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Development of an Interdigitated Pixel PIN Detector for Energetic Particle Spectroscopy in Space

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ABSTRACT

The development of a new two-dimensional position-sensitive detector for use in space-borne energetic particle spectrometers is described. The novel feature of this device is the use of interdigitated pixels to provide both dimensions of position information from a single side of the detector, while a measurement of the energy deposition is derived from the opposite side. The advantage of this approach is that both good position resolution and excellent energy resolution can be achieved while at the same time realizing significant reductions in the complexity, power, and weight of the associated read-out electronics.

1. INTRODUCTION

Solar flares frequently inject intense fluxes of energetic nuclei into the interplanetary medium. Studies of the composition of these nuclei can provide a direct measure of the present elemental and isotopic composition of the Sun (see, e.g., Mewaldt et al., 1984), providing crucial information for understanding the history of solar system material, and for studying solar particle acceleration and transport. Such measurements, however, require instrumentation capable of operation in the hostile environment of the largest solar flares. We describe the development of a new detector designed to provide the required high resolution measurements in the presence of intense particle fluxes, with greatly reduced weight and power requirements.

One proven technique for energetic particle spectroscopy employs a "telescope" made up of a stack of silicon solid state detectors (wafers of silicon typically ~ 10 cm^2 in area and 0.1 to 1 mm in thickness). By combining the energy loss measurements from these detectors it is possible to determine the nuclear charge, mass, and kinetic energy of incident nuclei that slow down and stop in the telescope over the element range from H to Ni ($Z = 1$ to 28). However, to resolve the isotopes of heavy nuclei ($Z \geq 6$) incident over a wide range of angles it is in practice also necessary to measure their trajectory. To provide this trajectory information, silicon strip detectors can be used as the first elements in the particle telescope (e.g., Althouse et al., 1978). In optimizing the design of an improved instrument of this type there are several (often conflicting) requirements on these position-sensitive detectors (PSDs):

1) Because solar flare energy spectra decrease rapidly with increasing energy, it is important to use two-dimensional detectors of large area that can serve as both trajectory and energy measuring devices.

2) Studies of rare isotopes require operation in the very largest solar events when up to 10^5 to 10^6 low energy (~ 1 MeV) protons per second may hit the front detector. During such periods "pulse pileup" involving accidental coincidences between low energy protons and the heavy nuclei of interest may result in incorrect trajectories, incorrect pulse height measurements, or both. Thus, to preserve isotope resolution in a large solar flare it is necessary to track multiple particles in the PSDs.

3) Finally, because space missions always place a premium on weight and power requirements, the electronics required to instrument the PSDs must be minimized while at the same time maintaining adequate position and energy resolution.

Two alternative approaches to this problem have been attempted. The "brute-force" approach (e.g., Althouse et al., 1978) of individually instrumenting each strip provides the required position and energy loss information on all particles, but leads to significant penalties in weight, power, and electronic complexity when the size of the detectors is increased, given that the number of strips can be several hundred. A second approach that minimizes electronic complexity by attaching the strips to a resistive divider (e.g., Lamport et al., 1980) does not resolve multiple particle trajectories and is subject to pileup effects in even small flares.

We are developing a new "Interdigitated Pixel PIN Detector" (IPPD) that will have the advantage that two-dimensional position information will be available from a single side of the detector, while the signal from the opposite side will be employed solely for precise measurement of the energy deposition. Thus, only a single high precision pulse height analysis chain is needed to read out the energy signal, while individual $x - y$ strips on the pixelated side can be read out with amplifier-discriminators implemented in low power, high density, custom VLSI. This approach can provide significant savings in mass, power, and overall system complexity.

