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**Position Sensitive Proximity Charge Sensing Readout of HPGe
Detectors**

by

Anders Peterson Priest

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Engineering, Nuclear Engineering

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Kai Vetter, Chair

Professor Eric Norman

Professor Steven Conolly

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Fall 2016

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Anders Peterson Priest

Abstract

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University of California, Berkeley

Professor Kai Vetter, Chair

Electrode segmentation is a necessity to achieve position sensitivity in semiconductor radiation detectors. Traditional segmentation requires decreasing electrode sizes while increasing channel numbers to achieve very fine position resolution. These electrodes can be complicated to fabricate, and many electrodes with individual electronic channels are required to instrument large detector areas. To simplify the fabrication process, we have moved the readout electrodes onto a printed circuit board that is positioned above the ionization type detection material. In this scheme, charge from radiation interactions will be shared amongst several electrodes, allowing for position interpolation. Because events can be reconstructed in between electrodes, fewer electrodes are needed to instrument large detector areas. The proximity charge sensing method of readout promises to simplify detector fabrication while maintaining the position resolution that is required by fields such as homeland security, astrophysics, environmental remediation, nuclear physics, and medical imaging.

We performed scanning measurements on a proof of principle detector that we fabricated at Lawrence Berkeley National Laboratory (LBNL). These measurements showed that position resolution much finer than the strip pitch was achievable using the proximity charge readout method. We performed analytic calculations and Monte Carlo modeling to optimize the readout electrode geometry for a larger detector to test the limits of this technology. We achieved an average position resolution of $288\text{ }\mu\text{m}$ with eight proximity electrodes at a 5 mm pitch and 1 mm strip width, set 100 μm away from the detector surface by a Kapton spacer. To achieve this resolution using standard technologies, 300 μm pitch strips are necessary, and would require 100 channels to instrument the same area. Through our optimization calculations, we found that there is a trade-off between position resolution and energy resolution,

and this system provided comparatively poor energy resolution by HPGe standards, with 4.7 keV FWHM at 59.5 keV. With another electrode geometry, we were able to achieve 2.9 keV FWHM at 59.5 keV. This dissertation describes the work we completed to achieve these results.

To Loral, David, Brita, Eric, Alexis, Grandma Pete, and Grandma Gen
Your love, support, nurturing and inspiration gave me all the tools I needed to
achieve my goals.

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Chapter 1

Introduction

1.1 Radiation Detection

It has become abundantly clear over the last century that ionizing radiation (“radiation”) is a resource that can be used to our benefit to learn about our world. Studying naturally occurring radiation sources as well as using radioactivity as a tool provides insight into the parts of our world that are otherwise very difficult to see or understand. The scientific utility of radiation is undeniable, and the tool used for its measurement is the radiation detector.

Advances in radiation detection are achieved through improved position resolution, energy resolution, or time resolution by employing new detection materials, novel information carrier readout methods, advanced electronics, or data processing methods. Advancements in these areas can lead directly to achievements in the fields that use these instruments through the additional information provided. Radiation detector applications will also spur advancements in the detectors due to requirements that are not met by existing technologies. The cyclical nature of detection techniques advancing applications and applications necessitating further advances in detectors requires constant detector development.

The goal of the work presented here is to investigate one possible step forward in the readout of position sensitive ionization detectors, which has been named *proximity charge sensing*. In Chapter 1, I will lay out the motivation for the development of advanced, position sensitive detectors. The method we investigated will be presented at the end of Chapter 2, after presenting the background and motivation for this method. Chapter 1 covers radiation sources and applications for which radiation detectors are used, as well as a short history of radiation detectors. In the beginning of Chapter 2, semiconductor physics, semiconductor device physics, and semiconduc-

tor detector physics will be described in detail. Chapter 3 will cover details regarding the extraction of position and energy data from proximity charge sensing detector data. Because proximity charge sensing readout operates differently from conventional strip detectors, optimization of the strip geometries was needed, the method for which will be presented in Chapter 4. Chapter 5 describes the proximity charge sensing detectors that were fabricated at Lawrence Berkeley National Laboratory (LBNL), as well as the experimental setup. Chapter 6 covers the results of the measurements made with these detectors. Chapter 7 includes a summary, conclusions, and potentials for future research.

1.1.1 Radiation Detector Technologies

Many detector materials, leveraging varying detection methods with diverse applications, were under development simultaneously starting in the 1890s. Photographic papers, glasses, and films were used both as radiation imaging media and in dosimetry [1]. Here, ionizing radiation interacts with an emulsion, where the ionization changes the chemical properties of the film. When developed, the color or opacity of the film will be altered based on the amount of ionization that has occurred. Because the film is continuous, this method is suitable for imaging by x-ray projection, which maps the integrated x-ray attenuation of the object imaged.

Calorimeters were the first attempt at measuring the energy emitted by a source. Calorimeters measure increases in temperature of a well known material or pressure increase in a vacuum caused by temperature increase. Today, the term calorimeter detector is used to describe large scintillator detectors often used in high energy physics experiments [2, 3]. The term bolometer is now used for ultra-low temperature detectors that measure minute temperature changes caused by radiation interactions, a more recent technology made possible by advances in cryogenic cooling [4, 5].

Ionization chambers and, therefore, Geiger-Muller counters, proportional counters, and a multitude of other gas ionization based detectors were under development as early as the 1890s as well, and continue popular use today. In this technology, pressurized gases are ionized by radiation and an electric field applied across the gas will cause the liberated charge to drift and subsequently be collected and measured. Depending on the gas used and the voltage applied, the response to ionizing radiation will vary. Low fields allow for recombination of some or all of the ionized atoms. Higher fields will separate all the ions from the electrons, and, above a threshold dictated by the gas and the pressure, electron multiplication will occur, increasing the electrical signal measured. Eventually, the field will cause enough multiplication that the ion electric field will dominate, terminating the multiplication. This operational regime is known as the Geiger-Mueller mode. All events in this regime cause

the same amount of ionization, and are preferred for radiation counting because of their simplicity, low cost, and ease of operation [6].

Scintillation detectors were introduced in 1903, with the observation of zinc sulfide scintillation when subjected to ^{226}Ra α -particles by William Crookes [1]. In a scintillating material, radiation interactions promote electrons into excited states in the material. These states subsequently decay, emitting visible light with the wavelength set by the energy difference between states. To measure a signal, the visible photons are converted to an electrical signal either by a photocathode or a semiconductor material. This signal is often amplified and then measured. These steps all happen within 1-10 ns, making scintillators excellent for timing measurements. Over the last century, vast improvements have been made not only in the materials but also in the readout electronics needed for spectroscopy and imaging. Scintillator detector systems continue to be used today in a wide range of applications due to their versatility and relatively low cost when compared to semiconductor systems.

Semiconductor radiation detectors first came into use 30-50 years later, depending on the classification of “crystal detectors” used the 1930s and 40s. Bell Laboratories produced the first radiation detector based on a semiconductor that can be compared to modern systems [7]. Within a decade, advances in materials and electronics revealed the promise of semiconductors for spectroscopy, in part due to the direct measurement of charges liberated by ionizing radiation events. With a high electric field applied across a semiconductor, electrons and the positively charged vacancies left in their absence can be conducted through the material and collected by electrodes. The number of charge carriers generated is linear with energy, and the average ionization energy for semiconductors leads to many more charge carriers than the light output of scintillator detectors, which contributes to semiconductors’ comparatively superior energy resolution. At the time semiconductors were first used, there were limitations in the size of the active volume achievable due to impurities in the crystals grown, and many crystals could not be used for radiation measurements. Poor energy resolution and low efficiency made it difficult to compete with scintillator detectors. With the introduction of lithium-drifted silicon and germanium detectors (Si(Li) and Ge(Li) detectors), much thicker active volumes could be achieved with much better energy resolution [8]. Ge(Li) detectors were capable of energy resolution an order of magnitude better than the standard at the time, NaI(Tl). This was a revolutionary discovery in radiation measurements.

Because of lithium’s high mobility in germanium, Ge(Li) detectors are required to remain cooled to cryogenic temperatures to remain operational. In the 1970s, the Atomic Energy Commission began funding efforts to develop processes to purify germanium such that impurity levels were below 10^{10} cm^{-3} [1], a level at which appreciable active volumes could be achieved without the addition of lithium. This

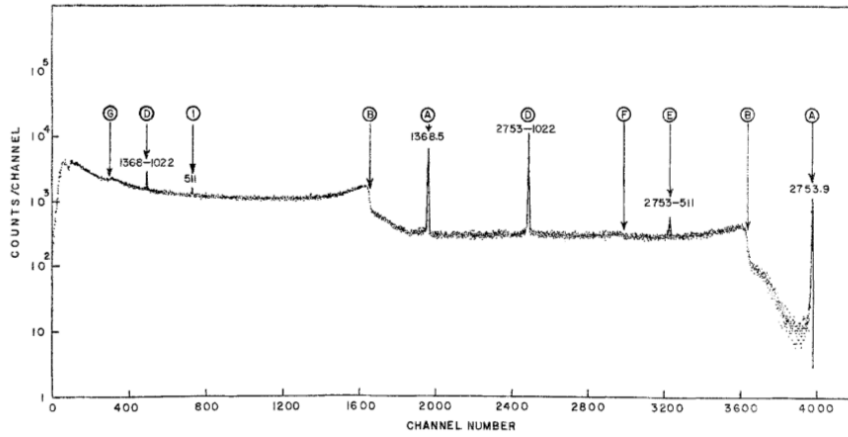


Figure 1.1: Gamma ray energy spectrum for ^{24}Na taken with an early Ge(Li) detector, showing excellent energy resolution across the entire energy range [9].

effort proved fruitful, and high purity germanium, or HPGe, became a viable detector material. With exceedingly low impurity concentrations, it was no longer necessary to perform the lithium drift process. The material could be grown into large, perfect crystal boules, and large volume detectors could be fabricated because appreciable active volumes were achievable with high voltages well below the breakdown voltage. HPGe has many desirable features (discussed in Section 2.3) that lead to excellent energy resolution and high intrinsic efficiency, which has led to HPGe's dominance in radiation spectroscopy since the 1970s.

The most common modern detector technology groups are direct electrical signal detection based on semiconductors, conversion to visible light through scintillating materials, and direct electrical signal measurement through gas ionization. Broadly speaking, semiconductors offer superior energy and position resolution, but can introduce complexities stemming from material quality standards and tend to be quite expensive. Gas ionization and scintillation detectors can often be made much larger, but lack the energy resolution that semiconductors offer. This means these detectors are better suited to high efficiency counting than high precision energy measurements. Organic scintillators can also offer fast response, where the signal from a radiation interaction is measured within several nanoseconds, compared with HPGe where signals typically take hundreds of nanoseconds to be fully integrated. These factors, along with many others, dictate the best material to use for a given application. When energy resolution is the most important factor, HPGe offers the best resolution of the options described here.

