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A TWO-DIMENSIONAL POSITION SENSITIVE SI(LI) DETECTOR

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Abstract

Circular, large-area two-dimensional Si(Li) position sensitive detectors have been fabricated. The detectors employ a thin lithium-diffused n^+ resistive layer for one contact and a boron implanted p^+ resistive layer for the second contact. A position resolution of the order of 100 μm is indicated.

Introduction

Thick two-dimensional position-sensitive silicon lithium-drifted Si(Li) detectors having a boron implanted p^+ layer and a very thin lithium-diffused n^+ layer have been fabricated in our laboratory. Extensive work has been done previously[1-4] on position-sensitive detectors (PSD's), but, to our knowledge, ion implantation has not been combined with lithium drifting to produce the thick (< 2 mm) PSD's required for high-energy particles or x-ray imaging. The advantages of ion implantation have been recognized[5] and applied to the fabrication of thinner (~ 2 mm) PSD's[6], but these devices were made on very high resistivity silicon (~ 5,000 Ω-cm) which is difficult to obtain in large (~ 40 mm) diameters. Gigante[7] has reported PSD's with thin lithium-diffused resistive contacts, fabricated by thinning down thick lithium diffusions. For the PSD's reported here, very shallow lithium diffusions are used, thereby eliminating the mechanical thinning of the lithium layer which is a potential source of non-uniformity.

Interest in the identification of the isotopic composition of solar and galactic particles in space is stimulating refinements in solid-state detectors and detector telescopes. The low particle intensity generally encountered on space flights requires the use of large area detectors with a corresponding wide acceptance angle. The resulting variations in the path lengths through the detectors in the telescope means that, for correct isotopic identification, the trajectories of the incident particles must be known. The availability of thick PSD's as discussed here permits the determination of the coordinates of the

particle's passage through each detector in the telescope. Since solid-state telescopes currently employ large area circular Si(Li) detectors, the PSD's to be reported on are circular with the intent of being geometrically compatible with existing detector telescopes.

Design Considerations

The development of circular one-dimensional PSD's was first reported by Nakamoto et al[8], and the detectors described here parallel their design in using 90° contacts to the resistive layer. While a two-dimensional PSD can be obtained by using just one resistive layer with two sets of orthogonal contacts to it, the signal current flow is then split four ways instead of two, thereby worsening the signal/noise ratio. Perhaps more important, interaction between the two sets of contacts, as indicated by Petersson et al[9], leads to a non-linearity in the positional response. Consequently, the PSD's described here have two resistive layers, one on each side of the device, with orthogonally-oriented 90° contacts on the opposite faces. Figure 1 shows the geometry employed.

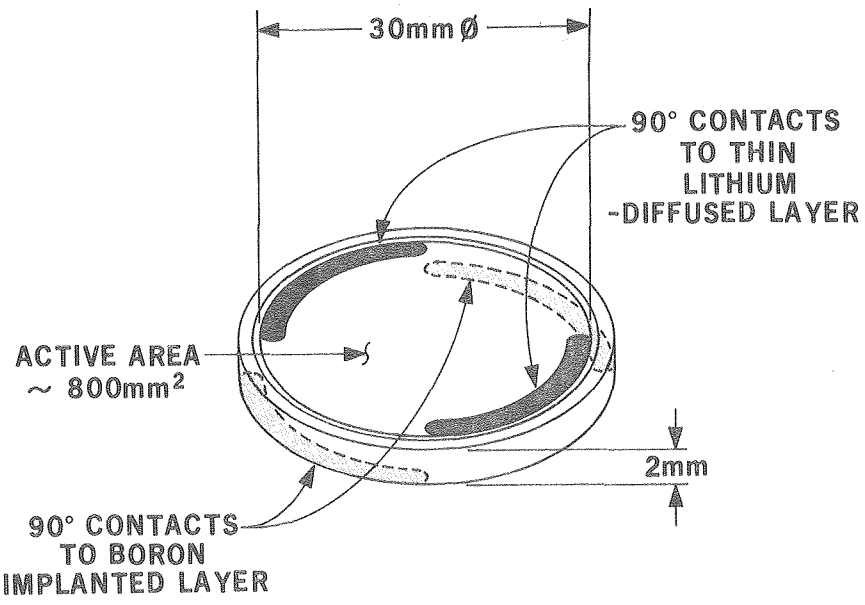

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Fig. 1. Basic geometry of a two-dimensional PSD with 90° contacts on each side of the device. Dimensions of devices fabricated are indicated.