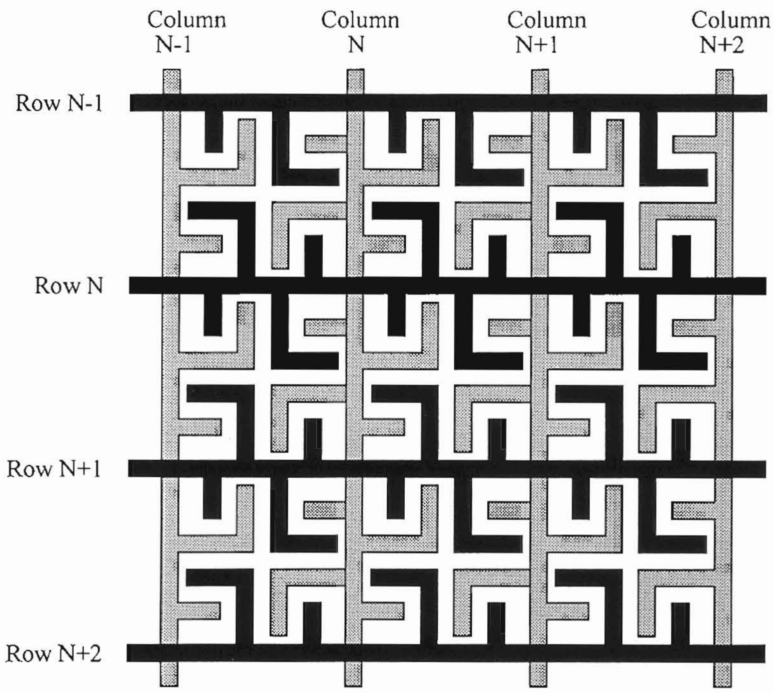

FIGURE 1 Top view of a conceptual 3 × 3 IPPD array.

2. TECHNICAL APPROACH

Position information from the IPPD will be derived from a two-dimensional array of pixels covering one side of the device (see Figure 1). Each pixel is divided into two sub-pixels, one associated with the "row" coordinate and the other with the "column" coordinate. The sub-pixels form a pair of interdigitated contacts, which should have a finger spacing smaller than the lateral spread of the electron-hole plasma generated by a typical particle of interest to ensure charge sharing between the row and column sub-pixel. All "row" sub-pixels in a given row are connected to a row wire; these row wires are brought out to the edge of the array. The "column" sub-pixels are connected in a similar manner. A particle impact at any given pixel will deposit charge on both the row and column sub-pixels at that location, which is carried to the edge of the detector along one row wire and one column wire. The detector readout electronics discriminate which row and which column have "fired", yielding the coordinates of the impact. The electronics can be designed to record multiple particle positions.

The operation of each sub-pixel in this array is identical to that of conventional fully depleted PIN detectors. As illustrated in Figure 2, a high resistivity (nominally intrinsic or "*i*" type) silicon wafer has a *p*-doped region introduced on one side and an *n*-doped region introduced on the other side. By applying a reverse bias sufficient to fully deplete the nominally undoped region (~ 35 volts), one

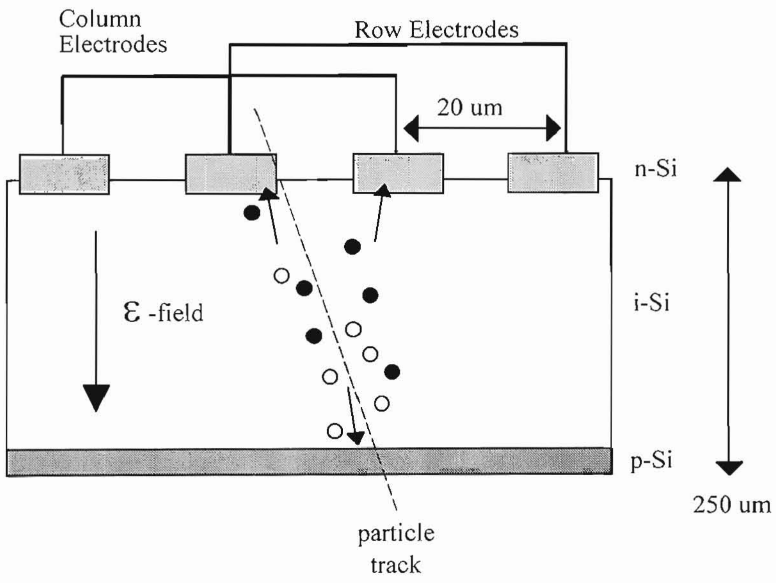

FIGURE 2 Schematic cross section of an IPPD pixel. The passage of a charged particle leads to electron collection at the interdigitated row and column electrodes (n-doped) and hole collection at the p-doped contact at the opposite side of the device.

obtains a detector in which all of the generated electrons throughout the entire thickness of the wafer are collected at the n-doped contact, and all the holes are collected at the p-doped contact.

