CHARGE TRAPPING CORRECTION IN GE SPECTROMETERS

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Abstract

In their fundamental work on ballistic deficit correction, Goulding and Landis noted evidence that their circuit corrected for charge trapping as well as ballistic deficit [1]. The reduction in trapping was proposed to be due to shallow traps whose capture/emission times were short enough to be processed by their circuit, yet long enough to cause a ballistic deficit like effect with semi-Gaussian shaping, even at long time constants [1]. In this work, a charge trapping model is developed which does not require the assumption of shallow level detrapping. The model shows the charge trapping deficit to be proportional to $S_o t_{coll}^N$, where S_o is the peak amplitude of the shaping amplifier pulse, t_{coll} is the charge collection time for the carrier being trapped, and $1.5 < N < 3$ for most practical cases. A class of circuits to correct for charge trapping was developed and tested; the results were used to evaluate the main features of the model. A radiation damaged, conventional electrode detector and a reverse electrode detector, which exhibited a significant amount of deep-level, majority carrier charge trapping, were used to evaluate the usefulness of the circuits. At the 1.33-MeV ^{60}Co line, the uncorrected FWHM of the radiation damaged detector was 4.30 keV, while the $N = 2.3$ corrected FWHM was 2.00 keV. The uncorrected FWHM of the reverse electrode detector was 2.20 keV, while the $N = 3$ corrected FWHM was 1.84 keV. In both cases, a gated integrator made no improvement to the resolution of the detector, leading to the conclusion that deep-level trapping was the dominant mechanism.

Introduction

In the ideal case, the signal produced by a Ge gamma-ray spectrometer is proportional to the charge generated by a radiation event in the detector, but is independent of the charge collection time. This condition is approached by many modern HPGe detectors when long shaping times are employed to avoid ballistic deficit effects. However, spectra may still be degraded due to charge carrier trapping. Trapping effects are often exhibited by radiation damaged reverse and conventional electrode detectors as well as very large reverse electrode devices [2,3].

In their fundamental work on ballistic deficit correction, Goulding and Landis noted evidence that their circuit corrected for charge trapping as well as ballistic deficit [1]. The reduction in trapping was proposed to be due to shallow traps whose capture/emission times were short enough to be processed by their circuit, yet long enough to cause a ballistic deficit like effect with semi-Gaussian shaping, even at long time constants [1]. If this were correct, a gated integrator circuit would also reduce trapping effects caused by such levels. In most cases, however, it was found that a gated integrator did not improve the resolution of detectors exhibiting incomplete charge collection, while dramatic improvements in resolution were obtained using circuits similar to the Goulding and Landis ballistic deficit correction circuit.

In this work, a model not requiring the assumption of shallow level charge carrier detrapping is proposed to explain the resolution enhancement made by the Goulding and Landis circuit at long shaping times. The model suggests the existence of a class of circuits to correct for charge trapping, of which the Goulding and Landis circuit is a special case. These circuits were developed and tested for their ability to correct for charge trapping; the results were used to evaluate the main features of the model.

Theory

The shape of a charge pulse occurring in a HPGe coaxial detector is a result of the summing of contributions due to both majority and minority carrier motion. The measured charge pulse risetime, on the other hand, is solely determined by either the majority or minority carrier charge collection time, whichever is longer. The type of carrier having the longer collection time depends on which carrier travels the greater distance since both carrier types have roughly equal drift velocities. HPGe coaxial detectors are usually fabricated using a contacting arrangement such that majority carriers are collected by the central contact and minority carriers by the outer contact. Hence if an interaction occurs in the $r > 1/2(r_1 + r_2)$ region, the pulse risetime is determined by the charge collection time for majority carriers. For interactions occurring in the $r < 1/2(r_1 + r_2)$ region the risetime is determined by the charge collection time for minority carriers. Since the volume of a coaxial detector varies as r^2, the majority of gamma-ray interactions occur in the $r > 1/2(r_1 + r_2)$ region with only a 30% contribution to the total coming from the $r < 1/2(r_1 + r_2)$ region. The measured risetimes, thus, mainly correspond to majority carrier charge collection times.

