Capacitive Charge Division Readout of a Double-sided Germanium Strip Detector

S. E. Inderhees
Universities Space Research Association, Washington, D.C.

R.A. Kroeger, W.N. Johnson, R.L. Kinzer, J.D. Kurfess
Naval Research Laboratory, Washington, D.C.

N. Gehrels
Goddard Space Flight Center, Greenbelt, MD

Abstract

We have implemented a capacitive charge-division read-out for a germanium 5x5 orthogonal strip detector. Response of the detector was tested at two energies (60 and 662 keV) and for several values of the network capacitance. Non-linearities appear in the response along the charge division network, as well as along the length of each strip. Non-linearity effects behave as predicted and can be corrected by using an independent gain calibration for each pixel.

I. INTRODUCTION

Position sensitive radiation detectors, such as wire chambers and strip detectors, are widely used in physics, medicine and industry. A common feature of many of these detectors is a large number of electrodes. Charge division networks have been proposed to reduce the number of read-out channels.[1] Resistive charge division networks have been employed for read-out of wire chambers and silicon strip detectors. As an example, the EPACT Isotope Telescope on the WIND spacecraft utilized two-dimensional Si strip detectors with resistive charge division.[2] Another approach is to use capacitive charge division. Bloyet et al.[3] demonstrated theoretically that capacitive charge division is superior to resistive charge division in position and energy resolution, and constructed a capacitive charge division network for a one-dimensional germanium detector. We have implemented a capacitive charge division network for read-out of a double-sided Ge strip detector,[4] which we discuss in detail here.

Proper choice of the optimal value for the capacitances requires a compromise between linearity and resolution. For optimal linearity, a higher value for the capacitors is required, at the cost of degraded position resolution. We show that it is possible to correct for the non-linearities of a low-capacitance network, allowing the use of a lower value of capacitance for the network, and hence better position resolution. Data from our double-sided detector indicate that the response of an individual strip is also non-linear along the length of the strip. We speculate that this additional non-linearity arises from charge deficit effects due to the charge division network on the opposite face of the detector, which provides an additional capacitive coupling to ground.

II. EXPERIMENT

The detector used for these measurements was fabricated from p-type Ge by Eurisys Mesures (formerly Intertechnique) using a photomask technique,[5] with a 9 mm pitch by 45 mm long strips. The ohmic contact is fabricated with boron and is less than 1 μm thick. The non-rectifying contact consists of a lithium strip approximately 500 μm thick. The active volume of the device is 45x45x12 mm, with a guard ring around the periphery. Capacitance to ground (C_d) is fairly high, approximately 30 pF per strip, and is mostly due to parasitic capacitance in the cabling between the detector and the room temperature electronics. Because of this high front-end capacitance, the energy resolution for the individual strips is dominated by electronic noise, and ranges from 2.2 to 2.4 keV for 662 keV γ-rays, measured with conventional JFET preamplifiers.

Figure 1: Detector and capacitive charge division network. Figure shows one side of the detector. A similar network is employed for signals on the opposite (high voltage) face of detector, with the exception that each strip is coupled to the charge division network through 1500 pF blocking capacitors.

This work supported in part by the Office of Naval Research and NASA, under contract No. W--18486.

The charge division network (Fig. 1) consists of six polystyrene (low-leakage) capacitors (C_n) connected in series. A single strip of the detector is connected to the network at each node between capacitors. A separate network is used for each side of the detector. All four signals are processed ($\tau_s = 3\ \mu$sec) in separate 13 bit ADC's read out in an event-by-event list mode and stored for later processing. A master gate signal is formed by discriminating on the sum of signals from one of the networks. Measurements were made with network capacitances C_n = 100, 500 and 1000 pF.