The other side of this detector is a full area contact that collects all of the deposited charge independent of the position of the particle impact. Precision pulse-height analysis of this electrode will accurately determine the total energy loss of the particle. To recover individual pulseheights of multiple particle events, an eventual detector might have several segments on this back electrode, but such segmentation is not required to validate the basic design and function of this device.

Detector Characteristics

We are presently developing a prototype detector that will test the IPPD concept. We discuss below some of the desired characteristics of this detector.

Size: Although an eventual detector diameter of ~ 5 to 10 cm is desirable, a prototype size of ~ 1 cm is sufficient to demonstrate the approach.

Thickness: The prototype devices will be 250 μm thick; potential applications might involve thicknesses anywhere from ~ 50 μm to 1 mm.

Pixel Size: A pixel size of ~ 0.5 to 1 mm should provide the required position resolution for the present application. Smaller pixel sizes are possible.

Number of rows and columns: A 9×9 array of rows and columns is planned for the prototype devices.

Row or column capacitance: To allow low power electronic readout of the individual rows and columns it is necessary to keep the net row or column capacitance below a few hundred picofarads.

Inter-strip resistance: The inter-row and inter-column resistance determines the amount of spreading of the charge signal to adjacent rows or columns that occurs before the charge is collected by the readout electronics. While a value of 100 kilohms is acceptable, a value > 1 Megohms is preferable to allow a lower power (i.e. slower) readout.

Row and column leakage current: The net leakage current for any row or column should be kept below ~ 100 nA at 35 degrees C to simplify the design of low power readout electronics.

Interdigitation feature size: The width of the interdigitating fingers of a pixel should be small enough to ensure that the charge signal from a vertically incident nucleus is adequately shared between row and column (see discussion below). Prototypes will be fabricated with several different finger spacings to allow assessment of the charge sharing efficiency.

3. PROGRESS TO DATE

Although the development of the IPPD is still in its initial stages, significant progress has already been achieved. Following the definition of the detector characteristics described above the pixel structure was designed using modeling and simulation tools. A process sequence for fabricating the detector has been developed, and an initial mask set for defining the material layers in the semiconductor device has been created.

Detector Simulation

The IPPD was simulated using a two-dimensional semiconductor device model called PISCES which simulates the steady-state or transient electrical behavior of arbitrary device structures by simultaneously solving Poisson's equation and the electron and hole continuity equations. The device structure being modeled is similar to Figure 2. Two electrodes are included, and the mesa structure is approximated by placing a rectangular oxide region between the *n*-regions. As an example, Figure 3 shows electric field vectors in the device for a bias of 25 V. Only the top 15 μm of the structure is shown in this figure, but the thickness in the simulation was 100 μm.

A requirement for successful operation of this device is for charge to be collected simultaneously on both row and column electrodes, although an even split is not necessary. Generated carriers drift toward the electrodes very nearly along the electric field lines. An important issue for near-vertical-incidence particles is that the generated carriers may drift and be collected by only one electrode, since the electrode pitch is 10%–20% of the wafer thickness, and the consequent field lines are nearly vertical. Initially it was hoped that carriers collected primarily on one electrode could build up sufficient bias on the electrode (depending on the RC time constant of the electrode line) to steer the remainder of the carriers to