Two basic approaches exist in determining the location of an ionizing particle in a PSD having resistive layers. The first approach employs resistive division of the output signal, while the second utilizes rise time variations in the output

signal. Alberi and Radeka[10] discuss the relative merits of each and conclude that charge division is the more suitable for most solid-state detector applications. Consequently, the detectors described here were designed to be used with charge division. Three parameters are then of interest, the charge collection time τ_R, the detector resistive contact time constant τ_D, and the measurement time τ_F. Alberi and Radeka indicate that the following relationship should apply for optimum signal processing:

$$2\,\tau_R \leq \tau_D \leq \tau_F \qquad (1)$$

where $\tau_D = R_D\,C_D$
R_D = resistance of layer (ohms),
C_D = capacitance of detector (farads).

Experimental requirements demanded that the detectors should be 2 mm thick and 800 mm^2 in area. The maximum charge collection time for a detector is given by[11]

$$\tau_R = W^2/V\mu \qquad (2)$$

where W = detector thickness,
μ = carrier mobility,
V = voltage applied.

Since $\tau_R \simeq 0.3$ μs for holes traversing the 2 mm, Eq. 1 becomes:

$$2 \times 0.3 \times 10^{-6} \leq C_D\,R_D \leq \tau_F \qquad (3)$$

which yields a nominal value of 15,000 Ω for R_D since $C_D \simeq 40$ pF. Further τ_F must be greater than 0.6 μs.

Finally, considering the noise due only to the resistive layer and assuming optimum filtering, Alberi and Radeka give the FWHM position resolution as:

$$\Delta\ell/\ell = 2.54\,(kTC_D)^{1/2}/Q_S \qquad (4)$$

where $k = 1.38 \times 10^{-23}$ Joules/°K
$T = 300$°K
$C_D = 40 \times 10^{-12}$ F
$Q_S = 8 \times 10^{-13}$ Coulombs for a 15 MeV signal.

Thus $\Delta\ell/\ell = 1.3 \times 10^{-3}$, or, since $\ell \simeq 30$ mm, a spatial resolution of approximately 40 μm should be possible with a 15 MeV signal.

Fabrication

The overall procedure used to make the devices was to lithium compensate 1000 Ω-cm p-type silicon by drifting lithium from an n^+ layer on one side to produce an intrinsic region reaching a boron implanted p^+ layer on the opposite side. The resistivity of the p^+ layer can be accurately controlled by using ion implantation. After completion of the lithium drifting, the proposed procedure calls for the removal of the thick n^+ layer, to be replaced by a very shallow lithium-diffused n^+ layer. Again the resistance of this layer must be accurately controlled.

Fabrication of the devices required examination of the implantation and annealing properties of relatively high resistivity ($\sim$ 1000 Ω-cm) silicon. Not only is the activation of the implanted boron and the removal of the damage produced by the implantation of interest, but also changes in the silicon affecting the ability of lithium to compensate the material. It was experimentally determined that implantations of 30 KeV boron ions at a dose of 2×10^{13} ions/cm^2, annealed at 500°C for 30 minutes, produce sheet resistances of about 10,000 Ω/□ without substantially effecting the lithium-drifting capabilities of the silicon. Annealing at temperatures greater than 500°C introduces defects which affect the lithium-drift process by increasing leakage currents during drift and slowing down the drift process.

The detectors require two implantations on the silicon wafer, one at 2×10^{13} ions/cm^2 to provide the resistive layer and one at 2×10^{15} ions/cm^2 in the contact regions to obtain a good ohmic contacts to the resistive layer. Once the wafers are annealed the standard Si(Li) fabrication procedure which we have used for some years is followed. During the lithium-drifting process, lithium is allowed to drift up to the boron implanted layer. Completion of the drift is determined by the presence of full-energy signals from an alpha source scanned across the boron layer. The boron-implanted resistive layers were thus shown to behave as non-injecting contacts during the drift process and in the final detector.

