17**(1), 252 (1970).
29. D. A. Gedcke and W. T. McDonald, A Constant Fraction of Pulse Height Trigger for Optimum Time Resolution, *Nucl. Instrum. Methods* **55**, p. 377 (1967).
30. R. L. Chase, Pulse Timing System for Use with Gamma Rays on Ge(Li) Detectors, *Rev. Sci. Instrum.* **39**, p. 1318 (1968).
31. M. O. Bedwell and T. J. Paulus, A New Constant Fraction Timing System with Improved Time Derivation Characteristics, *IEEE Trans. Nucl. Sci.* **NS-23**(1), 234 (1976).
32. T. J. Paulus, R. D. McKnight, and T. L. Mayhugh, Experimental Characteristics of the Timing and Energy Resolutions of Charged Particle Detectors, *IEEE Trans. Nucl. Sci.* (to be published).
33. ORTEC Application Note 41, Techniques for Improved Time Spectroscopy.