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SELF-CALIBRATING POSITION-SENSITIVE SILICON DETECTORS

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Abstract

Position-sensitive silicon detectors with fifteen discrete position output signal levels have been developed for heavy ion reaction studies at the Lawrence Berkeley Laboratory. The detectors, both 300 μm and 5000 μm thick, for use in ΔE -E telescopes, employ a series of high and low conductivity strips to provide quantization of the position signal. This technique allows for self-calibration of the detector linearity, ready correction of nonlinearities, and on-line monitoring of detector performance. Some aspects of the fabrication of both the 300 μm and 5000 μm detectors are discussed along with their operating characteristics. Illustrative experimental results of ^{139}La -induced reactions on ^{40}Ca targets are presented.

I. INTRODUCTION

Semiconductor detectors, and silicon detectors in particular, capable of energy and/or position detection have been in demand for many years for a wide variety of experimental conditions. These experimental requirements have led to many diverse detector designs, especially for position detection.

Existing position-sensitive detector designs can be broadly classified as either discrete (strip detectors, pixel) or continuous (resistive charge division) [1]. Various factors determine the applicability of one detector design versus the other. For example, the requirement for precise ($\sim 10 \mu\text{m}$) position resolution in vertex detectors has led to the development of strip detectors, while less stringent position requirements ($\sim 1 \text{ mm}$) in beam monitoring applications have resulted in X-Y detectors using resistive charge division readout schemes.

This paper will discuss the design, fabrication, evaluation, and experimental use of position-sensitive detectors (PSD's) in a ΔE -E telescope array. The telescopes were designed to detect and identify fragments produced by reverse kinematic reactions (heavy projectile on a light target) with atomic numbers, Z, from 4 to 60 and energies from 100 to 15,000 MeV. The telescope PSD's employ resistive charge division where the resistive layer has strips of alternating high and low conductivities. On each detector there are fifteen high

conductivity strips present which produce fifteen discrete position signal levels. This approach facilitates detector calibration, correction for position nonlinearities, and on-line monitoring while only employing two or three channels (one for energy and one or two for position) of electronics with each detector.

II. DETECTOR DESIGN

The telescopes were designed to be used in reaction dynamics studies where the energy, charge and trajectories of the fragment particles are needed to reconstruct the reaction dynamics. One sided PSD's were incorporated into the ΔE - E telescope design to measure the total energy, the charge (deduced from the ΔE -energy loss) and the X-Y position of each particle. Since the particles have sufficient energy and mass that scattering in the detectors can be neglected, ΔE -E detector telescope arrays with the ΔE detector providing the X axis position signal and the E detector, the Y axis signal, have been fabricated in the Lawrence Berkeley Laboratory (LBL) Silicon Detector Laboratory and employed in a series of reaction measurements at the LBL BEVALAC.

The characteristics of semiconductor PSD's employing resistive charge division have been extensively discussed [2-4]. However, for clarification, some basic concepts will be repeated here. A one sided, linear resistive charge division PSD can be modeled as shown in Fig. 1. Also shown in the figure are the charge sensitive preamplifiers normally employed to detect the charge signals. For a particle incident at X, on a detector of length L, producing a total charge, Q_T , the position signals:

$$\frac{Q_1}{Q_T} = \frac{L - x}{L}$$

and

$$\frac{Q_2}{Q_T} = \frac{x}{L}$$

(1)

are available for processing. Further, to a first approximation, the position resolution, ΔL , is given by:

$$\frac{\Delta L}{L} = \frac{\Delta Q}{Q_T} \quad (2)$$

where ΔQ is the electronic noise in the position channel. Finally, the signals Q_1 or Q_2 have position dependent rise times which can cause a nonlinear response if the main amplifier shaping time constant, τ , is comparable to the detector RC time constant. This nonlinearity can be avoided by selecting $\tau > RC$, as discussed further in Section IV.

Fig. 1 A RC transmission line model for a position sensitive semiconductor detector employing resistive charge division [1].