On completion of the drift, the standard thick ($\sim$ 150 μm) lithium-diffused n^+ layer used for drifting is removed by grinding and lapping. A shallow lithium-doped layer is then formed by evaporation and diffusion. The process is

similar to that which we reported[12] in the fabrication of detectors for the ISEE-C telescope. A diffusion schedule of 5 minutes at 140°C gives sheet resistances of about 10,000 Ω/□ . The 90° metal contacts are applied to both the boron implanted (2×10^{15} ions/cm^2) contact regions, and to the thin lithium-diffused resistive layer. A Cr-Au (approximately 1000 Å each) contact is used over the boron. A good ohmic contact to the n^+ lithium-diffused resistive layer proved difficult to make. A Hf-Au (approximately 1000 Å each) evaporation was finally employed to make ohmic contacts to the thin lithium diffused layer.

Measurement Techniques

Measurements on the devices involve three parameters;

a) Determination of the resistance of the resistive layers between the contacts.

b) Characterization of the leakage current, noise, and depletion voltage.

c) Examination of the position linearily and spatial resolution.

A pulse test is used to measure the resistivity between the contacts on the devices since this simulates the actual application better than a dc test. A voltage pulse is impressed on one contact and is detected on the second with a charge-sensitive preamplifier. The rise time of the preamplifier output signal is used to estimate the resistance beween the contacts. For ten devices an average value of 13.5 ± 4.3 KΩ was obtained for the thin lithium-diffused resistive layers while an average value of 11.3 ± 3.5KΩ was obtained for the boron-implanted resistive layers.

Leakage current, noise and depletion voltage are measured with equipment similar to that outlined in Ref. 13. Figure 2 shows representative values of FWHM resolution as a function of amplifier time contstant.

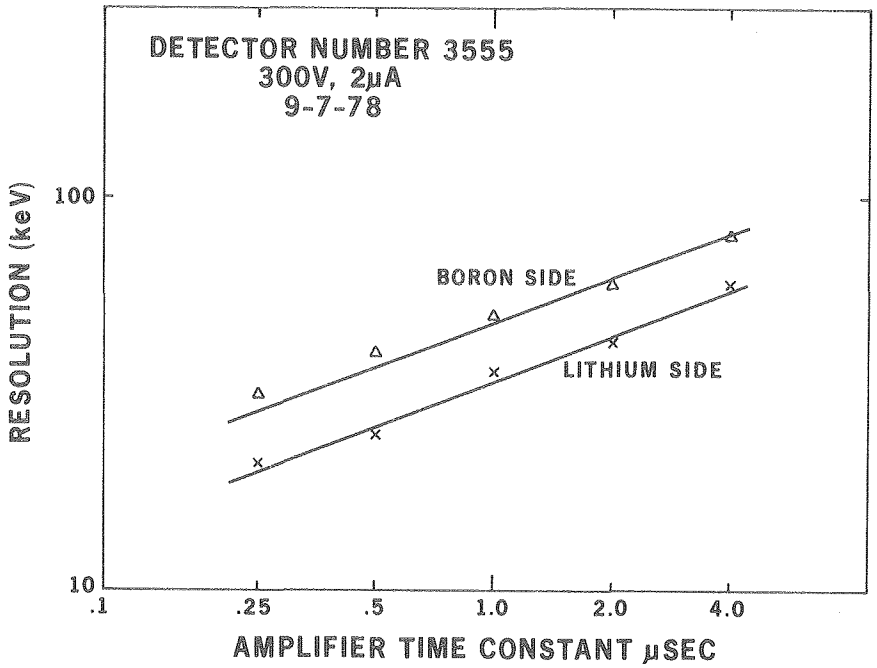

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Fig. 2. Electronic noise (FWHM) measured on the boron implanted side and the lithium diffused side of a two-dimensional PSD as a function of the amplifier filter time constant.