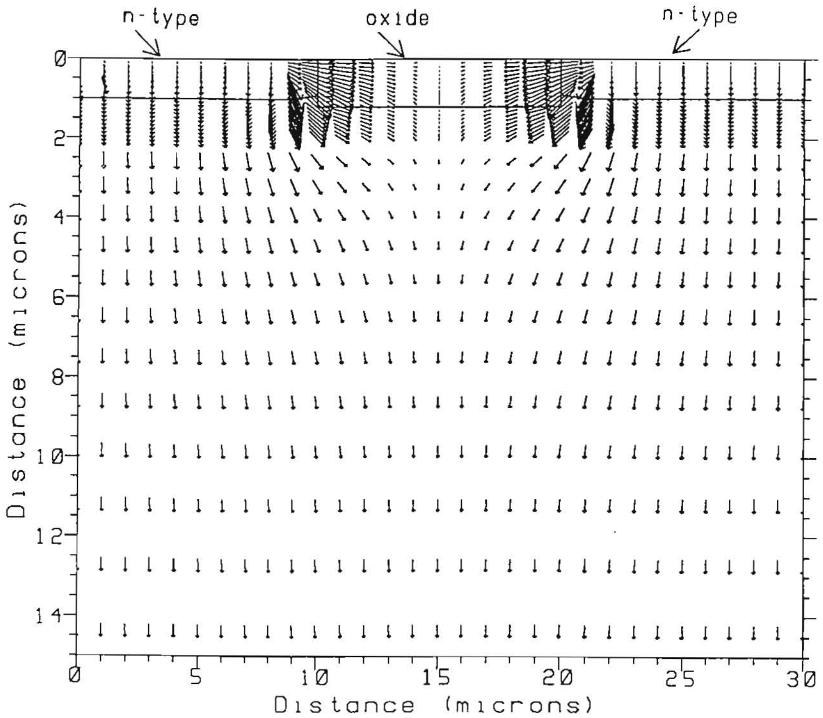

FIGURE 3 Electric field vectors in top 15 mm of device with 25 V bias. The x-axis is distance across the detector and the y-axis is depth into the device.

the other electrode. Simulation shows that this effect is only significant for very small electrodes and gaps.

Another mechanism for achieving charge splitting between adjacent electrodes is carrier diffusion. A simple analysis shows that this mechanism is significant for the detector geometries under consideration. From the solution to the diffusion equation for a limited point source diffusing in three dimensions, the charge density Q at a point r from the source is given by a Gaussian distribution:

$$Q(r,t) = Q_p(t)\exp(-r^2/4Dt)$$

where Q_p is the peak charge density at time t, and D is the diffusion coefficient for the carriers. For a wafer of thickness L the field is V/L, where V is the applied potential. For charge generated midway through the wafer the distance of the collecting electrode is $L/2$, and the transit time t can be expressed as $L^2/2\mu V$, where μ is the carrier mobility. D is related to μ by the Einstein relationship, $D = kT\mu/q$, where k is the Boltzmann constant and q the electron charge. Upon substitution we find:

$$r = [(2kTL^2/qV)\ln(Q_p/Q)]^{1/2}.$$

Taking Q to be 1% of Q_p, using $L = 250$ μm, and $V = 25$ volts, we find $r = 24$ μm. This suggests that the electrode pitch be less than $2r$, or 48 microns, and that V be as low as possible, consistent with full depletion of the wafer. For the pixel size under consideration (0.5–1 mm), there must be relatively many fingers within a single pixel.

Detector Fabrication

It is desirable to keep the fabrication process as simple as possible. High resistivity wafers were obtained through U. C. Berkeley where a highly n-doped polysilicon layer was deposited on one side of the wafer. This polysilicon layer insures high wafer resistivity by getting contaminants introduced during fabrication (Holland, et al., 1990). The other side of the wafer is implanted with p-type dopants to form the continuous electrode (see Figure 2). The n-type polysilicon layer is then etched to form mesa contacts to the high-resistivity silicon. Some n-type dopants diffuse into the silicon during processing. A thin passivating oxide is grown on the silicon between mesas. Metallization of row and column lines is performed in two steps since two layers of metal are required to allow crossing of row and column lines. A first layer of metal is deposited and patterned, and then an insulating layer is deposited. Contact holes are etched and a second layer of interconnect metal is deposited and patterned.

Masks have been designed and fabricated in accordance with the modeling and simulation as well as the fabrication process. The mask includes several pixel designs with electrode pitches of 20, 40, and 80 μm, as well as test structures for evaluating the fabrication process and device quality. Seven different arrays will be fabricated simultaneously for evaluating the performance of the different designs. Each array is a 9×9 pixel format, with pixels 1 mm $\times$ 1 mm. Figure 4 shows an example of the interdigitated finger pattern for a single pixel. At the time of this writing, the first complete detector arrays are just being fabricated.

4. PLANNED ACTIVITIES

Detector Testing

In the near term, the prototype devices processed using the current mask set will be characterized for both electrical as well as detector performance. Capabilities to measure particle position and energy will be tested in the laboratory with radioactive sources, including mono-energetic alpha-particles and ^{252}Cf fission fragments collimated to < 1 mm. In addition, heavy ion accelerator calibrations are planned with beams such as ^{12}C and ^{56}Fe. Prototype detectors will also be subjected to thermal-vacuum tests to assess their suitability for operation in space. This testing should provide detector performance data that will allow redesign of the sensor for improved operation.

