A Monolithic Segmented Germanium Detector with Highly Integrated Readout


Abstract—We have constructed a pixelated germanium detector using a technique which has been shown to provide good isolation between adjacent pixels. In this work we present initial tests of the application of a low-noise CMOS ASIC to read out this detector. The detector has 64 pixels, each 0.5 mm x 5 mm, arranged as a series of strips. It is connected by wire-bonds to two 32-channel ASICs (Application-Specific Integrated Circuit) which provide a complete photon-counting chain for every channel. Since the size of the pixel array is no longer restricted by the difficulties of instrumenting large channel-count conventional electronics, this development will open up the possibility of even larger arrays, similar to those offered by silicon detectors.

I. INTRODUCTION

The use of germanium for the detection of high-energy photons is well developed. Silicon detectors having thousands of channels have also been developed for particle tracking, x-ray position sensing and spectroscopy, based on tight integration of their readout systems. Germanium detector arrays have also been developed, typically using individual devices packaged in a common cryostat and read out using discrete electronics. This places an upper limit on the number of channels which can be implemented in a practical array. Current commercially available arrays have up to 32 discrete detectors with discrete-component preamplifiers mounted on the detector head. Monolithic arrays as large as 100 elements have been developed using discrete component readout, but to go further will demand greater integration of the readout electronics. In this work we present the result of exactly such a combination based on segmented germanium detectors made by Semikon using a process which provides excellent pixel-pixel isolation and the ability to define device geometries on the micron scale, and on low-noise integrated circuits developed at BNL.

II. SEGMENTED GERMANIUM SENSORS

The fabrication of segmented germanium detectors has been described previously [1] and so we will only briefly describe the process here. Planar detectors are formed by diffusing Lithium ions to create an n-type contact on one side, and implanting Boron ions to create a thin p-type layer on the other. The p-type side is then lithographically patterned to form the desired segmentation and shallow trenches etched between the segments. The resulting detectors show remarkably low leakage and high inter-segment isolation. The detector we have used for this study consists of 64 rectangular devices, each 0.5 mm x 5.0 mm, formed on a 3 mm thick germanium slice. The trench between each device is approximately 50 micrometers wide and 50 micrometers deep. The drawing in figure 1 illustrates the overall structure of the detector.

![Fig. 1. The dimensions of the segmented germanium detector used in this study. All dimensions are in millimeters. There are 64 strips, each 0.5 mm x 5 mm.](image)

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III. READOUT ELECTRONICS

The primary objective of this work was to establish the feasibility of using integrated circuits to read out germanium detectors, which operate at a temperature of around 100K. We already had a 32-channel integrated circuit designed to read out p-on-n silicon detectors which generate hole signals. The ASIC is called HERMES, and has been used in our laboratory for several years as the basis of silicon strip detectors and multi-element spectroscopy detectors [3]. An existing printed circuit board (PCB), designed to accept twelve such ASICs, was modified to accept two ASICs. A temperature sensor was attached to one of the unoccupied...
ASIC positions in order to provide an estimate of the ASIC temperature. This PCB was mounted adjacent to the sensor block, and the ASIC inputs were wire-bonded to the sensor strips, as shown in figure 3.

![Image of finished detector](image1)

**Fig. 3(a).** Photograph of the finished detector, showing the two 32-channel ASICs and the wire-bonds connecting them to the sensor. When installed in a liquid nitrogen cryostat, the sensor stabilizes at 100K, and the ASICs at -50C.

![Image of wire bonds](image2)

**Fig. 3(b).** Closeup view of the wire bonds between the ASIC and sensor. These bonds are significantly longer than industry standards, but provide the lowest possible interconnection given the constraints of the project.

The wire bonds are rather extreme in length and angle, an inevitable result of a mismatched sensor and ASIC pitch if one is not willing to accept the additional capacitance and dielectric losses of an interposer. This ASIC is intended to mate with detectors on a 0.125mm pitch. Nevertheless, as will be shown, this arrangement functions perfectly well. This PCB was designed to connect to a controller based on a microprocessor implementation of the EPICS control system which we have used for several detector projects based on this ASIC. It provides access to all operating modes and parameters of the ASIC, and a high-voltage bias supply for the sensor. Although it was designed for counting applications with a hardware window discriminator, it was designed for very low-noise operation, and eventually became the heart of the Maia spectroscopy detector. We therefore had every expectation that it would provide good performance with this sensor.