Position linearity is examined using a linear array of ten pulsed GaAs light-emitting diodes (LED's). The LED's are mounted behind 150 μm diameter holes spaced 3 mm apart on a moveable plate. The LED's are driven sequentially thereby permitting examination of the detector response as the array is scanned across the detector. The current drive to each LED was adjusted to give a 15 MeV equivalent signal in the detector. Since the signals are equivalent to mono-energetic ionizing events the usual ratio circuit[14] need not be used in making this test. A simplified diagram of the testing arrangement for the assessment of the boron layer linearity is shown in Fig. 3. The same spatial arrangement is used, but with energy and position channels reversed, to assess the lithium-diffused layer linearity (i.e. the LED's still illuminating the boron layer).

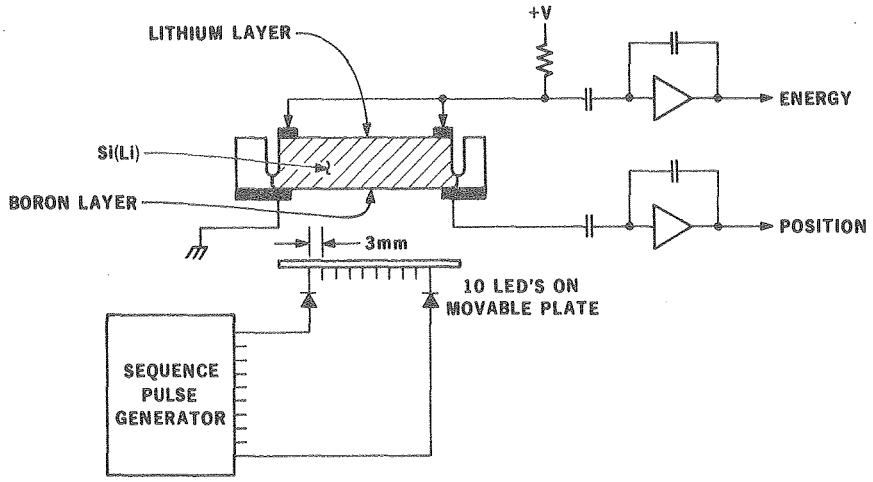

Fig. 3. Arrangement for assessing the linearity of the PSD's. As shown the response of the boron layer is being measured. The spacing of the LED's is 3 mm.

Characteristics Of PSD's

Figure 4 shows a detector's response when operated as a one-dimensional PSD with the LED array illuminating across the diameter while Fig. 5 shows the normalized response of the PSD as the array is scanned across the PSD's surface in 2 mm increments. For clarity, in Fig. 5, only half of the scan is shown since the results are essentially symmetrical about the center. Furthermore, no appreciable differences in linearity were noted between the boron-implanted and lithium-diffused layers.

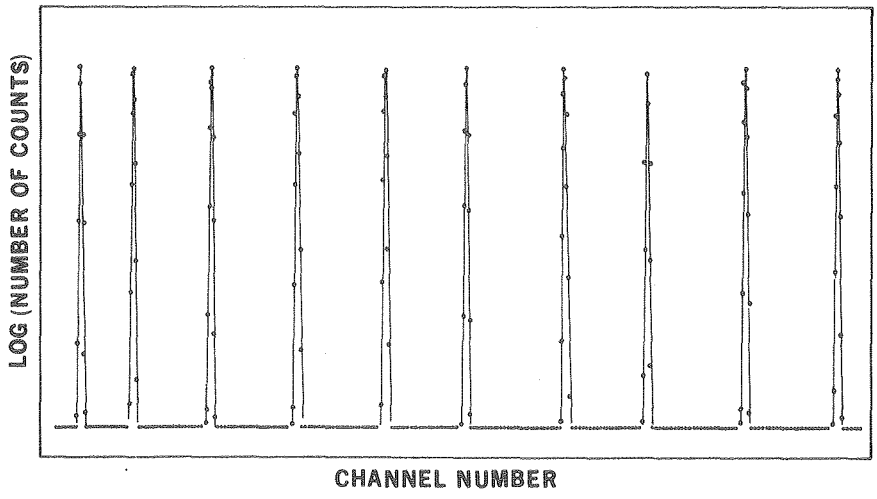

Fig. 4. Position response of a PSD using the equipment schematically shown in Fig. 3. The spectrum was taken with the LED's giving a 15 MeV equivalent signal. The amplifier filter time constant was 1 μs.