1.1.2 Radiation Sources and Detector Application Areas

Both anthropogenic and naturally occurring radiation sources are ubiquitous. Characterization of a radiation source can be difficult, if not impossible, because sources vary in distribution, intensity, decay products, decay energy, and lifetime. Radiation detection systems have been developed that are able to analyze one or several of these quantities, though, unfortunately, not all can be measured simultaneously. There are particular applications that drive most of the detector development. Those applications and the radiation sources that they seek to characterize are presented here, with a special focus on high purity germanium (HPGe) as the detection material. This demonstrates the possible application spaces that exist for the technology presented in this dissertation.

Homeland Security

Within the field of homeland security, the radiation detection initiative is focused on the detection of radioactive or fissile materials that are being clandestinely transported or stored into, out of, or within the United States, as well as abroad. This definition allows for many interpretations of the nature of the smuggled material composition, form factor, shielding, and transportation mechanism. This has led to a wide array of advances in detector materials, signal readout mechanisms, novel detector configurations, and data analysis methods that have advanced the field of radiation detection, especially when applied to finding hidden sources. The sources of interest are special nuclear materials (SNM), assembled nuclear weapons containing SNM, and materials that could be used for or are assembled in a radiological dispersal device [10].

The SNM that pose a particular risk are highly enriched uranium (HEU) and weapons grade plutonium (WGPu). These are typically not highly radioactive and are easily shielded, limiting γ -ray and x-ray signatures that can be measured. To illustrate this point, a table of ^{235}U and ^{239}Pu properties are shown in Table 1.1.2. WGPu can be detected passively by either its γ -ray signature or neutron signature. WGPu has a 414 keV γ -ray and the spontaneous fission of ^{240}Pu produces sufficient neutrons for detection. HEU has a 186 keV γ -ray that is easily shielded and does not produce neutrons at an appreciable rate, making it difficult to detect by passive means [10].

The majority of current detection systems that are deployed in the field are simplistic in nature, are based on the plastic scintillator polyvinyltoluene (PVT), and provide only radiation count rate measurements with little energetic and no imaging information [10, 12]. With simple systems such as these and many commercial

Table 1.1: Properties of uranium 235 and plutonium 239 relevant to homeland security measurements [11]

Isotope	Property	Value
^{235}U	Half Life	700 MYr
	Specific Activity	2.2×10^{-6} Ci/g
	Decay Mode (%)	α (100)
	γ -rays of interest (I_γ (%))	185.7 keV (57.2)
		143.8 keV (10.96)
	Neutron Signature	Difficult to detect
^{239}Pu	Half Life	24,110 Yr
	Specific Activity	0.063 Ci/g
	Decay Mode (%)	α (100)
	γ -rays of interest (I_γ (%))	129.3 keV (0.63)
		375.1 keV (0.16)
		413.7 keV (0.15)
	Neutron Signature	Detectable (Spontaneous fission of ^{240}Pu)

products containing naturally occurring radioactive materials, there are many false alarms, which slow commerce. There are a number of passive [13] and active [14] technologies that would improve on the current deployed technology.

Passive detection methods that could reduce the rate of false alarms include deploying detection systems that provide energetic and/or imaging information [15]. The aversion to more advanced detectors stems from their cost and the fact that detectors with better energy resolution often sacrifice efficiency. It is for this reason that many research groups are working on detection systems that can provide more information than existing passive detection systems deployed in the U.S. [10], thus driving advances in radiation measurement systems.

Astrophysics

Astrophysics is the study of basic physics and cosmological entities by the observation of radiation signatures that reach earth's vicinity. Sensors can be ground based, with the most obvious example being visible light telescopes, but many sensors must be in the upper atmosphere or in space where radiation is uninhibited by atmospheric gases. The sensors that are relevant to this work are searching for γ -rays and x-rays emanating from active galactic nuclei, neutron stars, x-ray binaries, and the radioactive progeny of supernovae [16]. In the soft γ -ray regime (200 keV - 20 MeV),

where the Compton imaging technique is viable, it is necessary to maximize efficiency by using high Z detector materials or large volume detectors. In older Compton telescopes (e.g., COMPTEL [17]), this was achieved by using large volumes of liquid scintillator (in this case, NE 213A) as the scatterer and NaI(Tl), a higher Z and higher density material, as the absorber [17]. This setup enhances the probability of γ -rays scattering at least once in the scattering plane, then undergoing photoelectric absorption in the absorber plane. When this sequence of events occurs, it is possible to reconstruct the original γ -ray energy and to extract the direction from which it originated.

Since COMPTEL's flight during the 1990s, there has been a push in the astrophysics community to reduce the size of these Compton imaging telescopes. There have been a number of different implementations of so-called "compact Compton telescopes," at least one of which was based on high purity germanium (HPGe): the Compton Spectrometer and Imager (COSI) [18, 16]. With advances in HPGe processing techniques and mechanical cooling systems, it has become advantageous to use HPGe as the detection material due to its high Z , excellent energy resolution, and the achievable position resolution. Germanium's high Z allows for smaller detector volumes needed to achieve the same efficiency, while the combination of fine position resolution and superior energy resolution reduce the necessary spacing between detectors for good image resolution.

Accelerator Instrumentation

The nuclear physics community utilizes many of the sensor technologies that exist today, several of which were originally developed as instrumentation for accelerator experiments. This field often has interesting requirements for detection systems that combine energy, spatial, and timing resolution, with the possible added complications of very high or very low count rate, high magnetic fields, charged and uncharged particles, and radiation damage to the detector or the electronics.

In high energy accelerator experiments, where charged particles are accelerated to near the speed of light in opposite directions and then set on a collision path, enormous detector arrays comprised of many detectors [19, 20, 21], made from different detector materials, surround the collision point and track the many particles that are produced in a collision. To reconstruct tracks made through the detectors by the particles created, it is crucial that the position, timing, and energy resolution of the detectors is excellent. HPGe is ill-suited to this application for several reasons: first, the production of HPGe detectors is expensive and these systems require many detectors; second, HPGe does not recover well from radiation damage to its crystal structure caused by energetic particles; third, HPGe has inadequate timing

resolution when using thick detectors; finally, the need to cool the detectors would be challenging in these large detector systems. Therefore, silicon or gas-based detectors are more often used since these materials provide better performance with these requirements.

Searches for and characterizations of isotopes that are super heavy or on the boundaries of stability examine short-lived nuclei produced in collisions of heavy ($Z > 1$) nuclei with other heavy nuclei. These experiments are designed to produce particular isotopes in fragmentation collisions or by forming compound nuclei, both of which have very low production rates. The nuclei being researched are separated from other nuclei by a series of bending magnets, where the production rate is measured by the incidence of measured particles that have been separated on a detector. The decays from these nuclei are also measured to infer the nuclear structure. HPGe detectors are often used for these γ -ray measurements because of their superior energy resolution and because they provide high efficiency due to large volume crystals and high γ -ray attenuation. Systems such as GAMMASPHERE and the Gamma Ray Energy Tracking Array (GRETA) (which is currently being fabricated at LBNL) employ arrays of HPGe detectors arranged to cover 4π radians around a beam line to measure correlated events, γ -ray polarization, and nuclear deformation [22, 23]. Another method that serves to measure correlated decays is to implant the nucleus directly into a segmented HPGe radiation detector [24]. This allows for the measurement of short-lived charged particle decays in addition to γ -ray measurements. Detector segmentation is important for correlating the ion implantation and subsequent decay in a high background environment. HPGe segmentation provides the position resolution necessary for these measurements in addition to excellent energy resolution. I will discuss segmentation methods for HPGe further in Section 2.3. These are not the only ways that HPGe detectors are used in nuclear physics, but give representative examples of the methods employed.

Medical Imaging

There are many different imaging modalities that offer different views into the human body: magnetic resonance imaging (MRI), x-ray computed tomography (CT), projection x-ray, single photon emission computed tomography (SPECT), positron emission tomography (PET), and many others [25]. The modalities relevant to this work are based on high energy photons – either x-rays or γ -rays. These photons are highly penetrating and offer two modes for imaging: emission and transmission. Emission-based imaging techniques rely on a molecular tracer designed to target particular tissues, marked with a radioactive atom. Imaging the γ -rays from this tracer shows the uptake and perfusion, from which metabolic functionality can be inferred.

Transmission imaging uses an external radiation source that maps attenuation by measuring the transmitted x-ray intensity through the human body. This modality is most useful for imaging bone structures, but can provide soft tissue contrast with the addition of contrast agents. Transmission imaging does not rely on measuring energetic information, and the detection methods are well established [25].

Emission imaging would benefit most from advanced radiation imaging detectors, where energetics and position resolution could provide better image reconstruction. This modality is subdivided into two techniques: SPECT employs radioactive nuclei that emit a single photon following what is typically a β -decay, whereas PET utilizes the positron from a β^+ -decay, which annihilates and produces two anti-parallel photons. All current clinical imaging systems utilize scintillation-type radiation detectors. These systems utilize small scintillator crystals and position sensitive visible light detectors to achieve position sensitivity [26]. This technology is limited in spatial resolution and energy resolution. Using a semiconductor system can improve detector spatial resolution and, therefore, image resolution and contrast. Superior energy resolution can also provide the means to reduce some of the noise sources caused by scattering, either in the patient or in the detector. There are a few examples of the application of semiconductor detectors to PET imaging. The SmartPET system uses two HPGe detectors with 3D position sensitivity to image small animals [27, 28, 29, 30], and was able to achieve millimeter resolution images. Cadmium zinc telluride (CZT) has also been investigated as a possible replacement for scintillators in PET imaging and can also provide 3D position sensitivity and enhanced energy resolution over scintillation detectors, while operating at room temperature [31, 32].

Environmental Remediation

The field of environmental remediation refers to extended distributions of radioactive contamination that must be characterized in order to facilitate decontamination. Situations such as the accidents at the Chernobyl Nuclear Power Plant or the Fukushima Daiichi Nuclear Power Plant resulted in widespread contamination that led to the evacuation of tens of thousands of civilians and required the work of many more to aid in decontamination. In Fukushima, decontamination work includes the removal of tens of thousands of cubic meters of topsoil that is contaminated primarily with ^{137}Cs . The removal of the topsoil is performed with dose rate meters, which only maps the dose rate at one position and cannot provide imaging information or specific contamination distributions, likely because the time and manpower needed for surveying all of the land is impractical with current methods. This results in the removal of much more material than may be necessary.

With the additional information that can be garnered from more advanced semi-

conductor detector imaging devices, decontamination can be restricted to the areas in which it is required. Radiation imaging maps contamination (sometimes in 3D [15]), and, combined with energy information, can map radiation by isotope. Several systems have been used for environmental remediation purposes [33, 15] and have shown promising results in assisting with the mapping of contamination. These systems use CZT detectors because they can be operated at room temperature, but with advancements in hand portable cryogenic coolers, HPGe imagers are being used in hand portable technologies as well [34].

Chapter 2

Background

The concepts necessary for understanding both semiconductor radiation detectors and the charge readout method described in this dissertation require the discussion of background material to fully understand the method. The first topics are the interactions of radiation with matter. Then, I will present the physics governing semiconductors and semiconductor detectors. Next, I introduce the operating theory of proximity charge sensing; this chapter concludes with an overview of some of the research completed in this field prior to our work.