Majority carrier trapping

Assume the electric field, E, existing in the detector is great enough that the carrier drift velocity, v_{drift}, is close in value to the saturation drift velocity, v_{sat}. The carrier collection time, t_{coll}, is then directly proportional to the distance traversed from r, the interaction position. For majority carriers $t_{coll} = (r - r_1)/v_{sat}$ with $r_1 \leq r \leq r_2$ or

$$r = r_1 + v_{sat}t_{coll} \quad \text{for} \quad t_{coll} \leq (r_2 - r_1)/v_{sat} \,. \tag{1}$$

Assume that majority carrier (but no minority carrier) trapping is present. This case corresponds to hole traps created by neutron damage in HPGe coaxial detectors of conventional geometry [4] or electron trapping in reverse electrode coaxial detectors. Let δ be the fractional loss of pulse height, $\Delta Q/Q_o$. Then [3]

$$\delta = \frac{1}{\lambda \ln (r_2/r_1)} [r \ln(r/r_1) - (r/r_1)] \tag{2}$$

where λ is the mean free majority carrier drift length. Equation (1) may be substituted for r in order to express δ as a function of t_{coll}. To an excellent approximation δ can be expressed by a simple power law of the form

$$\delta = A\, t_{coll}^N \tag{3}$$

where A is a constant. If v_{sat} is 10^7 cm/sec and r_1 is 0.5 cm, then N = 1.61. Thus, the longer the charge collection time, the larger the fractional loss of pulse height.

Expression (2) for δ was derived [3] assuming λ to be independent of r. However, in the general case, λ may be quite dependent on the electric field, E, which in turn can have significant r dependence [3,5]. From reference [2], $\lambda = v_{drift}/(n_t \langle v \rangle \sigma)$ where $\langle v \rangle$ is the carrier thermal velocity, σ is the trap cross section, and n_t is the trap density. Assume that n_t has no r dependence; i.e., the trap density is uniform. The term $v_{drift}/\langle v \rangle$ is only weakly E dependent at the fields which usually occur in coaxial detectors [2]. On the other hand, σ can vary as E^{-1} [6]. E in turn may have an r dependence approaching r^{-1} in the case of a coaxial detector operated at high overbias. Thus σ can vary directly as r, which in turn varies linearly with t_{coll} by equation (1); i.e., $\lambda \propto 1/(r_1 + v_{sat}t_{coll})$.

It is not strictly correct to substitute an r (or t_{coll}) dependent λ into (2) since, as stated above, (2) was derived assuming a constant value of λ. As an approximation, however, this may be done with less than 10% error [2]. Equation (2) then becomes

$$\delta \approx \frac{r_1 + v_{sat}t_{coll}}{B \ln (r_2/r_1)} [(r_1 + v_{sat}t_{coll})\ln(\frac{r_1 + v_{sat}t_{coll}}{r_1}) - v_{sat}t_{coll}]. \tag{4}$$

where B is a constant. This expression can also be approximated extremely well by a power law having the form of equation (3). If r_1 and v_{sat} have the same values as before, then N = 2.38. In the general case, n_t may also be a function of r. For example, n_t is often greater on the periphery of a detector than toward the center. For such a situation, the dependence of δ on t_{coll} may be even higher than shown by equation (4). Thus, more generally, $\delta \propto t_{coll}^N$ with N ranging from about 1.5 to 3.