Detector Readout

Readout of the detector array will be performed using custom VLSI circuits now under development. Each row and column will be pulse-height analyzed with

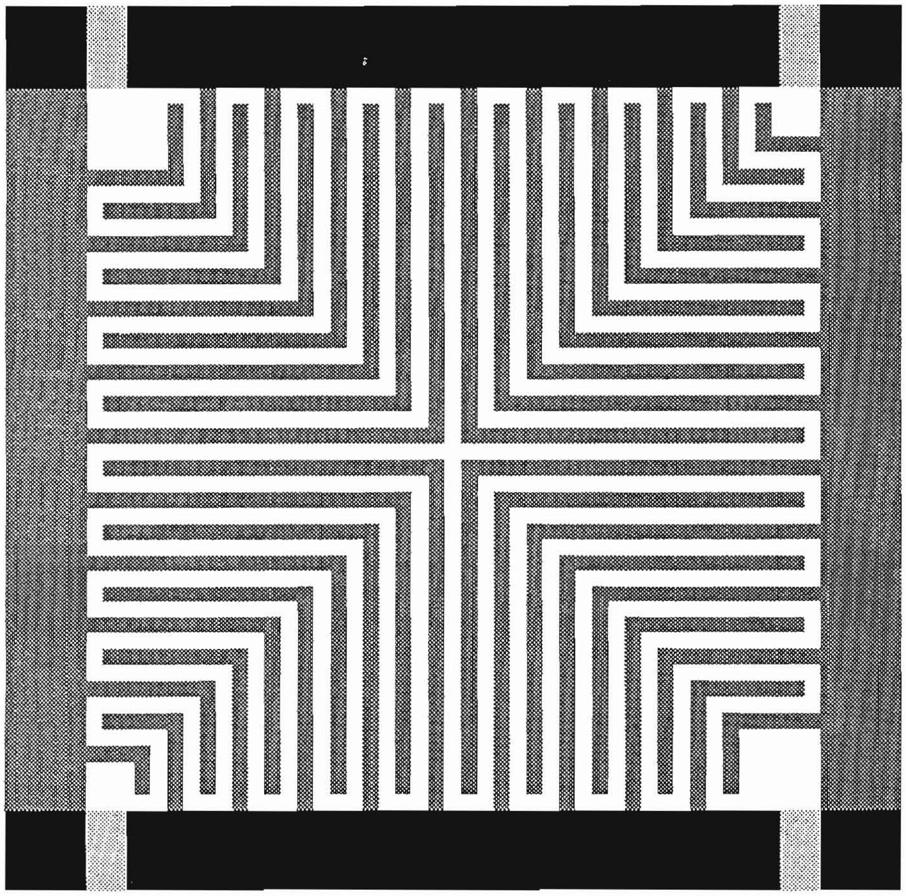

FIGURE 4 Interdigitated row and column pattern within a single 1 mm × 1 mm pixel. The electrode pitch is 40 μm.

an independent linear chain consisting of a low-noise charge-sensitive preamp, gated integrator, sample and hold, and Wilkinson-type ADC. We expect sixteen complete pulse height analysis chains to fit on a single integrated circuit, with each chain consuming only ~ 5 mW. The energy signal from the other side of the detector will be pulse height analyzed with a standard circuit consuming $\sim$ 100 mW. Thus, a typical detector for space flight application having 100 rows and 100 columns could be instrumented with a small number of integrated circuits consuming only ~ 1 watt.

5. SUMMARY

The interdigitated pixel detector described here promises to provide both two-dimensional position resolution and excellent energy resolution with significantly reduced electronic complexity, leading to applications in future space-borne instruments that study energetic heavy nuclei in a solar flare or magnetospheric environment. This novel device may also have applications in other areas of astrophysics, and in nuclear and high energy physics. In addition to its technical benefits, this project has provided a valuable opportunity to combine the resources of Caltech's Space Radiation Laboratory and NASA's Jet Propulsion Laboratory, and to involve graduate students and new Ph.D.s in device microfabrication and instrument design.

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