2.1 Interactions of Radiation with Matter

To motivate the use of ionizing radiation detectors, the interactions of ionizing radiation with matter must be understood. Ionizing radiation can be split into three groups: photons, charged particles, and uncharged particles. These particle types undergo different interactions with matter that are governed by numerous physical properties. Photons, specifically x-rays and γ -rays, are of particular interest for this work. I will present a brief introduction of the interactions of these different radiation types here.

2.1.1 γ -Ray and X-Ray Interactions

Photons originating from an excited nucleus making a transition to a lower energy state are considered γ -rays. The term x-ray, colloquially, encompasses many other sources of high energy photons, including characteristic x-rays emanating from electronic transitions, Bremsstrahlung (or “braking”) radiation emitted by decelerating charged particles, and synchrotron radiation, produced by electron beams bending

into a circular orbit by a magnetic field. Regardless of the source, γ -rays and x-rays typically have energies ranging from the keV range to the low MeV range. The interactions of photons in this energy range are photoelectric absorption, Compton scattering, and pair production.

Photoelectric absorption is the transfer of the entire photon energy to an electron. The energy is converted into electron kinetic energy, minus the binding energy of the electron. This process is dominant at lower photon energies, below ~ 100 keV. Above 100 keV, Compton scattering dominates. Compton scattering is the interaction of the photon with an electron resulting in partial energy transfer from the photon to the electron and a change in the direction of the scattered photon. The exiting photon will have a new energy, equal to the difference between the original photon energy and the exiting electron's kinetic energy. The electron binding energy can be ignored because it is several orders of magnitude lower than the energies of the photon or the scattered electron. The photon can scatter at any angle, with the probability that it will scatter at that angle given by the Klein-Nishina formula [35]. At energies above 1022 keV, the pair production process is possible. Pair production is the transformation of the photon into an electron-positron pair. Any additional energy above 1022 keV will be split between the electron and positron as kinetic energy. The electron will slow and eventually be captured by an atom, while the positron will slow, capture an electron (creating positronium) and eventually annihilate, releasing two 511 keV γ -rays. A final photon interaction exists called coherent scattering, but no energy transfer occurs with the material with which the photon interacts. This type of interaction is not of interest for this work because we rely on ionization to measure radiation.

Photons are attenuated in matter exponentially according to the attenuation coefficient, which is dependent on the energy of photon, and the density of the material. The dependence of photon intensity on the distance traveled in a material is given by Equation 2.1. In this equation, $I(x)$ is the intensity at depth x , I_0 is the intensity entering the material, μ is the attenuation coefficient, and x is the distance traveled in the material. See Figure 2.1 for the germanium mass attenuation coefficient as a function of energy. This is crucial knowledge in considering the efficiency of a detector. This equation says that the larger the detector is, the more photons it will detect. It also says that if the detector material is highly attenuating, fewer photons will pass through the detector, leading to higher detector efficiency.

$$\frac{I(x)}{I_0} = e^{-\mu x} \quad (2.1)$$

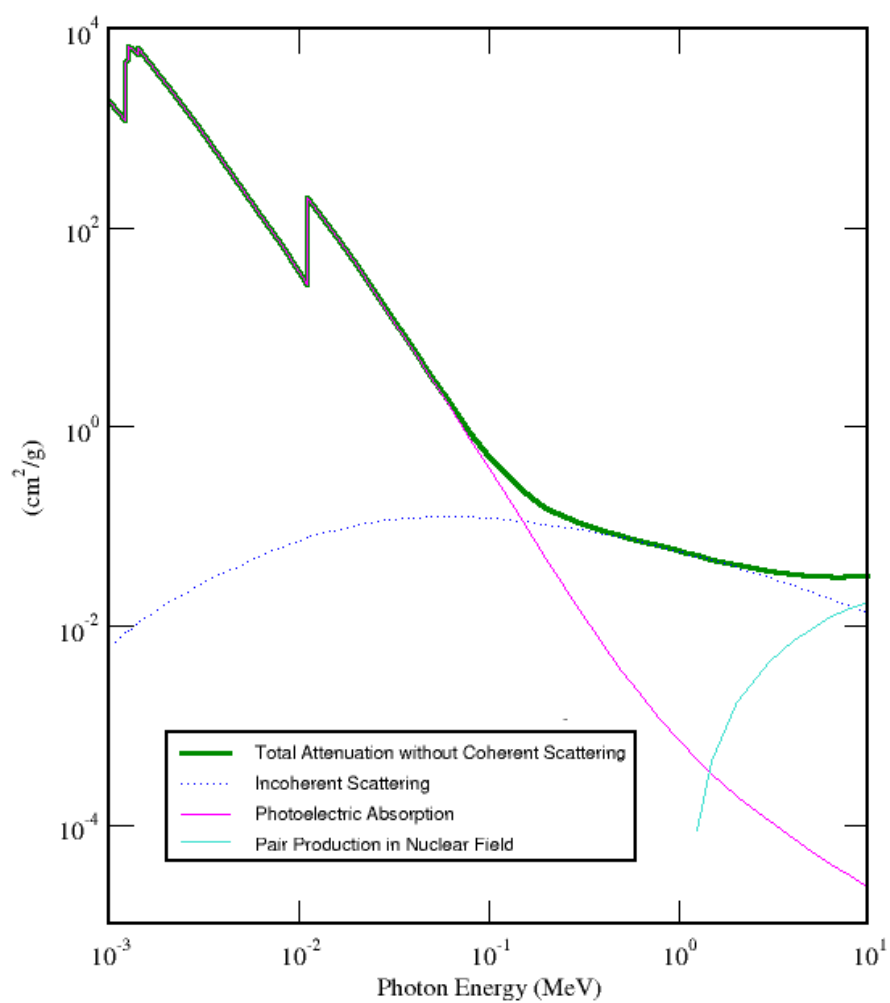


Figure 2.1: Germanium photon attenuation. The peaks at 1.2 keV and 11 keV correspond to electron energy shells. [36]

Because the photon interactions of interest are electronic¹, the electron density of a material will have the largest affect on its attenuation coefficient. This means that higher atomic number (Z) and higher density materials will have larger attenuation coefficients. For this reason, high Z and high density detector materials are desirable to increase efficiency.

2.1.2 Charged Particle Interactions

The interactions of charged particles with matter fall into two categories: nuclear interactions and electronic interactions. Nuclear interactions refer to scattering of the charged particle with the nucleus of an atom in the material. Electronic interactions refer to electron scattering in the material. Energetic heavy-charged particles, or ionized nuclei, generally follow a straight path due to collective Coulomb interactions with the material's electrons. Nuclear interactions generally do not contribute to the slowing of ions and do not contribute to detector signals. The energy deposition per unit length of an ion traveling in a material is peaked at the end of the track. This is called the Bragg peak. Ions will typically fully stop in most materials, depending on the ion energy and atomic number. Helium nuclei from alpha decays, for example, are easily stopped by a sheet of paper.

Energetic electrons interact individually with other electrons, and, because they are equal in mass, can scatter through large angles, leading to tortuous paths while the electron is slowing down. The overall range of electrons is generally larger than ions, but they still can often be stopped with a sheet of aluminum [35].

2.1.3 Neutron Interactions

Neutrons interact with matter via nuclear scattering or absorption. These events can lead to ionization, but the amount of ionization is not always proportional to the energy transferred in the interaction because absorption or nuclear excitation may occur, reducing the recoil energy. Variable electronic signals can make neutron sources difficult to characterize. Nuclear recoil can also cause damage in structured materials, which can be detrimental to detector performance. This is particularly true for the detectors presented in this dissertation. It is for this reason that neutrons are not of interest for this technology.

¹There exist photon interactions with nuclei, but these are outside the scope of this dissertation.

2.2 Semiconductor Radiation Detectors

Radiation detector systems comprise a radiation absorber and an electronic signal measurement system. The absorber converts ionizing radiation into information carriers. Two common absorber material types are scintillators and semiconductors. Scintillation detectors convert ionization electrons into visible light, which is then converted into an electronic signal by a photomultiplier tube. Semiconductors measure the ionization signal directly. With both types of materials, the electrical signal from the detector is typically integrated using a charge sensitive preamplifier. This integrated charge is proportional to the energy deposited by the ionizing radiation interaction. The specifics of charge generation and measurement for semiconductor materials will be presented in this section.

2.2.1 Basic Operation of a Semiconductor Detector

The most simple semiconductor detector structure is a volume of semiconducting material with two flat, parallel faces and readout electrodes on the two opposing sides, which I will refer to as a basic planar geometry. Ionizing radiation events such as those outlined above will create electron-hole pairs that are mobile in the material. A hole represents the absence of an electron where one could exist in the atomic lattice, with a net positive charge, and moves as if it were a positively charged electron. The electrons and holes occupy the same space when created, and therefore the system has no net charge. To separate the charges, an electric field is applied across the semiconductor by biasing the attached electrodes relative to each other. The electrons will move towards the positive electrode and the holes will move towards the negative electrode in opposing directions.

As the charge moves, the field created by the charges changes, and field lines increasingly terminate at the electrodes. This process induces charge on the electrodes, which can be measured by an external circuit. A charge-sensitive preamplifier, represented by the ammeter in Figures 2.2 through 2.4, measures the amount of charge, Q , that is induced on the lower electrode. The measured charge is proportional to the energy of the interaction, which is given by $E = h\nu$ in this example. In this equation, h is Planck's constant, and ν is the frequency of the photon.

2.2.2 Semiconductor Physics

The concept of allowed electron energy bands is useful for classifying materials based on electrical conduction behavior. As atoms are brought close together in an organized structure, the discrete allowed energy levels of the isolated atoms become

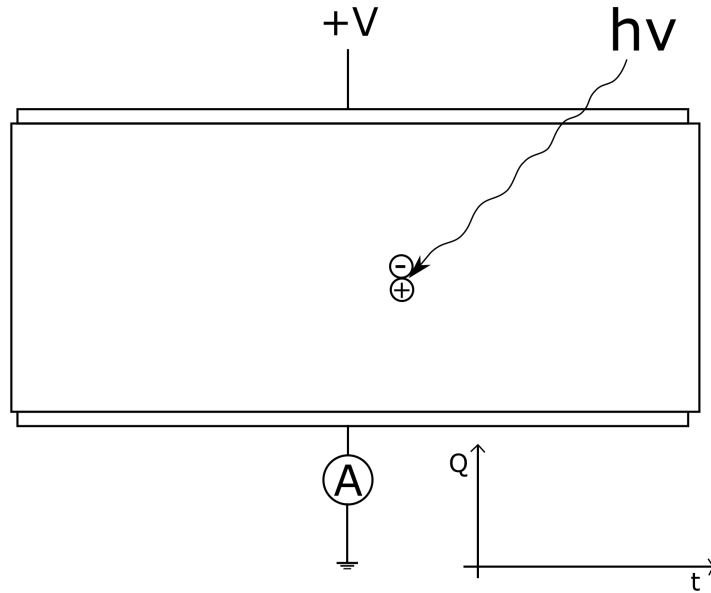


Figure 2.2: Basic planar semiconductor detector showing photoelectric absorption of a photon with energy $h\nu$. The electrons and holes occupy the same space, resulting in no net charge as perceived by the electrodes.

bands of allowed energy levels separated by energy regions disallowed for electron occupation. If states exist in an allowed energy band that are unoccupied, this band can conduct current. At temperatures above absolute zero, a large number of electrons are then free to move throughout the material. If an allowed energy band is completely filled, there are no allowed states into which a given electron can move; this band is not available for conduction. The structure of these bands defines a material's electron conduction properties.