An electronic circuit that reduces the effect of majority carrier trapping by adding a small correction to the pulse height, proportional to some power of the charge collection time, is described later in this work. At the beginning of this section it was shown that most measured risetimes correspond to majority carrier collection times (i.e., $t_{coll} = t_{risetime}$) but about 30% of them do not, corresponding instead to minority carrier motion. Pulses having risetimes due to minority carrier collection will also be "corrected" by the electronic circuit, thereby adding some error to the spectral peak shape. Fortunately the number of such pulses which have risetimes long enough to receive significant "correction" is only a fraction of the 30%. For this reason, a trapping compensation circuit based on the above principle will be demonstrated to operate well.

Minority carrier trapping

Minority carrier trapping corresponds to electron trapping in coaxial detectors having conventional geometry and the important case of neutron damage in reverse electrode detectors. The electronic compensation of minority carrier trapping effects is complicated by the fact that the measured charge pulse risetimes mainly correspond to majority carrier collection times. However, the sum of majority and minority carrier charge collection times is given by $(r_2 - r_1)/v_{sat}$, which is a constant equal in value to the longest measured risetime, $(t_{risetime})_{max}$. Therefore, the minority carrier collection time, which in this subsection will also be denoted by t_{coll}, and the risetime are related by $t_{coll} \approx [(r_2 - r_1)/v_{sat}] - t_{risetime}$, or

$$t_{coll} \approx (t_{risetime})_{max} - t_{risetime} \qquad (5)$$

Charge pulses with long minority carrier charge collection times will require the greatest electronic correction. From equation (5), it is seen that such pulses correspond to measured charge pulses with short risetimes!

As pointed out at the beginning of this section, minority carriers are collected at the outer contact of a HPGe coaxial detector. Once more assuming saturation velocity for the carriers, $t_{coll} = (r_2 - r)/v_{sat}$ for $r_1 \leq r \leq r_2$, or

$$r = r_2 - v_{sat}t_{coll} \quad \text{for} \quad t_{coll} \leq (r_2 - r_1)/v_{sat} \quad . \qquad (6)$$

In this case, δ is given by [3]

$$\delta \approx \frac{1}{\lambda \ln (r_2/r_1)} [(r_2 - r) - r \ln(r_2/r)] \quad . \qquad (7)$$

δ may be expressed as a function of t_{coll} by substituting equation (6) in (7). Curve (A) in Fig. 1 shows the variation of δ with t_{coll}, δ being normalized to its maximum value. As in previous cases, δ can be approximated very well by a simple power law such as equation (3), with N = 2.44 corresponding to values of v_{sat} and r_2 of 10^7 cm/sec and 3 cm, respectively. The squares shown in Fig. 1, superimposed on curve (A), are calculated using this power dependence.

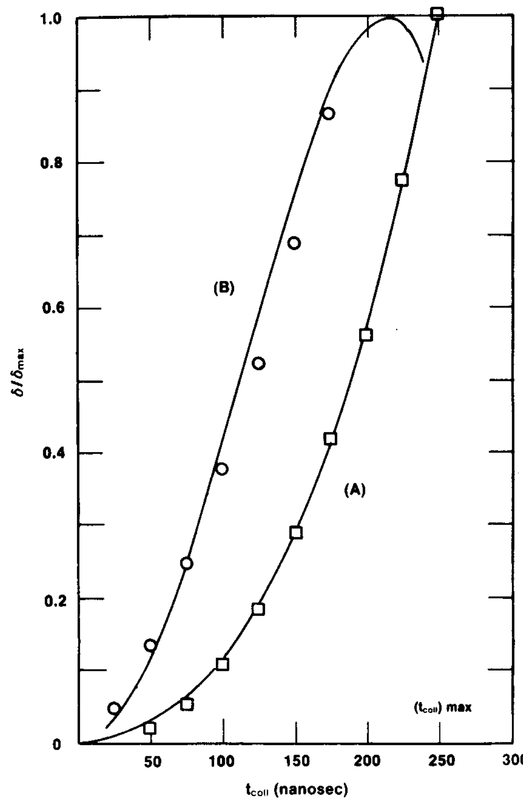

Fig. 1. Variation of δ with t_{coll} for minority carrier trapping. Curve (A) depicts the case for constant λ. The squares indicate a 2.44 power dependence. Curve (B) shows the effect of a t_{coll} or r dependent λ. The circles indicate a 1.48 power dependence. Both curves are normalized to their maximum values.