For the range of particles ($Z = 4$ to 60 , $E/A = 50$ MeV/nucleon) expected in the beam reaction studies, a ΔE -E telescope consisting of a $300 \mu\text{m}$ thick ΔE and a $5000 \mu\text{m}$ thick E detector was selected as optimum. Further, since the telescopes were to be used in closely packed arrays with high geometric efficiency, square detectors were required. The detectors developed have an outside dimension of $5.08 \text{ cm} \times 5.08 \text{ cm}$ with an active region of $4.48 \text{ cm} \times 4.48 \text{ cm}$, the overall size limited by the diameter (3 inches) of suitable high resistivity p-type silicon crystals for the E detector fabrication. Since discrete position signals were also required, principally for on-line monitoring of detector performance, a 15 strip design, shown in Fig. 2, was selected as meeting the experimental design requirements of $\pm 1.5 \text{ mm}$ position resolution. Figure 2 also shows the overall detector dimensions, strip width, gap width and nominal design resistance across the detector. To obtain the required resistance of about 350 ohms in the gap between the high conductivity strips, a sheet resistance of about $25 \text{ K-ohm}/\square$ is needed. With the nominal 5 K-ohm position sensing resistor the detector RC time constant is $4.6 \mu\text{sec}$ for the ΔE detector and $0.3 \mu\text{sec}$ for the E detector.

III. DETECTOR FABRICATION

Two different technologies were employed in the fabrication of these detectors. The ΔE detector is an oxide passivated diffused junction, n^+p , diode fabricated on 5000 ohm-cm p-type silicon, while the E detector is a lithium drifted, $\text{Si}(\text{Li})$, diode fabricated on 1000 ohm-cm p-type silicon. The basic details and attributes of these technologies are well known [5,6]. The formation of the resistive layers to make the detectors position sensitive is discussed below.

Since both detectors are fully depleted, the resistive contacts, as shown in the detector cross sections of Fig. 3, must not only have the required resistivity profile (shown in Fig. 2) but must also sustain an electric field without injecting minority carriers into the detector active volume. The technologies used to form the resistive layers on the ΔE and E detectors are tabulated below.

Table 1 Resistive Layer Technologies

DETECTOR	DIFFUSED ΔE	$\text{Si}(\text{Li})$ E
Technique	Boron Implant (25 keV)	Metal Evaporation
Gap	$3.5 \times 10^{12} \text{ Ions/cm}^2$	Pd ($\sim 80 \text{ \AA}$)
Strip	$2 \times 10^{14} \text{ Ions/cm}^2$	Au ($400 \text{ \AA}$)

DIMENSIONS FOR 300μ AND Si STRIP DETECTORS

Fig. 2 Dimensions and resistive profile for the position sensitive detectors with fifteen discrete position output signal levels.

The resistance across the E detector, with the Au strips previously deposited, was monitored during the Pd evaporation to give the desired 5 K-ohm across the detector; the Pd film thickness in the table, therefore, is only approximate.

Fig. 3 Cross sections of the diffused junction, n+p, and Si(Li) detectors with resistive contacts.

Fig. 4 Packaging arrangement for the ΔE and E detectors. The frames are machined from fiberglass board material. The 2.42 mm wide Au strips appear as horizontal bright lines on the E detector while the 0.607 mm wide Pd gaps appear dark. The implanted strips on the ΔE detector run vertically but are not visible in the figure.

Figure 4 is a photograph of the ΔE -E detector packaging. In the actual array there is a scintillator plastic behind the E detector to stop energetic light particles. In the figure the

strips on the ΔE detector are implanted layers and cannot be seen visually; they are orthogonal to the evaporated gold strips on the E detector which can be seen in the figure. In use, the ΔE package mounts directly onto the E package and is held in place by the pins which are visible in the figure. The E detector package, in turn, is held in place with pins from the shield surrounding the scintillator. The energy and position signals for both the ΔE and E detectors are also brought out through these pins.