If an allowed energy band is filled with electrons and the next allowed energy band is at a significantly higher energy ($\Delta E > 5.5eV$, generally), the material is considered to be an insulator. For bound electrons to be freed, the electron would have to gain an amount of energy greater than the energy band gap. This energy band gap is not easily overcome by room temperature thermal energy, and, therefore the material generally does not conduct. As previously described, electrons may freely move in materials with an energy band that is only partially filled. These materials are conductors. Semiconductors occupy a space between conductors and insulators.

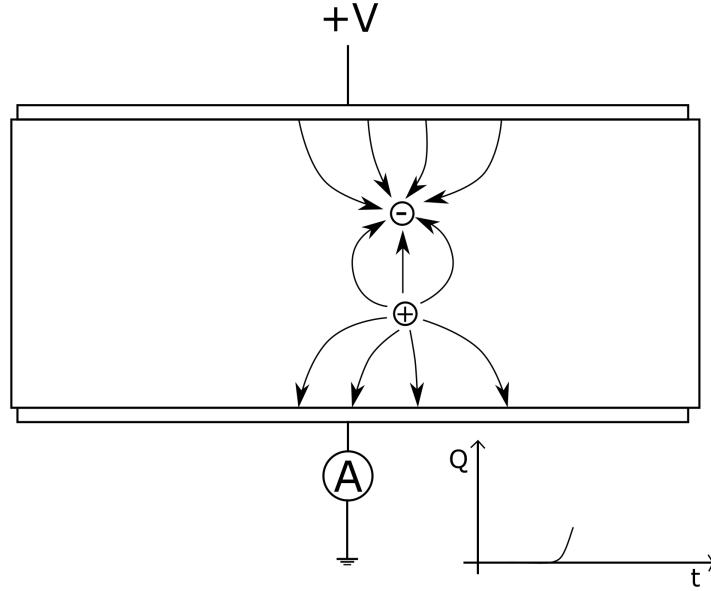


Figure 2.3: Basic planar semiconductor detector after the electrons and holes have been separated by the applied voltage. At this stage, some of the field lines emanating from each of the charges will terminate on the readout electrodes and some charge is induced, as indicated in the plot at bottom.

Semiconductors have a fully occupied energy band with a disallowed band directly above it, as an insulator does. However, the next allowed band creates a band gap that is small enough to allow a significant number of electrons to be thermally excited into the higher band at room temperature ($\Delta E < 5.5\text{eV}$). With this band structure, this material will be a perfect insulator at absolute zero, with the lower energy band fully occupied and no electrons in the upper allowed band. At temperatures above absolute zero, some electrons will have enough energy to overcome the band gap energy and will be free to move in the upper allowed band. The space left by these electrons in the lower allowed band can also be used for conduction by close range motion of electrons into the unoccupied states. This is referred to as a hole. Conventionally, the lower allowed energy band is referred to as the valence band; the upper allowed band is referred to as the conduction band [37].

Because electrons are fermions, they are governed by the Fermi-Dirac equation, given in Equation 2.2 [38]. This equation gives the probability that an electron occupies a certain energy, where E is the electron energy, E_F is the Fermi level, k_B

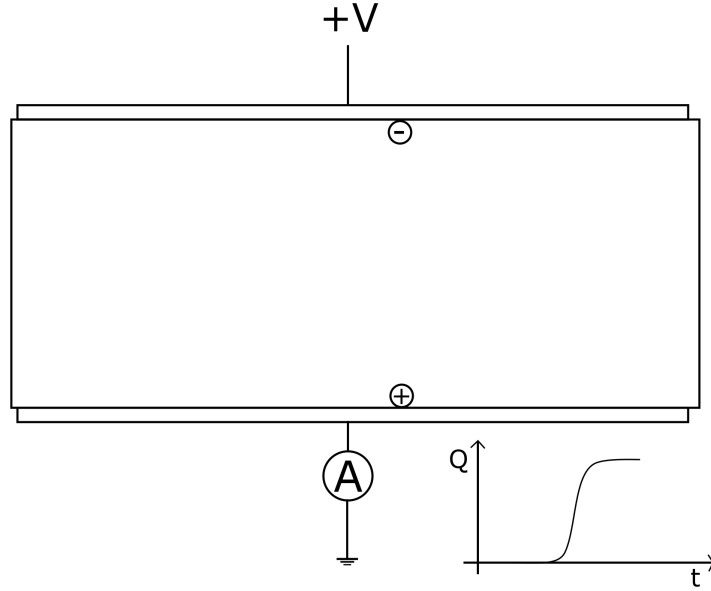


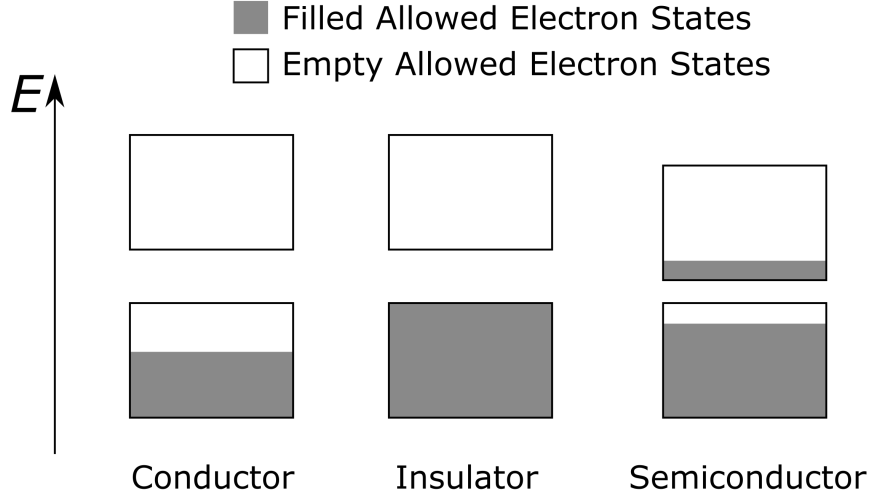
Figure 2.4: Basic planar semiconductor detector after full charge collection. The charges have reached the electrodes on either side of the detector; the full charge that was liberated has been induced on both electrodes and measured on the lower electrode.

is Boltzmann's constant, and T is the temperature. The Fermi level is defined as the energy at which the probability of an electron occupying an allowed state drops to 0.5, as a function of energy. This equation does not give the electron population, however, because it does not take into account allowed and disallowed states and how many states exist in allowed bands. Therefore, the electron population in a semiconductor is given by the integral of the Fermi function multiplied by the density of states. Similarly, the probability of a hole occupying an energy E is given by Equation 2.3; the hole population is given by the integral of the density of states multiplied by the Fermi function for holes. Note that decreasing electron energy is equivalent to increasing hole energy.

$$f_e(E) = \frac{1}{e^{(E-E_F)/k_B T} + 1} \quad (2.2)$$

$$f_h(E) = 1 - f_e(E) = \frac{1}{e^{(E_F-E)/k_B T} + 1} \quad (2.3)$$

Figure 2.5: Energy band diagrams for metals, semiconductors, and insulators.



Electrons in a material move with an effective mass that is dictated by the wave nature of the electron and the periodic nature of the atoms in a crystal. This mass, m_e , is an important quantity for calculating the electron populations in semiconductor materials. Holes have a similar effective mass, m_h . The Fermi level of a semiconductor is given by Equation 2.4 [39]. In this equation, E_g is the band gap energy, k_B is Boltzmann's constant, and T is the material temperature. This equation applies for semiconductor materials without impurities, which are referred to as intrinsic semiconductors.

$$E_F = \frac{E_g}{2} + \frac{3}{4}k_B T \ln \frac{m_h}{m_e} \quad (2.4)$$

When impurities are added to a semiconductor material, they can drastically affect the conduction properties. The impurity addition process is referred to as doping. For example, an impurity atom that bonds pentavalently would substitute a Ge atom in crystalline germanium, which forms a diamond lattice structure (each atom forming covalent bonds tetrahedrally), leaving one extra electron bound to the impurity. An example of such an impurity atom is arsenic. The energy level of this impurity falls within the band gap of the semiconductor at a level above mid-gap. At temperatures above absolute zero, this atom can be ionized and its electron promoted to the conduction band, leaving a positively charged impurity atom core behind. For this reason, this type of impurity is known as a donor impurity. When many

donor impurities exist, the conductivity of the semiconductor increases at non-zero temperatures because the amount of energy needed to promote the donor electrons to the conduction band is smaller than the band gap of the semiconductor. Because the generation of these conduction electrons does not require the equal generation of valence band holes, there are more free electrons than there are free holes. A material with donor impurities is referred to as n-type. We refer to the electrons in this case as the majority carriers. Because there are more free electrons than holes, the effective Fermi level has been shifted up towards the conduction band.

When impurity atoms bond trivalently, a bond is left unsatisfied, and an electron can move up in energy from the valence band to satisfy this bond. This is equivalent to the impurity atom possessing an extra hole that, with sufficient energy, can be promoted to the valence band where it is free to move through the material, leaving a negatively charged impurity atom core. This type of impurity is called an acceptor impurity. The introduction of these impurities into a semiconductor leads to a p-type material, where holes are the majority carriers. The effective Fermi level, in this case, is shifted down from mid-gap towards the valence band.

The number of free electrons and holes in a given semiconductor material at temperature T are given by Equations 2.5 and 2.6, respectively. In these equations, m_e and m_h are the electron and hole effective masses, respectively, k_B is Boltzmann's constant, T is the temperature, h is Planck's constant, E_F is the Fermi energy, and E_g is the band gap energy. Multiplying these two quantities together yields the intrinsic carrier density squared, which tells us that an increase in one free carrier reduces the number of the other, as can be seen in Equation 2.7. This is referred to as the mass action law.

$$n = 2 \left(\frac{2\pi m_e k_B T}{h^2} \right)^{3/2} \exp \left(- \frac{E_g - E_F}{k_B T} \right) \quad (2.5)$$

$$p = 2 \left(\frac{2\pi m_h k_B T}{h^2} \right)^{3/2} \exp \left(- \frac{E_F}{k_B T} \right) \quad (2.6)$$

$$n_i^2 = np \quad (2.7)$$

In an intrinsic semiconductor, energy added to the material by an outside source such as radiation will promote a number of electrons from the valence band to the conduction band, leaving an equivalent number of holes in the valence band. The number of charge carrier pairs that are produced is loosely tied to the band gap of the material, E_g . The average energy needed to produce an electron-hole pair, E_i , is a measured quantity and is always greater than E_g . The average ionization energy is plotted for a number of materials in Figure 2.6. This quantity is not dependent on

the type of radiation, making semiconductors ideal for measuring radiation because, on average, the signal response is linear with deposited energy, i.e. $N = E/E_i$, where N is the number of carriers generated, and E is the deposited energy.