With a similar argument as in the majority carrier case concerning the variation of σ with E and of E with r: $\lambda \propto 1/(r_2 - v_{sat}t_{coll})$. This t_{coll} or r dependent λ is then substituted into (7) to make the same approximation as for majority carriers

$$\delta \approx \frac{r_2 - v_{sat}t_{coll}}{C \ln (r_2/r_1)} [v_{sat}t_{coll} - (r_2 - v_{sat}t_{coll}) \ln \frac{r_2}{r_2 - v_{sat}t_{coll}}]. \quad (8)$$

where C is a constant. Using the same values of v_{sat} and r_2 as before, δ appears to pass through a maximum then decreases slightly at long collection times. Curve (B) of Fig. 1 depicts the situation, showing δ as a function of t_{coll} for this case; δ is again normalized to its maximum value. The small decrease in δ at longer values of t_{coll} is probably more a result of approximations used in the mathematical development than a real effect. Physically, one might rather expect δ to approach a constant value at large t_{coll}. Unlike previous situations, this function of δ cannot be modeled nearly as well by a simple power dependence of t_{coll}. Nonetheless, from the viewpoint of designing electronic circuitry to compensate for trapping, it is highly desirable that any expression for δ fit a power law. Equation (3) with N = 1.48 was seen to approximate (8) within 15% for all but the longest collection times. This power dependence is demonstrated by the circles superimposed on curve (B) in Fig. 1.

An electronic circuit that compensates for minority carrier trapping, hence, should add a correction signal which varies as some power of the difference between the longest risetime value and the measured risetime. For uniform trapping, the power factor, N, will lie between about 2.5 and 1.5, depending on the electric field configuration in the detector and the field dependence of σ. As is the case for majority carrier trapping, some error will occur because all the risetimes do not correspond to majority carrier collection. In addition, the correction signal will contain more error than the majority carrier case because δ does not vary as a simple power of t_{coll} very closely. As before, an r dependent n_t will also affect the value of the power factor. An n_t greater at the detector periphery will act to reduce rather than to increase the value of N.

Charge Trapping Collection Circuits

As the theory suggests, the case of majority carrier charge trapping requires a class of correction circuits which calculate $S_o t^N_{coll}$, where S_o is the peak amplitude of the unipolar signal. The circuits shown in block diagram form in Fig. 2 [9] calculate an $S_o T^N$ correction, where T_d is the unipolar peak delay time. The unipolar peak delay time, as defined in reference [1], is the unipolar signal peaking time minus the unipolar signal peaking time for the case of instantaneous charge collection.

Under the assumption of linear risetime signals from the preamplifier, T_d is related to the majority carrier charge collection time, t_{coll}, as shown in Fig. 3A. This figure shows that an "over correction" is calculated for gamma-ray interactions at $r<0.5(r_1 + r_2)$. However, preamplifier signals are known to not rise linearly [7,8], and the relationship between T_d and t_{coll} is more like that shown in Fig. 3B. This curve shows that the T_d variation with t_{coll} is nearly linear for $r>0.4(r_1 + r_2)$ and the over correction is much less severe than curve (A) would suggest. Furthermore, since the volume of the detector goes as r^2, more than 80% of the interactions occur for $r>0.4(r_1 + r_2)$. The net result is that a majority of the signals from the detector receive the proper correction, while a small number are over corrected. In practice, the correction gain is adjusted to balance the correction/over correction for the best resolution and peak symmetry.