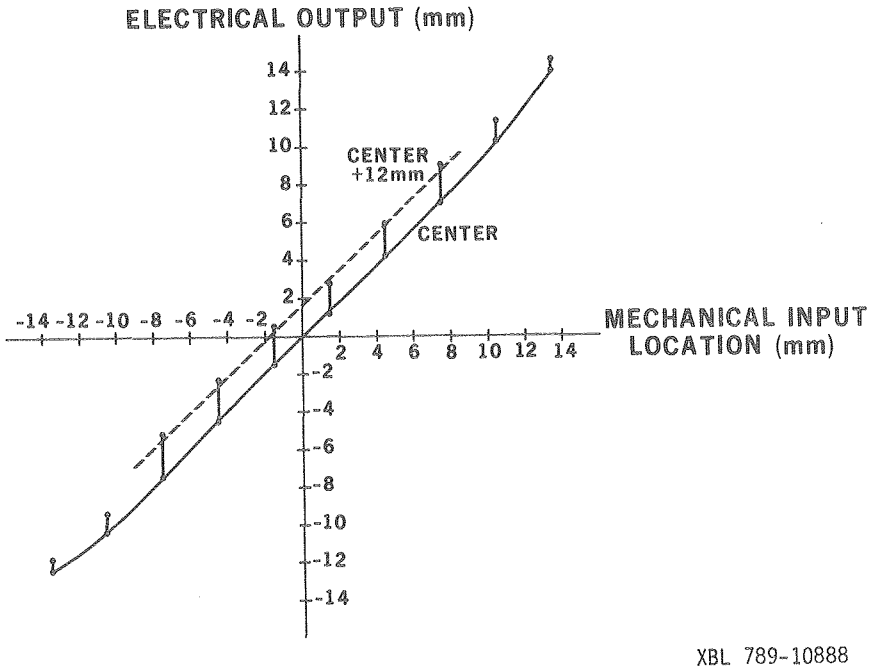

Fig. 5. Normalized response of a PSD comparing the electrical signal output against the mechanical location of the signal. The LED array of Fig. 3 was moved in 2 mm increments across the PSD. For clarity only half of the scan is shown, and only the center and the center +12 mm responses are indicated. The remaining scans fell on or between the indicated response curves.

With the 15 MeV equivalent signal from the LED's, the spatial resolution is about 80 μm FWHM for the PSD shown in Figs. 4 and 5. This compares well with the spatial resolution that would be expected strictly from noise considerations as this PSD had a noise FWHM of 40 KeV, which, for a 15 MeV signal, gives a spatial resolution of 40 KeV x 30 mm/15 MeV = 80 μm for the approximately 30 mm diameter PSD. The spatial resolution realized is about a factor of two worse than what was predicted by Eq. 4. However, Eq. 4 was derived assuming trapezoidal filtering and considered only the noise due to the resistive layer, ignoring the noise contribution of the leakage current which can be substantial when using thick detectors at room temperature.

Conclusions

Fabrication of these detectors was undertaken to examine the feasibility of making large-area thick PSD's with stable resistive layers employing boron implantations and shallow lithium diffusions. While the results obtained indicate the suitability of the approach, additional work needs to be done to confirm the long-term stability of the devices and of the layers.

The spatial resolution obtained on the devices is approximately of 100 μm with an applied signal equivalent to 15 MeV of absorbed energy. Good correlation is observed between the spatial resolution and the electronic noise measurements.

The linearity of the devices has been assessed and non-linearities appear to be related solely to the contact geometry, (i.e. the devices are symmetric about the center) and such distortions can easily be corrected in modern data-acquisition computers. The work has demonstrated that thick two-dimension circular Si(Li) PSD's compatible with detector telescopes can be produced with spatial resolutions of about 100 μm.

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