Without the application of an external field, the carriers generated by a radiation interaction will subsequently recombine. We can separate the electrons and holes by the application of a voltage differential to external electrodes, as presented in the previous section. The motion of these carriers is governed by the electric field, $\vec{E}$, in the material and the mobility, μ , of that carrier in the material. The electron mobility and hole mobility are not typically equal. The mobilities are dictated by three different scattering mechanisms: phonon scattering, electrically active impurity scattering, and electrically neutral impurity scattering [39]. The specifics of these scattering mechanisms are outside the scope of this dissertation.

$$\vec{v} = \mu \vec{E} \quad (2.8)$$

Carriers may undergo recombination with each other, impurity atoms, or crystal defects while they are in motion. These impurities are called trapping sites. Shallow dopant impurity traps are impurities with energies close to the conduction band for electrons and close to the valence band for holes. Deep level traps refer to dopant impurities that have energies close to mid-gap. Trapping may be followed by de-trapping, in which the carrier is promoted back to being a free carrier. This is much more likely in shallow traps. The exponential time constant that dictates the return of a free carrier to steady state, τ , is inversely proportional to the density of empty traps [39].

The carrier mobility, μ , and the carrier lifetime, τ , both indicate the charge transport quality of a material. High mobility with long lifetimes means a carrier can travel long distances before recombining. The product of these two quantities is often used as a measure of material quality, and is referred to as the $\mu\tau$ (“mu-tau”) product.

2.2.3 Semiconductor Device Physics

Semiconductor device physics refers to the physical properties of junctions between semiconductors and other materials, including other semiconductors. A discussion of some of these semiconductor junctions is crucial for understanding the current semiconductor radiation detector technologies.

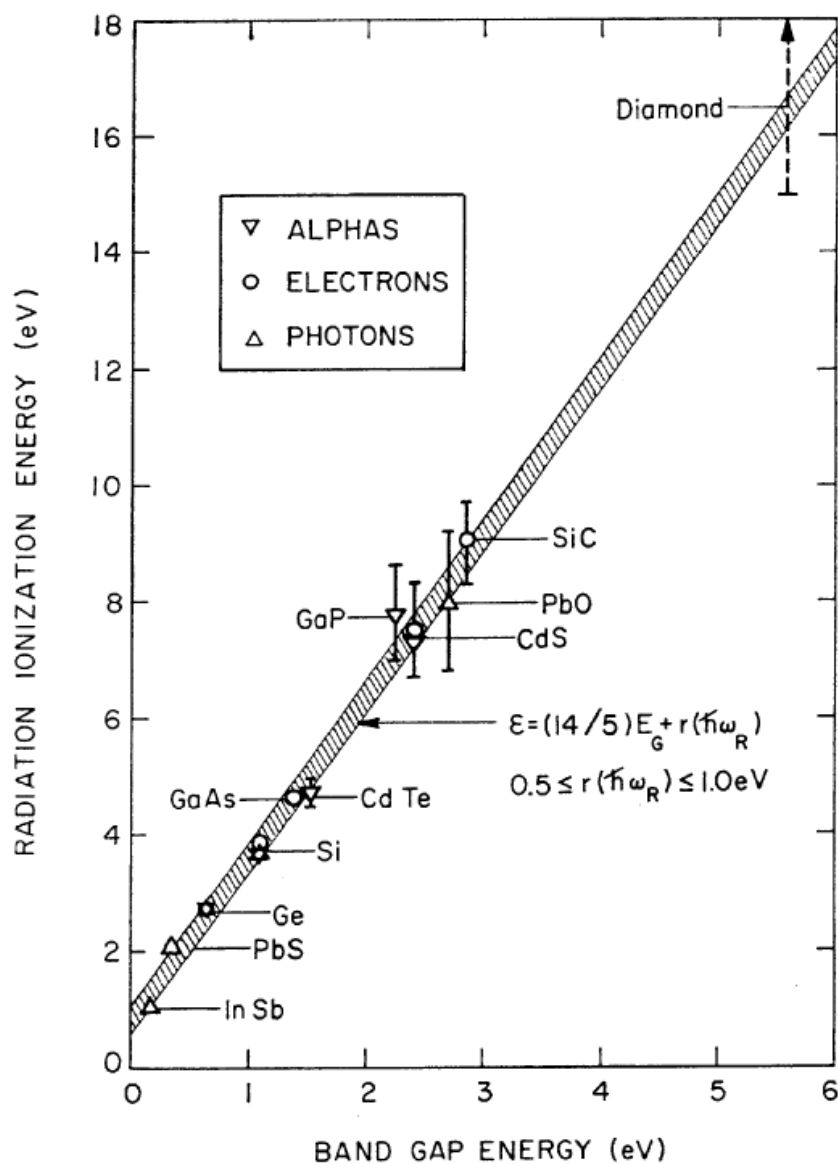


Figure 2.6: The average ionization energy, plotted as a function of the band gap energy, for a number of semiconductor materials [40]

Table 2.1: Properties of semiconductor materials often used for radiation detectors. The quantities quoted are given at $T = 300K$ for Si and CdZnTe and $T = 77K$ for HPGe. The units of $\mu\tau$ are cm^2/V [41].

	Ge	Si	CdZnTe
$\langle Z \rangle$	32	14	49.1
$\rho(\frac{g}{cm^3})$	5.33	2.33	5.78
$E_g(eV)$	0.67	1.12	1.572
$E_i(eV)$	2.96	3.6	4.64
$(\mu\tau)_e$	>1	>1	$4 \cdot 10^{-3}$
$(\mu\tau)_h$	>1	>1	$1.2 \cdot 10^{-4}$

Metal-Semiconductor Junctions

Semiconductor junctions can be understood using energy band diagrams. A metal, having a very high free carrier density, can be represented as shown on the left in Figures 2.7 and 2.8. The work function, $q\Phi_M$, of the metal sets the Fermi level, E_F , with respect to the vacuum level, E_0 . To the right of the metal band structure is the semiconductor band structure. The semiconductor work function, $q\Phi_S$, sets the semiconductor Fermi level, E_F , with respect to the vacuum level. The semiconductor electron affinity, $q\chi$, sets the conduction band level, E_C . The band gap of the semiconductor, $E_g = E_C - E_V$, sets the valence band level with respect to the conduction band level. This figure is representative of the two materials when not in electrical contact with one another.

Electrically connecting the materials allows for the flow of electrons between them. In the example given, the electrons will flow from the semiconductor into the metal to reduce their energy. The flow of free electrons into the metal results in the depletion of free electrons from the semiconductor near the interface. These electrons leave behind positively charged donor atoms, which have density N_d (this assumes an n-type semiconductor). This process will continue until the system reaches thermal equilibrium. The thermal equilibrium state is shown in Figure 2.8. In thermal equilibrium, the Fermi levels of the materials must be equal. The space charge in the semiconductor results in band bending to a depth equal to the depletion depth, where there are no free electrons. The total charge on either side of the junction must be equal, and the extent of the charge in the x direction is given by the impurity density, N_d , on the semiconductor side, and the density of states on the metal side. The metal density of states is assumed infinite in the ideal metal-semiconductor junction, so the charge is contained in an infinitesimally thick sheet at the surface

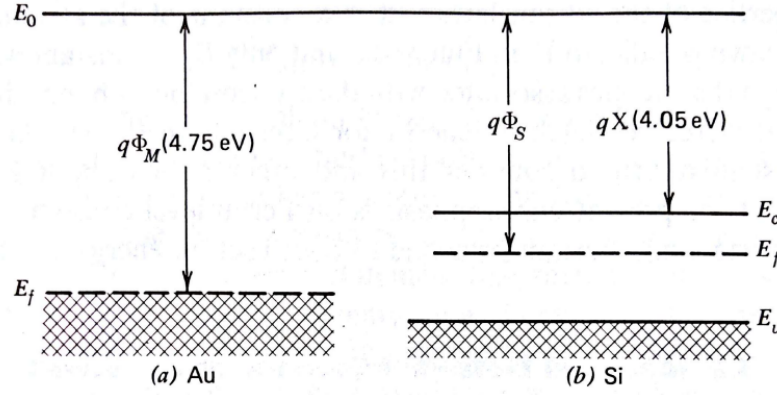


Figure 2.7: Metal (left, Au) and semiconductor (right, Si) band structures at thermal equilibrium when electrically separated. Labeled in the figure are the metal work function ($q\Phi_M$), the semiconductor work function ($q\phi_S$) and the semiconductor electron affinity ($q\chi$) [42].

of the metal. The field in the semiconductor is maximal at the interface and falls linearly out to the depletion depth, x_d [42].

If a voltage is applied across this junction with the semiconductor net positive bias with respect to the metal, a current will flow that is exponentially dependent on the applied voltage. Conversely, a negative bias will result only in a small, constant current that is dependent on temperature and the barrier to electron entry into the semiconductor, ϕ_b .

The quantity of interest for semiconductor radiation detectors is the barrier to electron movement into the semiconductor, $q\phi_b^-$. For lower work function metals (i.e. $\Phi_M < \Phi_S$) in a metal-semiconductor junction, a barrier to hole injection into the semiconductor can be established. These barriers are typically referred to as the electron and hole barrier heights. Metal-semiconductor junctions that exhibit this rectifying behavior are referred to as Schottky contacts.

If electrons are allowed to flow freely from the metal into the semiconductor, measuring the small amounts of charge liberated in ionizing radiation events would be nearly impossible. Therefore, larger barriers to charge injection into the semiconductor result in more accurate measurements in semiconductor detectors. The charge injected into the semiconductor from a contact is one of many factors affecting noise in a detector system, and must therefore be minimized.