The model developed in the theory section, as well as the argument above, assumed single gamma-ray interaction positions. The ^{60}Co 1.33-MeV gamma ray interacts at least twice before being absorbed [7], while higher energy gamma rays undergo even more interactions before total absorption. In the limit, if the number of interactions approaches infinity for a given

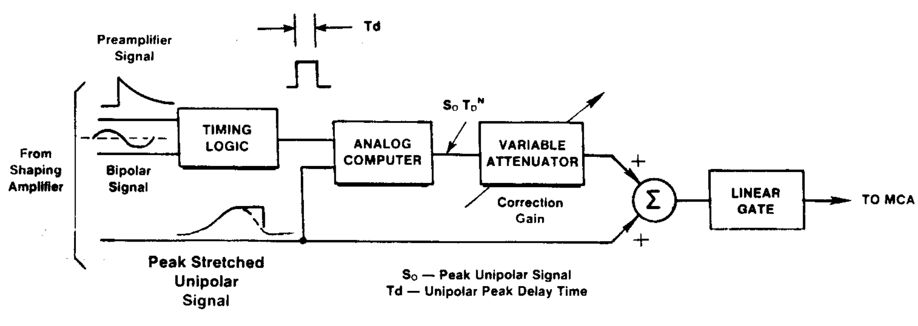

Fig. 2. Block Diagram Of Majority Carrier Charge Trapping Correction Circuits. $0 \leq N \leq 4.0$

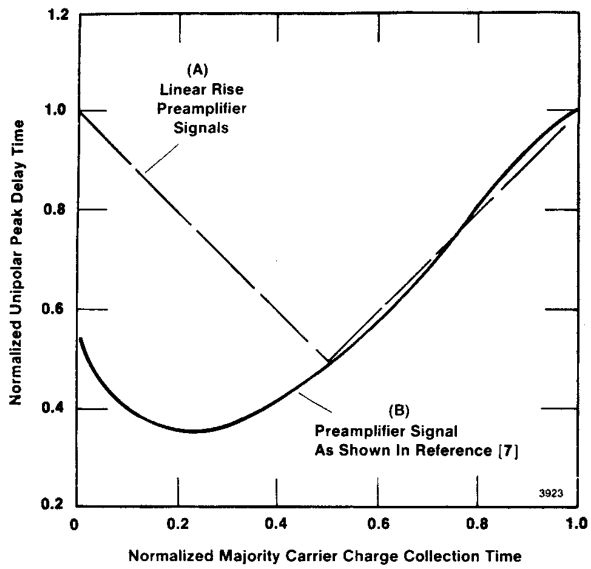

Fig. 3. Normalized Unipolar Peak Delay Time Vs. Normalized Majority Carrier Charge Collection Time For Single Gamma-Ray Interaction Point Preamplifier Signals.

gamma-ray energy, all the preamplifier signals would have the same risetime and shape. In this case, the charge trapping deficit would be equal for every pulse, and linearity, not resolution, would be degraded by trapping and subsequently corrected by the circuit. Using the principle of linear superposition, the delay time for a double-interaction pulse can be approximated by

$$T_d = K_1T_{d1} + K_2T_{d2} \quad , \qquad (9)$$

where K_1 is the charge fraction generated at the first point, K_2 is the charge fraction generated at the second point, T_{d1} and T_{d2} are the unipolar peak delay times for the first and second interaction points, respectively, and K_1 and K_2 sum to unity. Generalizing this result to p interactions,

$$T_d = K_1T_{d1} + K_2T_{d2} + ...K_pT_{dp} \quad , \quad (a) \quad (10)$$

$$K_1 + K_2 + ...K_p = 1 \quad , \qquad (b)$$

and

$$d_{eff} = S_o(K_1T_{d1} + K_2T_{d2} + ...K_pT_{dp})^N \quad , \qquad (c)$$

where d_{eff} is the effective charge trapping deficit corrected by the circuit. The actual charge trapping deficit, however, is given by

$$d = K_1S_o(T_{d1})^N + K_2S_o(T_{d2})^N + ...K_pS_o(T_{dp})^N \quad . \qquad (11)$$

Thus, the linear weighted average given by equation (10a) is a good first order approximation to the desired T_d with the error in the calculated correction being small compared to the magnitude of the correction.