Fig. 5 Representative noise in the energy and position channels of the 300 μm ΔE detector as a function of the amplifier time constant.

IV. DETECTOR CHARACTERISTICS

Because the 300 μm ΔE detector has a much greater capacitance than the 5000 μm E detector (920 pF versus 55 pF, nominal), the ΔE presents a more difficult instrumentation problem and consequently the characteristics of the ΔE will be mainly focused on here. As indicated by Eq. 2, central to the performance of a position sensitive detector is the resolution of the energy and position channels. The noise performance of a representative ΔE detector is shown in Fig. 5. The noise in the energy channel at short amplifier time constants is due to the detector capacitance, and at longer time constants, to the detector leakage current. The noise in the position channel is principally due to charge division resistance (here 3.2 k ohm) shunting the preamplifier input.

With the ΔE detector connected as shown schematically in Fig. 1, the detector linearity is examined by scanning a ^{241}Am alpha source (5.477 MeV) across the resistive contact. This measurement not only checks the linearity but also determines that the detector is fully depleted. The results of one of these scans, with an amplifier time constant of 1.6 μsec , is shown in Fig. 6. As can be seen from this figure, there is a small ($\sim 1\%$) departure from a linear response. This is due to the amplifier time constant to detector time constant ratio and not to a nonlinearity in the charge division resistor itself. The effects of the amplifier time constant are shown further in Fig. 7 where the ΔE detector linearity is shown to degrade significantly with decreasing amplifier time constant.

As noted earlier, the nonlinearities in the detector response as shown in Fig. 7 can be avoided by selecting the amplifier time constant to be longer than the detector RC time constant. However, as discussed in Section V, severe nonlinearities in the position signal response can be tolerated provided that the discrete position signals from adjacent strips can be resolved.

Fig. 6 The position channel response to scanning a ^{241}Am alpha source across the ΔE detector resistive contact. The straight line highlights the departure from linearity in this measurement.

Finally, as seen in Fig. 6, the discrete position signals are broadened by the noise in the position channel. The extent of this broadening can be estimated using Eq. 2:

$$\Delta L = L_x \frac{\Delta E}{E}$$

where ΔE is given in Fig. 5 (206 keV at 1.6 μsec), and therefore:

$$\Delta L \sim 40 \text{ mm} \times \frac{206 \text{ keV}}{5.477 \times 10^3 \text{ keV}} = 1.5 \text{ mm},$$

which agrees with the 1.5 mm FWHM value which can be obtained directly from Fig. 6.

Similar measurements of noise and position linearity were also made on the 5000 μm thick E detectors. Since the E detector RC time constant is about 0.3 μsec , the position linearity is not dependent on the amplifier time constant as it is with the ΔE detector. However, the inherent signal rise time in a 5000 μm thick Si(Li) detector is about 0.3 μsec (600 volts bias, electron collection) which can distort the position linearity if amplifier time constants approaching this value are employed. Consequently, in evaluating both the E and ΔE detectors, amplifier time constants of at least 1.6 μsec are normally used.

With both the ΔE and E detectors the noise in the position channel increases at amplifier time constants $\tau > 1.6 \mu\text{sec}$ mainly due to the position sensing resistor and this noise increases at $\sqrt{\tau}$. However, in the beam reaction studies presented in the following section, amplifier time constants of 3.2 μsec or greater were employed to ensure complete charge collection of the signals produced by the heavy ion reaction products.

Fig. 7 The ΔE detector linearity dependence on the amplifier time constant.

V. BEAM REACTION STUDIES

The ΔE and E detectors were used in a series of beam reaction studies which employed twin 3 x 3 telescope arrays shown in Fig. 8. The arrays contain eight detector telescopes consisting of a 300 μm ΔE Si detector, a 5000 μm Si(Li) detector and a 7.5 cm plastic scintillator, with the beam passing through the vacant position at the array center.

Fig. 8 The twin 3 x 3 telescope arrays employed in the heavy ion reaction studies. The beam trajectory is indicated as a line passing through the vacant position at the arrays' centers. The target, which is not shown, is located 37 cm upstream from the front array and 102 cm from the back array.