Schottky contacts are used in semiconductor detector systems, however a phe-

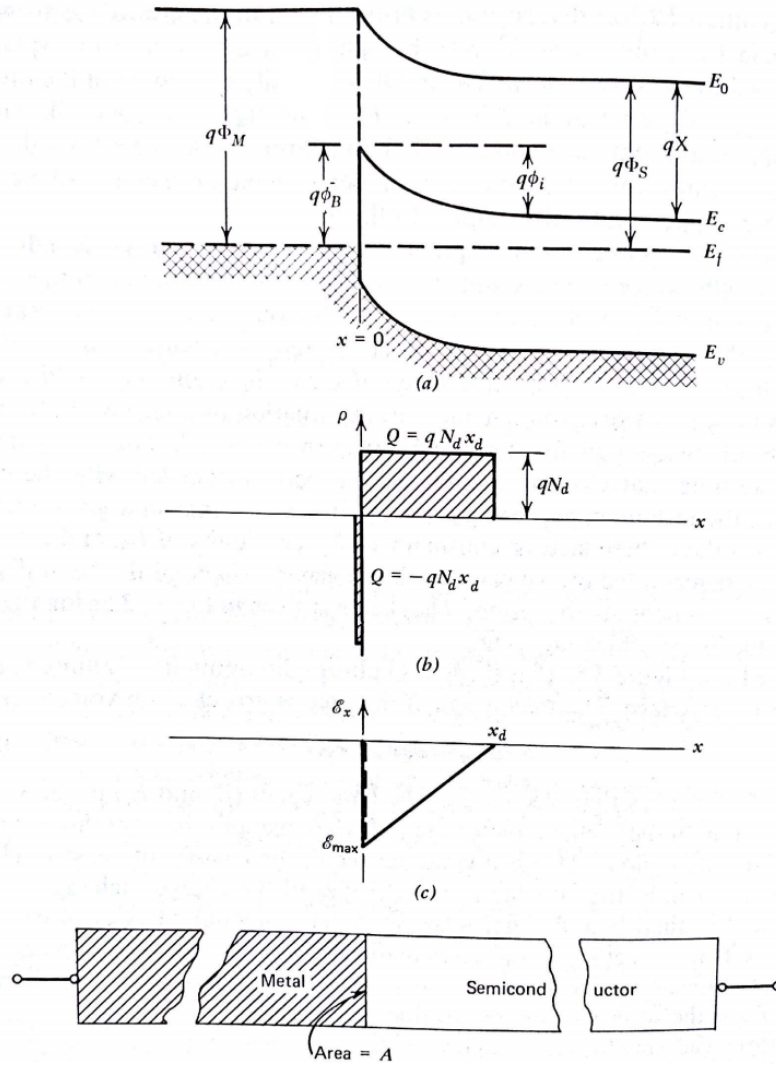


Figure 2.8: Metal (left) and semiconductor (right) band structures at thermal equilibrium when electrically connected. (a) shows the band structures of the materials, (b) shows the charge distribution at the junction, (c) shows the electric field at the junction, and at the bottom is a schematic of the junction materials in contact [42].

nomenon known as Fermi level pinning results in a larger electron barrier and a smaller hole barrier for most metals on Ge, regardless of the metal work function [43]. For this reason, Schottky barriers are not typically used as hole blocking contacts on Ge detectors.

Impurity Contacts

By adding impurities to a semiconductor, we can change the free carrier concentrations, as just shown in Section 2.2.2. With this in mind, consider an n-type semiconductor. By the mass action law (Eq. 2.7), if the concentration of free electrons is large compared with the intrinsic carrier concentration, the number of free holes will be low. Therefore, if a semiconductor is doped with donor atoms such that the free electron concentration meets this criterion, the hole concentration available for conduction will be very low. Similarly, a p-type semiconductor will have very few electrons available for conduction.

If we create a junction between a p-type and an n-type semiconductor, several things will happen when they are electrically connected. First, there will be a sharp concentration gradient at the junction, which will lead to the diffusion of carriers across the junction. Specifically, holes will diffuse from the p-type material into the n-type material, and electrons will diffuse from the n-type material into the p-type material. This process will begin to deplete the regions near the junction of free carriers as we saw in the metal-semiconductor junction above. This leaves fixed charge on either side of the junction in the form of ionized impurity atoms. The fixed charge results in an electric field, pointing from the n-type material towards the p-type material, that exists in the region depleted of free carriers. The diffusion process continues until the diffusion current contribution and the charge drift current generated by the electric field are in equilibrium. In thermal equilibrium, the Fermi levels of the two materials are equal, and, far away from the junction, the materials remain unaltered. At the junction, there is a depletion region that extends into either side of the junction to a distance dictated by the impurity concentration. High impurity concentrations lead to small depletion regions, and low impurity concentrations lead to depletion regions that extend deep into the material. A built-in voltage is established once thermal equilibrium is reached. This voltage is given by the shift in the bands needed to reach equilibrium, $q\phi$. This junction is referred to as a p-n junction. The band structure is given in Figure 2.9 [44].

Applying a positive bias to the p-type side of the junction relative to the n-type side increases the depletion depth on both sides of the junction, and, for the ideal p-n junction, no current will flow. This bias applied puts the p-n junction in reverse bias. If the voltage is too high, the rectifying behavior can fail due to carrier tunneling

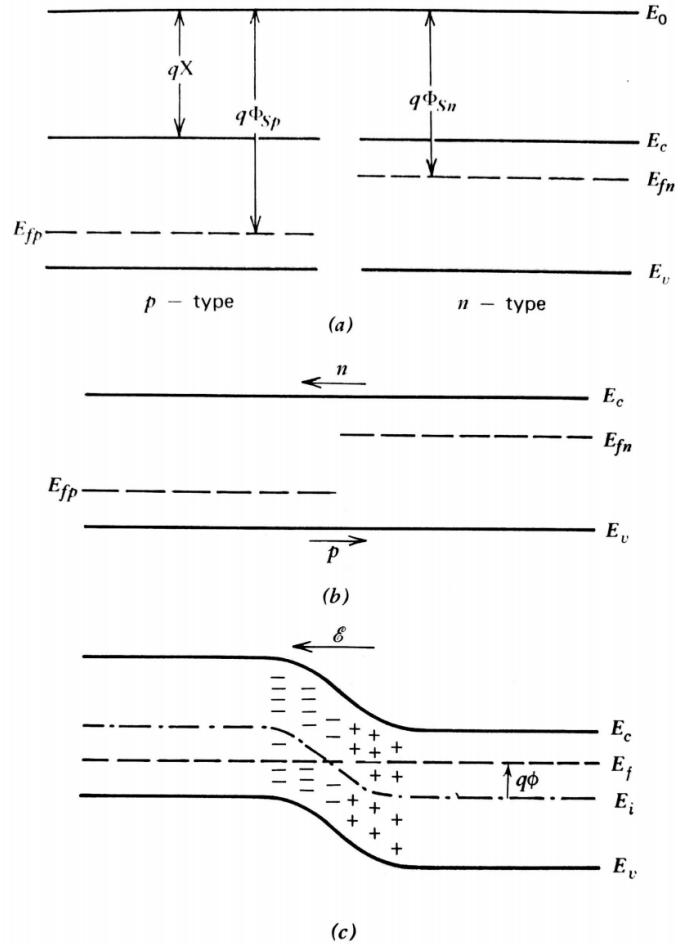


Figure 2.9: The energy band diagram of a p-n junction when: (a) electrically separated from each other, (b) first brought into contact, and (c) when in thermal equilibrium. When first brought into contact, diffusion dominates, and charges move as indicated in (b). At thermal equilibrium, carrier drift current and diffusion current contributions are equal, and the built in voltage is equal to $q\phi$ [44].

through the depletion region. If the bias applied to the p-type material is negative compared to the n-type material, the junction is in forward bias, and voltages above the built-in voltage will result in exponentially increasing current with voltage.

Considering a p-n junction in reverse bias, if a photon interacts with the material somewhere within the depletion region, free electron-hole pairs will be generated and quickly swept out of the depletion region by the electric field. This is the basic operating principle of a semiconductor radiation detector.

To increase the achievable depletion depths, an intrinsic material is inserted between the p-type and n-type materials. This structure is sometimes referred to as a p-i-n diode. The intrinsic material is easily depleted of free carriers, which allows for thick depletion regions and decreases the risk of tunneling breakdown. This is a common structure for Ge detector systems. The p-type and n-type regions are referred to as the blocking contacts and are often highly doped. A p-i-n diode in thermal equilibrium and under reverse bias is shown in Figure 2.10. This structure leads to very low carrier injection into the intrinsic material. The mass action law dictates that the heavily doped p-type material (p+) has very few free electrons. This means that, for electrons to reach the intrinsic material from this contact, they would need to diffuse from far away from the junction or be generated close to the junction by an external energy source.

Amorphous Semiconductor Contacts

Amorphous materials exhibit localized structure on the length scales of the inter-atomic distance, but lack an extended structure [45]. Materials of this nature will exhibit different electron energetics than a highly ordered structure with the same composition. N. Mott describes the conduction modes for amorphous materials by introducing a new conduction concept: variable range hopping near the Fermi level [46, 47]. In this mode, electrons occupy localized states with energies near the Fermi level. Thermal excitations allow for movement between these localized states, with resistivity generally proportional to $\exp(T^{-1/4})$, where T is the material temperature. Application of bias induces an overall drift of electrons, where the conductivity is influenced by the temperature and the density of states. In sputter-deposited amorphous germanium films, the density of states can be altered by adding hydrogen to the sputter gas mixture. The hydrogen atoms passivate dangling bonds in the amorphous structure, thereby removing states that would have been available for conduction. Overall, the important feature of these films with regards to semiconductor contacts is the conduction mechanism. Because conduction occurs near the Fermi level, these films can be treated somewhat like metals when forming a junction with crystalline semiconductors.

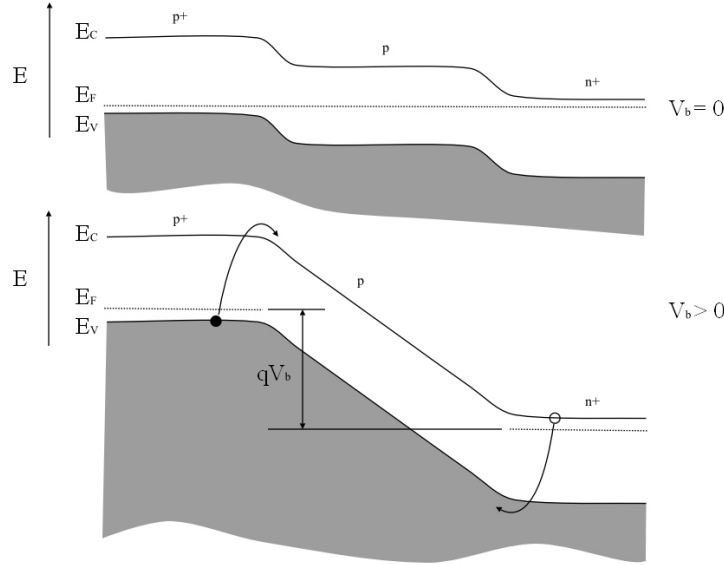


Figure 2.10: Energy band diagram of a p-i-n diode under thermal equilibrium (top) and under reverse bias, V_b (bottom). This is a common structure for Ge detectors. The Ge is highly pure, but low concentrations of impurities remain throughout crystal growth, rendering the material slightly p-type or n-type. Here, the Ge is slightly p-type. The highly doped contacts on either side lead to very low carrier injection.