The class of circuits reported in this work allowed N to vary continuously for $0 < N < 4$. The special case of $N = 2$ is functionally equivalent to the Goulding and Landis circuit. In the present case, however, the peak stretched unipolar signal was used instead of the unstretched unipolar signal.

As discussed in the theory section, the circuits used to correct for majority carrier trapping will not work for minority carrier trapping, since it is the minority charge collection time that is needed to calculate the correction instead of the majority charge collection time. Some preliminary work has been performed with the circuits shown in Fig. 4 [9]. Corresponding to equation (5) of the theory section, the minority charge collection time is estimated as the maximum delay time minus the delay time.

Experimental Results

The performance of the majority carrier charge trapping correction circuits was evaluated using a radiation damaged conventional electrode detector and a reverse electrode detector which exhibited significant charge trapping. Fig. 5 shows the corrected and uncorrected spectra for a radiation damaged, 14% efficient, conventional electrode detector. In this case, $N = 2.3$ and the shaping time was 6 μs. The uncorrected FWHM for the ^{60}Co 1.33-MeV line was 4.30 keV, while the corrected FWHM was 2.00 keV. It should be noted that a gated integrator made no improvement

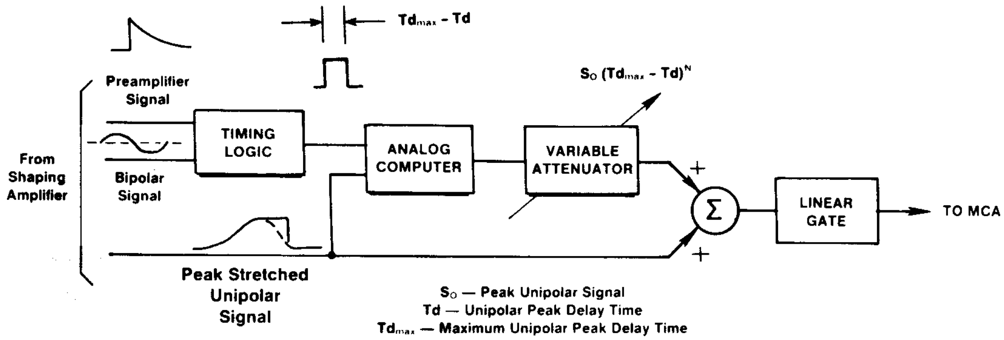

Fig. 4. Minority Carrier Charge Trapping Correction Circuits Block Diagram. $0 \leq N \leq 4.0$

in the resolution of this detector, demonstrating that deep-level trapping was dominant in this case.

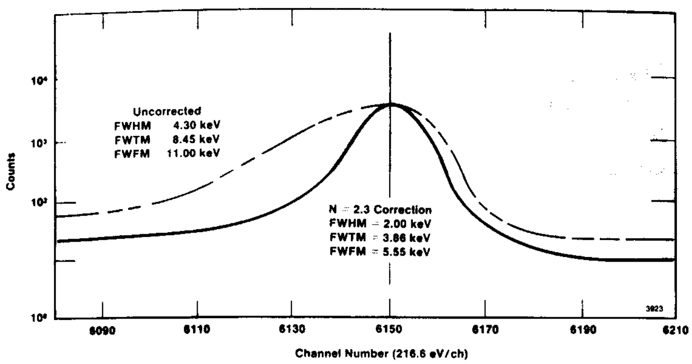

Fig. 5. N = 2.3 Corrected And Uncorrected Spectra For A Radiation Damaged, 14% Efficient, Conventional Electrode Detector.