Energy and position of each event are recovered by summing and subtracting the signals from each end of the charge division network, and then applying correction factors for the non-linearities. The uncorrected energy measured on the x and y sides of the detector is computed using:

$$E_x = (S_{xa} + S_{xb}) \qquad E_y = (S_{ya} + S_{yb}) \qquad (1)$$

and the position by :

$$P_x = \frac{(S_{xa} - S_{xb})}{E_x} \qquad P_y = \frac{(S_{ya} - S_{yb})}{E_y} \qquad (2)$$

where S_{xa} and S_{xb} are the signals from each end of the X charge division network, and S_{ya} and S_{yb} are the signals from each end of the Y charge division network. For the ideal situation with zero detector capacitance (C_d = 0), the measured energy is independent of the node (strip) where the charge was deposited into the charge division network, and the position coordinates P_x and P_y are linearly dependent on the node. For realistic detector capacitance, charge deficit effects lead to non-linearity in the response, with the central node of the network showing the greatest deviation from linearity. The variation is most pronounced for lower values of C_n / C_d. We find an additional non-linearity of the response along the length of each strip, also due to charge-deficit effects arising from the charge division network on the opposite face of the detector.

III. Results and Discussion

The detector was exposed to a near-uniform illumination from ^{137}Cs (662 keV) or ^{241}Am (60 keV). All four signal are calibrated such that the maximum photopeak signals (at 662 keV) have the same value. For example, the signal S_{x1} for a photopeak event in strip X1 was set equal to the signal S_{x2} for a photopeak event in strip X5, etc. The data are then added and subtracted according to Eqs. 1 and 2, to produce an event list of coordinates and energies.

A. Energy and Position Non-Linearity

In order to examine the non-linear response of the networks, we first select the data from a single strip of the detector. Figures 2a and 2b show the energy and position response at 60 keV of the X network, selecting only events for the central Y strip (Y3). Figure 2a shows the percentage residual energy signal (100 * (E_x - E_{x1})/E_{x1}) as a function of strip position. These data show the non-linear response as a function of strip position, as the middle X strips produce a smaller signal than the outer ones. The magnitude of the non-linearity decreases roughly as 1/C_n. Figure 2b shows the non-linearity in the X position coordinate derived from equation 2, again for events in strip Y3. In this Figure, we plot the percentage residuals at position P_x from a linear interpolation between the end positions P_{x1} and P_{x5}, scaled by the average value of the strip pitch ((P_{x5} - P_{x1})/4). Again, linearity improves with increasing C_n.

Figure 2a: Percentage energy non-linearity (100 * (E_x - E_{x1})/E_{x1}) of the x network for E = 60 keV, selecting events only from the Y3 strip. Non-linearity is greatest for small values of C_n.

Figure 2b: Percentage deviation of position P_x from a linear interpolation between edge positions P_1 and P_5, scaled by the strip pitch, selecting events only from the Y3 strip. Non-linearity decreases with increasing C_n.

The general dependence of the non-linearity of energy and position with C_n is as predicted by Bloyet. However, there is also variation of along the *length* of the x-strip. This effect is demonstrated for C_n = 100 pF and E = 60 keV in

Figure 3, which shows the measured energy of the full energy peak (E_{peak}) from the X network for every pixel in the detector. The deviation from linearity is most pronounced for the center pixel (coordinate X3,Y3) of the detector. For the center X-strip (X3) this *additional* variation along the strip of the measured photopeak energy is 6% for C_n = 100 pF, 3% for C_n =500 pF, and 1.5% for C_n = 1000 pF. Because energy resolution is on the order of 1% at 662 keV (see below), this amount of variation, if uncorrected, can seriously degrade performance of the charge-division read-out, even at relatively large values of C_n/C_d.

Figure 3: Peak energy E_{peak} at 60 keV (arbitrary units) determined from Eq. 1, for the X-network with C_n = 100 pF. E_{peak} is indicated for all pixels of the detector. Maximum non-linearity occurs for the center pixel of the detector.

B. ENERGY AND POSITION RESOLUTION

C_n (pF)	ΔE at 60	ΔE at662	ΔP at 60	ΔP at 662
100	6.2	6.3	17	2.5
500	5.4	5.6	27	3.4
1000	5.1	5.2	33	4.3

Table I : FWHM Energy and position resolution for the x network (average of all pixels). as a function of energy and network capacitance. Energy resolution is expressed as keV. Position resolution is expressed as percentage of strip pitch.