Amorphous semiconductor films deposited on crystalline semiconductors form a junction that behaves in a similar fashion to Schottky contacts. This type of junction using amorphous and crystalline germanium was first investigated by Grigorovici et. al. [48]. The first use of this junction as an HPGGe detector contact was by Hansen and Haller [49]. Brodsky and Dohler had predicted several years prior to Hansen and Haller's experiments that these junctions would exhibit rectifying properties [50, 51]. They argued that, because of the conduction mode in amorphous semiconductors, the system could be treated similarly to a Schottky contact. Examining the band structure of this system shown in Figure 2.11 makes clear why this is the case. The conduction in amorphous semiconductors is similar enough to metals that it can be treated as such. The main distinguishing difference is band bending in the amorphous film. Due to a low density of states (when compared to a metal), the mirror charge that must exist to balance the fixed depletion charge in the semiconductor must

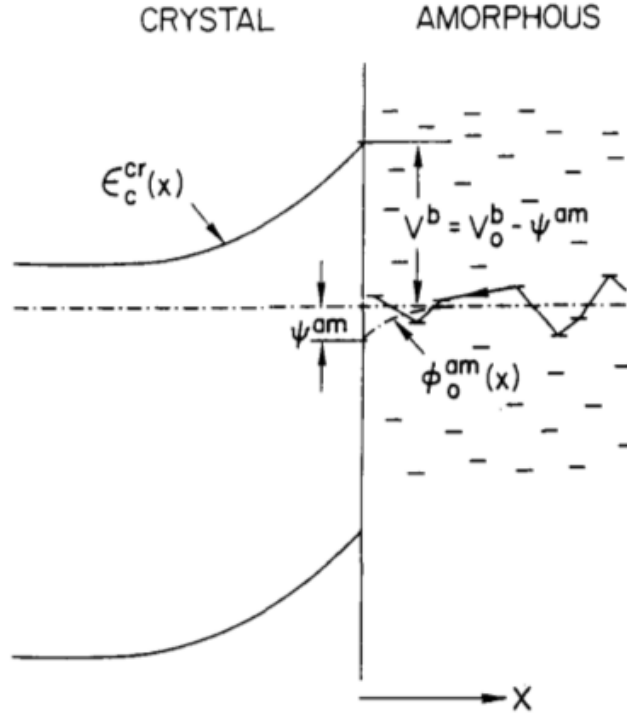


Figure 2.11: Junction between crystalline (left) and amorphous (right) semiconductors. This shows, schematically, the conduction mode in amorphous semiconductors and the barrier to charge injection in these type of junctions. The electron injection barrier, $V^b = V_0^b - \Psi^{am}$, is the standard Schottky barrier, V_0^b , defined as the difference between the effective work function of the amorphous semiconductor and the electron affinity of the crystalline semiconductor, minus the band bending in the amorphous semiconductor, Ψ^{am} , which is also known as the barrier lowering term. The amorphous semiconductor band bending is the result of the relatively low density of states in the amorphous semiconductor, leading to charge buildup that extends into the amorphous film. [50]

occupy states a certain depth into the film. This band bending results in an effective barrier lowering, resulting in increased leakage current into the crystalline material.

2.2.4 Charge Induction and the Weighting Potential

Charge transported through a semiconductor detector will induce charge on electrodes near the detector. Use of a quantity known as the weighting potential facilitates understanding of the charge induction process. The weighting potential is a mathematical construct that enables one to calculate, for an arbitrary geometry of electrodes and dielectric materials distributed in space, the amount of charge induced on an electrode by a charge in space. It was first described by Shockley [52] and Ramo [53] in their respective papers on the subject of moving charges in space as an alternative to more complex calculations using Gauss' law. The result of their efforts is a simple equation by which one can calculate the charge induced on an electrode of interest for a point charge at position $\vec{r}$.

$$Q_j = -q\phi_{0,j}(\vec{r}) \quad (2.9)$$

Then, for a charge moving in space, the change in induced charge is

$$\Delta Q_j = -q[\phi_{0,j}(\vec{r}) - \phi_{0,j}(\vec{r}_0)] \quad (2.10)$$

In these equations, Q_j is the induced charge on the designated electrode, j ; q is a point charge at position $\vec{r}$, and $\phi_{0,j}$ is the weighting potential for electrode j , as a function of position, $\vec{r}$. The term $\vec{r}_0$ refers to the initial charge position, whereas $\vec{r}$ is the position after charge motion. The weighting potential is calculated for each electrode individually, and is calculated by removing all space charge and then solving for the electric potential as a function of position after applying 1V to the electrode of interest and grounding all other electrodes. It is, by definition, bound by zero and one, and can be thought of as a fraction of the total charge that would be induced on an electrode for any point charge in space. This should not be confused with the physical electric potential that dictates charge motion in a detector. The weighting potential is a tool for the calculation of charge induction.

When a radiation interaction event occurs in a semiconductor, a cloud of electrons and holes are created and initially have no net charge because they occupy the same volume. The electric field present in the detector will separate these charges, and, as movement begins, charge induction on the detector readout electrodes will begin. Applying Eq. 2.10 to each charge cloud, the charge induction equation for an electrode becomes:

$$\Delta Q_j = -q_{h+}[\phi_{0,j}(\vec{r}_{h+}) - \phi_{0,j}(\vec{r}_{h+,0})] + q_{e-}[\phi_{0,j}(\vec{r}_{e-}) - \phi_{0,j}(\vec{r}_{e-,0})] \quad (2.11)$$

In this equation, the subscript 0 on the position vectors indicates the initial state of the system, directly after the radiation interaction. The subscripts $h+$ and $e-$

denote the quantities apply to the hole and electron clouds, respectively. We also assume all charge is contained in a point. Additionally, the quantities q_{e-} and q_{h+} must be equal to maintain conservation of charge.

$$q_{e-} = q_{h+} = q \quad (2.12)$$

The weighting potential is only dependent on position, and the electrons and holes must be generated at the same position, therefore:

$$\phi_{0,j}(\vec{r}_{e-,0}) = \phi_{0,j}(\vec{r}_{h+,0}) = \phi_{0,j}(\vec{r}_0) \quad (2.13)$$

Applying Eq. 2.12 and Eq. 2.13, the equation for induced charge becomes:

$$Q_j = q[\phi_{0,j}(\vec{r}_{e-}) - \phi_{0,j}(\vec{r}_{h+})] \quad (2.14)$$

This equation describes the amount of charge induced on electrode j by electron and hole clouds produced in an ionizing radiation event in a semiconductor material. The modifier Δ has been dropped because Equation 2.14 now describes the total amount of charge induced on electrode j by both electrons and holes and is applicable at the end of charge motion. This equation will hold true regardless of the path the charge takes, but becomes more complicated if the amount of charge is changing with time due to effects such as charge trapping. For HPGe, this is not typically a significant issue because charge transport is excellent in both polarities, and will be assumed to be perfect for the purposes of this work. This assumption will be carried through for all calculations.

2.2.5 Readout Electronics and Detector Noise

We have now covered the basics of charge generation and transport in semiconductors, as well as the charge induction on electrodes by moving charge. To measure this charge, a charge-sensitive preamplifier is connected to an electrode which integrates the charge as it is being induced on the electrode, converting the charge into a voltage signal. The charge-sensitive preamplifier can be modeled as an ideal amplifier with a capacitor tied between the input and output. In this configuration, any charge that is injected into the input will result in a voltage step on the output. If more charge is injected, a voltage step will again occur on the output, but this step will add with the previous step. This will continue until the voltage reaches the operating voltage of the amplifier, at which point it is saturated and no further charge can be measured. One way to address this is to implement a reset switch that quickly discharges the capacitor and returns the output to baseline. Another

method is to attach a resistor in parallel with the capacitor such that the capacitor can discharge with time constant RC , where R is the resistor's resistance and C is the capacitor capacitance. This is more commonly implemented than the reset switch and is referred to as a charge-sensitive preamplifier with resistive feedback. The resulting voltage signal from the preamplifier is a fast rise given by the charge transport in the detector, and a comparatively long decay given by the time constant of the RC circuit. The signal amplitude in Ge systems is typically of order 10-100 mV.

In analog radiation measurement systems, the preamplifier signal is routed to a filter that is typically referred to as a shaping amplifier. As the name suggests, this circuit serves to amplify the signal and filter the shape into a form suitable for amplitude measurement. Practical analog shaping is often done with a series of CR differentiators and RC integrators. The performance of different configurations is well documented [54].

The shaped pulse can then be used to measure the signal pulse height. In analog systems, this is performed by a multi-channel analyzer (MCA). The MCA converts the signal pulse height to a digital number that can be read by a computer, which gathers the digital pulse amplitudes of a large number of events and generates a histogram. This histogram is known as the energy spectrum.

An alternative to analog measurement systems is a digital system, which digitizes the preamplifier signal by sampling the voltage at a high rate (100s MHz), thereby creating a digital representation of the signal. Digital filtering methods such as the real time trapezoidal filter [55, 56] serve the function of the shaping amplifier, and the pulse height can be extracted from the shaped pulse. This configuration allows for the analysis of detector pulses that may have additional structure that is not distinguishable in the analog shaped pulses. This is broadly referred to as pulse shape analysis.

Electronic noise will limit the ability of a detector system to measure precisely or to be able to distinguish signal levels. As stated in Section 2.2.2, for a given interaction energy, E , the average ionization energy, E_i , dictates the number of liberated charge carriers, N , based on Equation 2.15.

$$N = E/E_i \quad (2.15)$$

This represents the mean number of charge carriers that are liberated based on a large sampling of measured signals. If the generation of each electron-hole pair were independent from all others, there would be no variance in the number of charge carriers generated from one event to the next. This is not what is observed in measurements due to multiple forms of excitation that can occur in a radiation

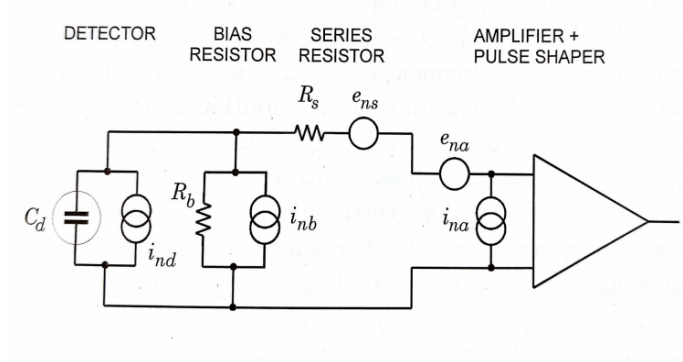


Figure 2.12: Equivalent circuit for noise analysis in the front end of a detector system [57].

detector material. In semiconductors, energy deposited by a radiation interaction can excite electron-hole pairs, but can also induce lattice vibrations known as phonons. This departure from Poisson generation is captured by the Fano factor, an adjustment to connect the observed to the predicted variance [6, 57]. The definition of the Fano factor can be found in Equation 2.16, and its effect on a material's energy resolution is presented in Equation 2.17.

$$F = \frac{\sigma_{N,observed}^2}{N} = \frac{\sigma_{N,observed}^2}{E/E_i} \quad (2.16)$$

$$\sigma_E = E_i \sqrt{FN} = E_i \sqrt{\frac{FE}{E_i}} = \sqrt{FEE_i} \quad (2.17)$$

Charge generation statistics set a lower bound on the achievable energy resolution based on the detector material shown. Other electronic noise sources will further obscure the signal. The noise sources can be modeled in an equivalent circuit that is shown in Figure 2.12.