Fig. 6 depicts the FWHM as a function of N for the radiation damaged detector discussed above. The resolution is a strong-function of N for N < 1.8. However, for larger N, the function is weakly N dependent, with a minimum FWHM occurring for N between 2.18 and 2.50. The flatness of the curve in the N > 1.8 region can be explained as follows. Fig. 3 shows the minimum delay time to be approximately 38% as long as the maximum delay time. For this small range of delay times and for values of N where 1.8 < N < 3.0

$$G_1 S_o T_d^{N_1} \approx G_2 S o T_d^{N_2} + D S_o \quad , \qquad (12)$$

where G_1 and G_2 are non-equal correction gains, $N_1 \neq N_2$, and D is a constant. The second term on the right side of equation (12) slightly alters the apparent gain of

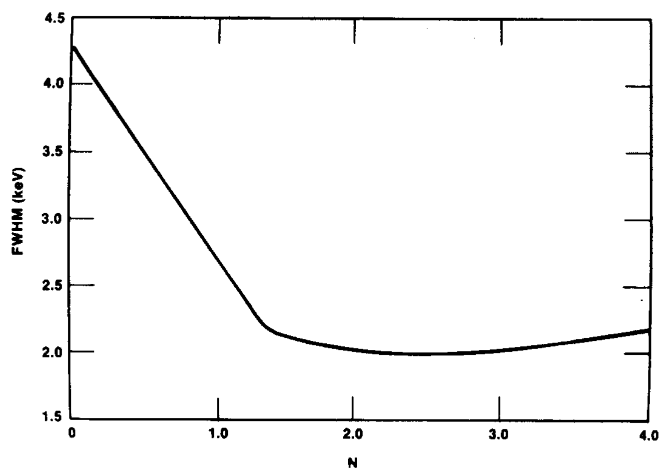

Fig. 6. FWHM Of The Radiation Damaged, Conventional Electrode Detector Vs. N.

the spectroscopy amplifier, but does not degrade the resolution enhancement or the linearity of the spectrum.

Fig. 7 illustrates the resolution improvement made by a charge trapping correction circuit used with a reverse electrode detector having a relative efficiency of 64% and exhibiting significant majority carrier charge trapping. The uncorrected FWHM for the ^{60}Co 1.33-MeV line was 2.23 keV, while the N = 3 corrected FWHM was 1.84 keV. The N = 3 correction also improved the full-width-at-fiftieth-maximum-to-FWHM ratio from 2.74 to 2.57 for this detector. Once again, a gated integrator made no improvement in the resolution of the detector. Fig. 8 depicts the FWHM as a function of detector bias. The uncorrected FWHMs using a semi-Gaussian shaping amplifier and using a gated integrator, as well as N = 2 and N = 3 corrected FWHMs, are shown in this figure. As predicted in the theory section, the optimum N is seen to be detector

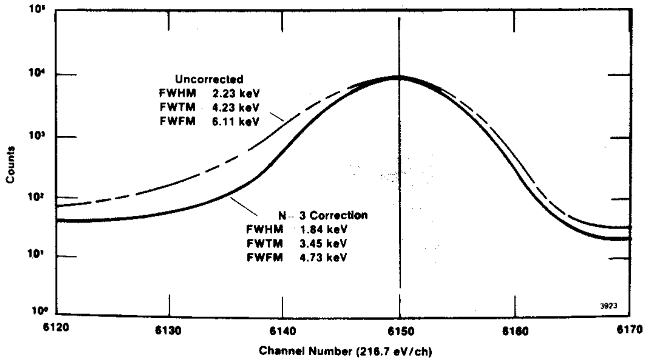

Fig. 7. Uncorrected And N = 3 Corrected ^{60}Co 1.33 MeV Line For A Reverse Electrode Detector With 64% Efficiency. The Detector Bias Was 4 kV, And The Shaping Time Was 6 μs.

bias dependent. The gated integrator curve suggests that some degradation due to shallow-level trapping is present at low detector bias, which can be likened to a ballistic deficit effect. This also tends to lower the optimum value of N, since an N = 2 correction is best for the case of ballistic deficit [10].