Bloyet's model predicts that the rms fluctuations (E_{rms}) of the energy determined from Eq. 1 should not vary with increasing C_n, while rms fluctuations (P_{rms}) of the position should increase with C_n and decrease as 1/E. For Gaussian noise the FWHM energy resolution is

$$\Delta E_{FWHM} = (2.335\ E_{rms} / E_{peak})\ E \qquad (3)$$

The non-linear response (i.e. variation of E_{peak}) over the surface of the detector leads to a variation of ΔE_{FWHM} with pixel. For the C_n = 100 pF network, measured FWHM energy resolution varies from approximately 6 keV for a corner pixel, to about 8.5 keV for the center pixel. This variation agrees with the dependence of E_{peak} on pixel shown in Figure 3. At the higher values of C_n, dependence of ΔE on pixel location was not significant (< 5% variation). The data in Table I show the variation of FWHM energy and position resolution (average of all pixels) as a function of C_n and E. We find that energy resolution improves with increasing C_n due to the improved linearity. As expected, position resolution is degraded with increasing C_n and decreasing E. The individual strips are still resolved from each other for C_n = 1000 pF and E = 60 keV. However, strips will become indistinguishable for larger values of C_n or for energies below 60 keV.

C. CORRECTIONS FOR NON-LINEARITIES

Figure 4 shows the event position map for C_n = 100 pF and E = 662 keV. We have chosen this capacitance because it shows the most dramatic non-linearities. Single-pixel events appear as the "clusters" on the event map. Compton-scatter events appear uniformly throughout the Figure. Those Compton events that interact in a single strip on one side of the detector, but distribute energy into multiple strips on the other side, fall along lines between the clusters.

Figure 4: Scatter plot of event positions from a uniform illumination of 662 keV γ-rays using charge division network C_n = 100 pF. Coordinates are determined from Eq. 2. Interactions in a single pixel appear as clusters of events. Lines between those pixels are from events that interact in multiple strips.

Fig. 5 Data from Fig. 4 with a mapping correction applied to transform to an orthogonal coordinate system. The mapping correction is a bilinear interpolation on the non-uniform grid of pixel positions determined in Fig. 4.

In order to correct for the energy non-linearity we first transform the non-orthogonal coordinate system into an orthogonal one, through a map of position correction factors at each of the pixel centers. The actual position correction factor for any location on this map is then determined by bilinear interpolation between the tabulated correction factors. We replot the event map in the corrected coordinate system (Figure 5). Events are now easily identified with the detector pixels by their corrected coordinates. The pixels are then each independently calibrated for energy. Applying these energy and position corrections to single-pixel events on the x-network, we find the energy resolution for the entire detector is ΔE_x = 6.3 keV FWHM at 662 keV. The same data for the y-network show an energy resolution of ΔE_y = 7.5 keV FWHM. This higher value of ΔE_y is due to the high-voltage blocking capacitors (C = 1500 pF). Performance is improved by using the weighted average of the x and y energies:

$$E = \frac{1}{2}\left(\frac{E_x}{\Delta E_x^2} + \frac{E_y}{\Delta E_y^2}\right) / \left(\frac{1}{E_x^2} + \frac{1}{E_y^{\,2}}\right). \qquad (4)$$

Figure 6 shows a spectrum of the 662 keV total energy peak obtained using Equation 4. We find an improved energy resolution of 4.2 keV for the entire detector by using the weighted average technique. This compares to an energy resolution of 2.3 keV for each strip when read individually. Performance can be improved by reducing the feedthrough capacitance (approximately 30 pF per strip for this detector).

Figure 6: Energy spectrum from a uniform illumination of 662 keV gamma rediation for C_n = 100 pF. Energy is determined by an independent calibration of each detector pixel, and taking a weighted average of the energies measured by both the X and Y charge division networks.

V. SUMMARY

We have presented measurements of the energy and position non-linearity of a capacitive charge division network, for several values of C_n and at two energies, 60 and 662 keV. For all values of C_n tested, non-linearities in the measured energy require independent energy calibrations for each pixel to maintain acceptable performance. Larger values of C_n would improve linearity, but at the cost of poor position resolution at low energies. We have demonstrated a technique for calibration and correction of the non-linearity effects. We show that combining measurements from both faces of the detector provides a significantly better measure of energy, in our case within a factor of 2 of the best performance of a single amplifier connected to a single strip. These techniques are applicable to other types of strip detectors, including Si and CdZnTe.

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