IV. ENERGY RESOLUTION

Since we are primarily interested in high-energy x-ray applications of germanium detectors, we started our study by illuminating the detector with a flood-field of the radiation from an $^{241}\text{Am}$ radioactive source. This has a strong line at 59.5 keV and several weaker lines around 10 keV. One spectrum from one strip is shown in fig. 4(a), together with a histogram of the distribution of resolution for all 64 strips in fig. 4(b).

![Spectrum of 241Am](image3)

**Fig. 4(a).** Spectrum of $^{241}\text{Am}$ as recorded by one of the 64 strips of the sensor. The resolution of the 60keV line is 450 eV.

![Histogram of energy resolution](image4)

**Fig. 4(b).** Histogram of the energy resolution of all 64 strips at 60keV. 59 of the 64 are below 550eV.

V. SPATIAL RESOLUTION

Since one potential application of structured germanium detectors is as efficient position-sensitive detectors for high-energy x-rays, i.e. those above 20keV, we studied the detector’s response to a microbeam of x-rays. A monochromatic beam of variable energy between 10 keV and 30 keV was prepared by passing it through a slit whose dimension along the short strip dimension was 20 micrometers. The detector was moved through this beam and the intensities in all 64 strips recorded, using the on-chip pulse-height discriminators and pulse counters. At the energy being studied, the counter threshold was set to half of the full-energy peak height. It is known that this setting should provide a uniform response as the beam is scanned across pixel boundaries since, statistically, under-counting and over-
counting of partial charge events are equally likely. The experimental arrangement is illustrated schematically in fig. 5.

Fig. 5. The experimental setup for microbeam scanning of the detector. White synchrotron radiation is incident from the left, is monochromated by the monolithic 2-crystal device, spatially shaped by a slit and incident on the multi-element detector on the right. The detector is moved vertically and horizontally by a precision X-Y stage with 1 micrometer resolution.

Fig. 6. Intensity recorded in each of the 64 pixels as the microbeam is scanned across the detector. The slow intensity variations seen in the scan are due to incident beam instability, not detector response.

The result of such a scan is shown in fig. 6. Each pixel shows intensity only when the beam is falling on it. Ideally, the curve for each strip should be smooth, with a flat top and monotonically falling edges. Inspection of the curves in fig. 6 shows non-monotonic behavior near the top of each curve. An expanded view of data from four strips is shown in fig. 7.

Scan of 20μm spot across 4 strips

Fig. 7. Expanded view of data from four of the 64 strips, showing the non-monotonic behavior near the peak.

One possible explanation of this result could be that our probe beam has spatial structure which could distort the scans. To explore this possibility we made another scan, this time with a thick absorber with a sharp edge covering half of one strip. Fig. 8 shows that result. It is clear that the left-hand edge is well-behaved. The derivative of this profile shows a smooth symmetric peak with a full width at half maximum of approximately 20 micrometers. Thus, the anomalous result seen in figure 7 is not an artifact of our beam preparation.

Fig. 8. A scan through a strip which is half-covered by a sharp-edged absorber, demonstrating that the incident x-ray beam does not have any spatial structure which could cause the anomalous results seen in figure 7.

To try to understand this behavior, we collected spectra at each point of scans similar to that of fig. 7, but only covering three strips. The scan was set to start in the middle of one strip, scan fully through the next, and stop half-way through the third. In this way we could examine both extremes of the central strip, and how it overlapped with adjacent ones. Unfortunately, the ASIC used cannot provide the analog output of all channels simultaneously, but only one at any one time. Consequently we had to collect each channel’s data sequentially. This precludes us from identifying coincident events in adjacent pixels such as would occur, for example, with a charge-shared event [2].

We made such measurements at three different energies, at 10 keV, just below the germanium K absorption edge, at 13 keV, just above the edge, and at 30 keV, well above the edge. This procedure gave data for differing penetration depths of the radiation, and also data with and without the influence of germanium K escape peaks in the spectra. Fig. 9 shows the result for 10keV illumination.

Fig. 9. Plot of spectrum vs beam position at a photon energy of 10keV.
The plot is made on a logarithmic scale to highlight the weaker features of the spectra. Of particular interest are the spectral distortions which take place near the boundaries. The figure shows three regions: the center of each strip, where there is a single photopeak and little background, the regions within $50 \, \mu m$ of the strip edge, which show significant reduced charge events, and the region beyond the boundary, showing full-charge events even when the beam is not within the strip. It is clear that the reduced charge features observed are correlated with the trench dimensions. Fig. 10 shows an expanded plot of the boundary region.