Some preliminary evaluation of the minority charge trapping correction circuits of Fig. 4 was performed using a radiation damaged, reverse electrode detector. As predicted in the theory section, the resolution enhancement for this case was not as dramatic as it was for the majority carrier charge trapping case. The FWHM of the ^{60}Co 1.33-MeV line was improved by the circuit from 2.74 keV to 2.46 keV. This small resolution enhancement, nevertheless, corresponds to nearly an order of magnitude difference in fast neutron exposure [4]. Further research in this area is continuing and will be reported later.

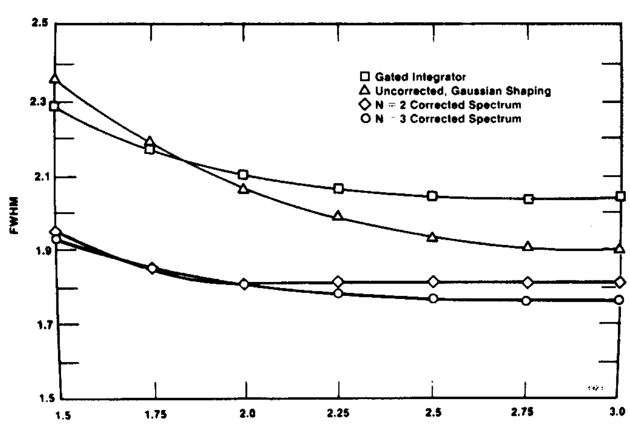

Fig. 8. FWHM Vs. Detector Bias For Uncorrected Gaussian Shaping, Gated Integrator, N = 2 Corrected and N = 3 Corrected Spectra For The ^{60}Co 1.33 MeV Line. 6 μs Shaping Time. The Detector Depletion Voltage Was 700 V. And The Detector Efficiency Was 41%.

Conclusions

The charge trapping model developed in the theory section allows several predictions to be made. First of all, the model predicted that the circuits of Fig. 2 would make a dramatic improvement in the resolution of detectors exhibiting significant deep level, majority carrier charge trapping. This is borne out by Figs. 5, 7 and 8 which demonstrate that substantial improvements in resolution can be obtained using the charge trapping correction circuits described in this work, even though a gated integrator could not provide significant resolution enhancement. For the case of uniformly distributed majority carrier traps in a detector where the E-field approaches a 1/r dependence, the theory predicts an optimum value of N of 2.38. The radiation damaged, conventional electrode detector used to generate Fig. 5 approximates this situation. According to Fig. 6, the optimum value of N for this device appears to be between 2.18 and 2.5. The model also suggests that detectors with an effective trap distribution larger near the outer radius than in toward the center will require the correction circuit to use a value of N greater than 2.38. Evidence of this is shown by Fig. 8, where the N = 3 correction is superior to the N = 2 correction at high detector biases.

The theory also predicts that the circuits of Fig. 2 will be ineffective in the case of minority carrier charge trapping, since values of the minority, not the majority, carrier charge collection time are required to calculate the correction. This was confirmed experimentally, since a majority carrier charge trapping correction circuit was observed to offer no resolution improvement with a radiation damaged, reverse electrode detector. In preliminary experiments, however, the circuits of Fig. 4, which estimate the minority collection time as $T_{dmax} - T_d$, did correct for minority carrier charge trapping with some success. As predicted in the theory section, the resolution enhancement was not as dramatic for the majority carrier case.

Finally, as Fig. 5 suggests, a charge trapping correction circuit can extend the lifetime of conventional electrode detectors exposed to fast neutrons. It should be pointed out, however, that reverse electrode detectors are still much less susceptible to resolution degradation due to radiation damage [4], and remain the detector of choice if anappreciable fast neutron flux is present in the detector environment.

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