XBL 8910-3650

Fig. 9 The raw position signal, $X\Delta E$, versus the energy deposited in the ΔE -detector, ΔE , obtained from the 35 MeV/A $^{139}\text{La} + ^{40}\text{Ca}$ reaction.

For the reaction 35 MeV/A $^{139}\text{La} + ^{40}\text{Ca}$ the raw online spectra for the position signal, $X\Delta E$ or YE , versus the deposited energy in the detector, ΔE or E , are shown in Figs. 9 and 10 for the ΔE and E detectors respectively. In these figures, lines corresponding to the fifteen discrete signal levels are clearly resolved. These results are combined online to yield an X-Y plot, such as that shown in Fig. 11, for particles passing through a telescope, in this example, located at the array top center. It is apparent in Figs. 9 and 10 that some nonlinearities are present in the position response as the lines

in the figures are not equally spaced. The nonlinearity in the E detector response is due to a nonuniformity in the Pd resistive layer. Control of the Pd evaporation to produce a uniform layer has been difficult and alternative approaches for making this contact are now under study. The nonlinearity in the ΔE detector response is not understood and further measurements are planned to understand its source. These nonlinearities, however, are readily software-corrected offline.

XBL 8910-3648

Fig. 10 The raw position signal, YE , versus the energy deposited in the E -detector, E , obtained from the 35 MeV/A $^{139}\text{La} + ^{40}\text{Ca}$ reaction.

XBL 8910-3652

Fig. 11 The X-Y scatter plot obtained from the data of Figs. 9 and 10.

Since the response of silicon detectors, especially Si(Li) detectors 5000 μm thick, to high energy heavy ions is not well documented, a series of energy calibrations, employing low intensity ion beams run directly into the detectors, were performed on both the ΔE and E detectors. Results of these measurements on one 5000 μm thick E detector are shown in Fig. 12, where it is seen that the detector response is quite linear over the energy range from 0 to 5000 MeV with a slight ($\sim 3\%$) pulse height deficit (PHD) for ^{139}La ions.

Fig. 12 The response of a 5000 μm Si(Li) detector to a variety of heavy ions stopping the the detector. The straight line is for full signal collection. There is a slight (3%) PHD present for ^{139}La ions.

Employing an empirical formula [7] to correct for the PHD in the E detectors and using the position information to correct for differences in fragment trajectories through the arrays' particle telescopes, a particle algorithm has been used to identify the nuclear fragments produced by a heavy ion beam hitting a light target. The data from the reaction 35 MeV/A $^{139}\text{La} + ^{40}\text{Ca}$, when corrected for the PHD and fragment trajectory, yield the fragment distribution shown in Figure 13(a). Figure 13(b) is the same data without fragment trajectory correction. Fragments with atomic numbers up to $Z = 50$ are clearly identified in 13(a) while fragments beyond $Z = 30$ are only poorly resolved in 13(b). The ability of this ΔE -E telescope design, employing self-calibrating position-sensitive silicon detectors, to provide sufficient information for

the unambiguous identification of heavy ion fragments produced by reverse kinematic reactions has led to a better understanding of the reaction processes involved [8].

Fig. 13 Heavy ion fragments obtained from the reaction 35 MeV/A $^{139}\text{La} + ^{40}\text{Ca}$ with (a) and without (b) fragment trajectory correction. Fragments with atomic numbers up to $Z = 50$ are clearly resolved in (a). The large peak at $Z = 57$ is the ^{139}La beam.

VI. CONCLUSIONS

The utility of employing self-calibrating position-sensitive detectors to study a large range of nuclear species produced in intermediate energy heavy ion reactions has been well demonstrated by our results. Using only two channels of

electronics on each detector a position resolution of about ± 1.5 mm has been realized in a series of studies on these reactions. This position information has greatly enhanced the identification of the nuclear fragments produced in heavy ion reaction systems.

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