Fig. 10. An expanded view of the region near the trench in one pixel. The regions discussed in the text are highlighted by magenta markings.

Those near the symmetry point between strips appear to be what one would expect from normal charge-shared events, with a correlation between position and pulse height (indicated by the magenta line in fig. 10). Those within the magenta oval in fig. 10 are not so easily identified. At $10 \, keV$, the penetration depth of the radiation is around $50 \, \mu m$. This is the same as the trench depth. Several possible explanations could account for these events. With the data we have to hand we cannot definitively decide which of these possibilities is the correct one. We need to perform coincidence measurements between adjacent pixels to identify which of these events are charge-shared and which, if any, may have suffered charge loss.

Fig. 11 shows similar data taken at $30 \, keV$. At this energy, the penetration length is over $150 \, \mu m$, and the reduced charge events appear weaker. We see the germanium K escape peaks, and also germanium K fluorescence lines. It is now the fluorescence which is seen in the adjacent strips, rather than the elastic scatter as we saw at $10 \, keV$. The escape peaks are enhanced in the trench region, probably as a result of the trench geometry providing additional surfaces through which the fluorescence can escape.

Fig. 12 shows similar data taken at $13 \, keV$, slightly above the germanium K edge. In this case the absorption depth is around $15 \, \mu m$. The escape peak appears at low energy, around $3 \, keV$, and again the germanium fluorescence is seen in adjacent pixels. Otherwise the features are similar to that seen at $10 \, keV$.

VI. APPLICATIONS

Our interest in germanium as a sensor material stems from the construction of the new synchrotron radiation source at Brookhaven National Laboratory, NSLS-II. Some of the new beamlines under development there will be focused on energies in the range $20-100\,keV$, in order to allow various studies of dense samples, often in-situ or in-operando, such as the development of improved battery designs or better catalytic processes. A good tool for this type of experiment is energy-dispersive x-ray diffraction (EDX). We have made proof-of-principle measurements of one potentially useful arrangement and present the results here.

Fig. 13 shows the basic idea behind the experiment. A white beam containing energies between $20$ and $150 \, keV$, collimated to around $100 \, \mu m$ cross-section is directed onto the sample. This beam selects a laterally-constrained volume of the sample for analysis. The sample at each point along the beam causes diffraction. Since the incident beam contains a continuum of x-ray wavelengths, Bragg planes in the (polycrystalline) sample select appropriate wavelengths and scatter them through the diffracted beam slit shown in the figure. Conventionally, this experiment is carried out with a single point detector and a pair of slits, to chose one particular Bragg angle. Mapping of the whole sample then involves scanning the sample through the resulting gauge volume. If the second slit is replaced by a position- and energy-sensitive detector, as shown in fig. 13, then all gauge volumes along the line defined by the incident beam can be analyzed simultaneously. The detector we have described above is just such a detector.
Fig. 13. Concept of an experiment to use a position-sensitive x-ray detector to separately measure different regions within a complex sample such as an operating battery.

The only potential issue with this arrangement is that each sample volume has a different diffraction angle, so each pixel in the detector needs to be individually calibrated on the Bragg spacing scale. To illustrate this (and possibly provide a way to make the calibration), we first measured a uniform sample, roughly 30mm thick, of alumina powder. The results from that measurement are shown in figure 14.

Fig. 14. Energy-dispersive diffraction from each strip of detector. Since Bragg angle changes systematically for each strip, energy of lines also changes.

The diffraction lines should be smooth. The small deviations in line position at certain points are the result of an inadequate energy calibration procedure. A better procedure can be devised, and will be used in future.

To verify that spatial discrimination is realized with this technique, we made a test sample consisting of three different compounds with different structures, silicon carbide, silicon and alumina. Each compound was placed in a plastic holder to form a 1 centimeter thick slab, and the three slabs were clamped together. The data from this experiment are shown in fig. 15.

VII. SUMMARY

We have shown that monolithic multi-element germanium detectors from Semikon Detectors GmbH can easily be combined with ASICs from BNL to form large arrays. This paper describes a 64-element array, but it will be straightforward to implement larger arrays, as we have done previously with silicon sensors. We need to make further studies in order to optimize the system performance. However, in its present form it is a powerful tool, and we have illustrated its potential with an experiment which absolutely demands this type of detector.

VIII. ACKNOWLEDGMENTS

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