Starting at the left, the detector noise contributions are modeled as the detector capacitance, C_d , in parallel with a current source, i_{nd} . The current source represents the contributions of “shot” noise, which includes any thermionic emission sources leading to current across the detector, I_d . This includes surface and bulk leakage current through the detector. The shot noise comprises independent processes, and therefore take on a power spectrum that is independent of frequency. Charge velocity fluctuations in resistive components result in noise as well, which is referred to as Johnson noise. Johnson noise from resistors shunting the detector input such as

the bias resistor, R_b , can be modeled as current noise sources, i_{nb} , in parallel with the detector. These noise sources are often referred to as current or parallel noise sources. Resistors in series with the detector output, R_s , represent all resistances that stand in the way of the signal. Examples include the contact resistance of the readout electrode and parasitic resistances along the signal line. This noise source can be modeled as a voltage source, e_{ns} , in series with the detector output. These noise sources are often referred to as voltage or series noise. The amplifier noise is modeled as a voltage source in series with the amplifier input, e_{na} , and a current source shunting the amplifier input, i_{na} . In addition to the noise sources presented, trapping and de-trapping processes in the detector, the resistors, and other dielectrics result in a power spectrum that is inversely proportional to the frequency, f . This noise source is often referred to as $1/f$ noise [57, 58].

Shot noise:

$$i_{nd}^2 = 2eI_d \quad (2.18)$$

Current noise:

$$i_{nb}^2 = \frac{4kT}{R_b} \quad (2.19)$$

Voltage noise:

$$e_{ns}^2 = 4kTR_s \quad (2.20)$$

$1/f$ noise:

$$e_{nf}^2 = \frac{A_f}{f} \quad (2.21)$$

In the equations above, k is the Boltzmann constant and T is the temperature. To assess the total contributions of these noise sources, they can be added in quadrature and represented as the equivalent noise charge, Q_n . To convert the voltage sources to charge, the detector capacitance is used.

$$Q_n^2 = \left(2eI_d + \frac{4kT}{R_b} + i_{na}^2\right)F_iT_S + (4kTR_s + e_{na}^2)F_v\frac{C_d^2}{T_S} + F_{vf}A_fC_d^2 \quad (2.22)$$

In this equation, F_i , F_v , and F_{vf} are factors dependent on the shape of the pulse. T_S is the characteristic shaping time of the shaping filter. Q_n takes on a shape that dictates the shaping time that should be used for measurements, where the equivalent noise charge is minimal. The curve, an example of which is shown in Figure 2.13, will vary for different detector geometries, electrode geometries, and the specific setup of

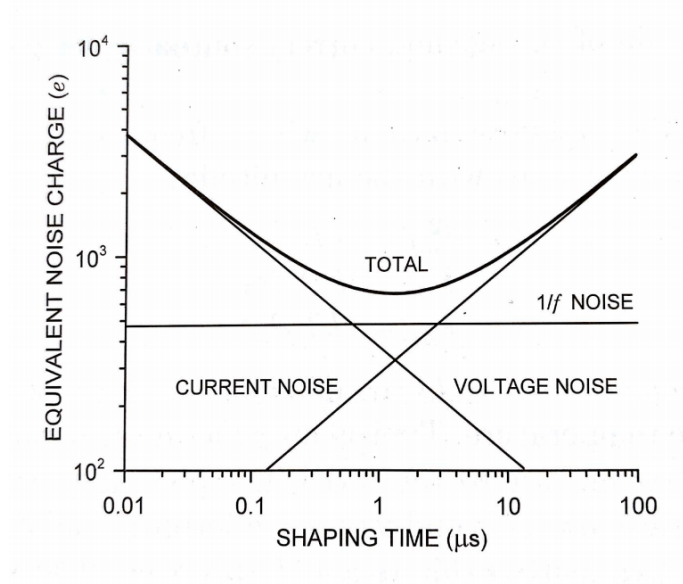


Figure 2.13: Example equivalent noise charge curve for a semiconductor detector system, as a function of the shaping time.

the readout electronics. This curve should be measured prior to making radiation measurements to ensure low noise operation.

The uncertainties in a signal height measurement from noise contributions (σ_{noise}) and from charge generation statistics (σ_{stats}), along with uncertainties associated with the radiation generation (σ_{source}) as well as any other uncertainties that may add to measurement uncertainty, add in quadrature to give the total measurement uncertainty, σ_E , as shown in Equation 2.23.

$$\sigma_E^2 = \sigma_{noise}^2 + \sigma_{stats}^2 + \sigma_{source}^2 + \dots \quad (2.23)$$

2.3 High Purity Germanium Detectors

Prior descriptions and equations in this dissertation have described the ideal state for semiconductors and semiconductor devices. In practice, there are complicating factors that will affect the operating characteristics, which are not ideal. One of the challenges alluded to previously is that semiconductor materials are difficult to purify. Insufficiently low impurity concentrations lead to materials that have small achievable depletion depths, even at high applied bias, and can lead to significant

trapping. One way to address this is to add impurities of the opposite type to a level that is equal to the original impurity concentration such that the material behaves as if it were intrinsic. This process is called compensating, and was the primary method for achieving appreciable depletion depths in the mid-1960s [9]. A Li drift process allowed for compensated Ge material usable as a radiation detector. These detectors were called Ge(Li) detectors. The complicated lithiation process left the material in a quasi-stable state that needed to be kept at cryogenic temperatures or the Li would diffuse such that perfect compensation was lost [59].

Methods were developed for purifying germanium, namely zone-refinement and the Czochralski crystal growth method [60, 61, 59, 62] that produced germanium with impurity concentrations on the order of 10^{10} cm^{-3} , several orders of magnitude better than the Ge used to produce Ge(Li) detectors. The low impurity concentrations meant thicker Ge volumes could be fully depleted of free carriers. The Ge materials made by this process are called high purity germanium (HPGe). HPGe has been the leading choice for high energy resolution radiation measurements since these processes were developed in the early 1970s.

The growth processes result in low impurity concentrations, which allow for thick detectors and reduce the effects of trapping, but these processes also produce large ingots with very few crystal defects [63]. These factors lead to excellent charge transport in HPGe. This is the main factor in dictating HPGe's excellent energy resolution. The relatively low band gap energy facilitates favorable charge carrier statistics, but also requires HPGe detectors to be operated at cryogenic temperatures to avoid high thermally generated currents and ensure low detector noise.

HPGe detectors can be fabricated using any of the three types of charge injection blocking contacts presented in Section 2.2.3. The choice of contact technology depends highly on the application for which the detector will be used.

The industry standard contact technology is the highly doped contact. The common dopants are boron for the p+ side, and lithium for the n+ side [64]. The B is introduced by ion implantation, which can be made very thin and is stable with time and temperature [65]. Li has high mobility in Ge, and is diffused into the Ge to achieve a contact surface. This results in a thick layer that is no longer active as detection material. Thick, inactive layers can shield low-energy radiation, which is often undesirable, depending on the detector application. However, HPGe detectors with doped contacts provide excellent noise performance due to low leakage current. For this reason, they remain the standard technology.

Schottky contacts are sometimes used as a substitute for p-type contacts, but, because of Fermi level pinning, are not suitable as hole blocking contacts. Because HPGe detectors can achieve very low measurement noise, the increased leakage that results from replacing the n-type contact is not acceptable for detector performance.

B-implanted, p+ contacts are thin and achieve very low carrier injection, therefore it is unnecessary to replace this contact type with a Schottky contact.

Amorphous semiconductor contacts on HPGe can produce low leakage currents in both polarities [66, 49]. The contacts are thin ($<1\mu\text{m}$), are simply deposited by sputtering or thermal evaporation, and can also serve the purposes of passivation and surface protection [64]. The common materials used for this type of contact on HPGe are germanium and silicon [67, 66]. This type of contact is commonly used, but research to fully characterize these films is ongoing.

2.4 Position Sensitive HPGe Detectors

Position sensitivity within a detector is desirable for radiation imaging, nuclear physics, and γ -ray astrophysics, as introduced in Section 1.1.2 [68]. This can be achieved in a monolithic HPGe detector by the segmentation of the readout contacts. Common, two-dimensional segmentation schemes for planar HPGe detectors include strip geometries in orthogonal orientations on two sides of a planar detector and square pixels on one side of a planar detector. More position information can be extracted from the shapes of the pulses on each electrode. Pulse shape analysis has been shown to provide depth of interaction [29]. Three dimensional position sensitivity is achievable by these methods.

While possible, contact segmentation is difficult for a Li-diffused contact due to the thickness of the contact [69, 70, 71], and the segmentation is limited to a pitch of approximately 1 mm [64]. Segmentation is readily done with B-implanted contacts, metal Schottky contacts, and amorphous semiconductor contacts [64]. Using amorphous semiconductor contacts for electrode segmentation simplifies the fabrication process. The amorphous film can be used for both polarities and as a surface passivant, and can therefore be deposited on all sides of a planar detector in two depositions [64]. Electrodes are deposited directly on top of the amorphous germanium by thermal evaporation, and the segmentation is often achieved by the use of a shadow mask [64]. Using this technique, electrode pitches on the order of 1 mm are achievable. Photolithography can provide much finer electrode pitches.

Position sensitive semiconductor systems are often limited in position resolution by the pitch of the readout electrodes. Single-sided pixel systems and double-sided strip systems define pixels within which an event position can be inferred to have occurred simply by using the physical extent of the electrode(s) that collected the charge and assuming the electric field lines are straight. Therefore, to achieve finer position resolution, it is necessary to reduce the strip pitch, but to instrument the same area, more electrodes must be fabricated and more signal readout channels

must be used. This can be expensive, has high power consumption, and may add complication in design and fabrication [72].

While it is possible to achieve fine electrode pitch on HPGe, the challenge then becomes making connections to each of the electrodes [72]. Each electrode must be connected to a preamplifier and shaping amplifier or digitizing circuits, which can add up to hundreds of channels from a single side of the detector. Connections to readout electrodes can be achieved through spring-loaded pins, wire bonding, or bump bonding processes; however, complications arise with each method. Because it is typical to connect to the active area of an HPGe detector, damage to the electrodes or the crystal itself can render the detector inoperable. The spring-loaded pin approach, in which board mounted pins are simply pressed down onto the detector electrodes, has the potential to cause damage, and is limited to coarse electrode spacing [72]. Wire bonding uses fine wires that are ultrasonically welded to thicker bonding pads on the electrodes and is commonly used for strip-based electrode readout, but is ill-suited to pixelated systems and requires extreme care to avoid damaging the detector. Bump bonding uses soft metals that are pre-fabricated on a board connected to the readout electronics that are pressed down onto the detector electrodes. This method is common in pixelated systems, but is difficult to implement in systems that must be cryogenically cooled. Differences in thermal expansion of the metals can cause disconnections between the board and the detector electrodes.

2.5 Introduction to Proximity Charge Sensing

Proximity charge sensing takes advantage of charge sharing between adjacent electrodes. Instead of fabricating the electrodes directly onto the surface of the detector, the electrodes are suspended a known distance away from the surface of the detector. This ensures that, for every radiation event, the signal charge that is collected is distributed between the electrodes. Using the weighting potential, the position and energy of the event can be extracted from the induced charge on two or more electrodes.

For planar, position sensitive, HPGe proximity electrode systems (see Figure 2.15), the principle of operation is as follows. Ionizing radiation events liberate charge in the detector that is separated and swept to the opposing sides of the detector material by an electric field established by an applied high voltage. The high voltage is applied to a full area electrode that is fabricated onto the detector, and therefore will fully collect the charge that arrives at that electrode. At the opposing face, the charge will arrive at the detector surface that is coated with a-Ge, but will stop short of the readout electrodes. This results in the induction of

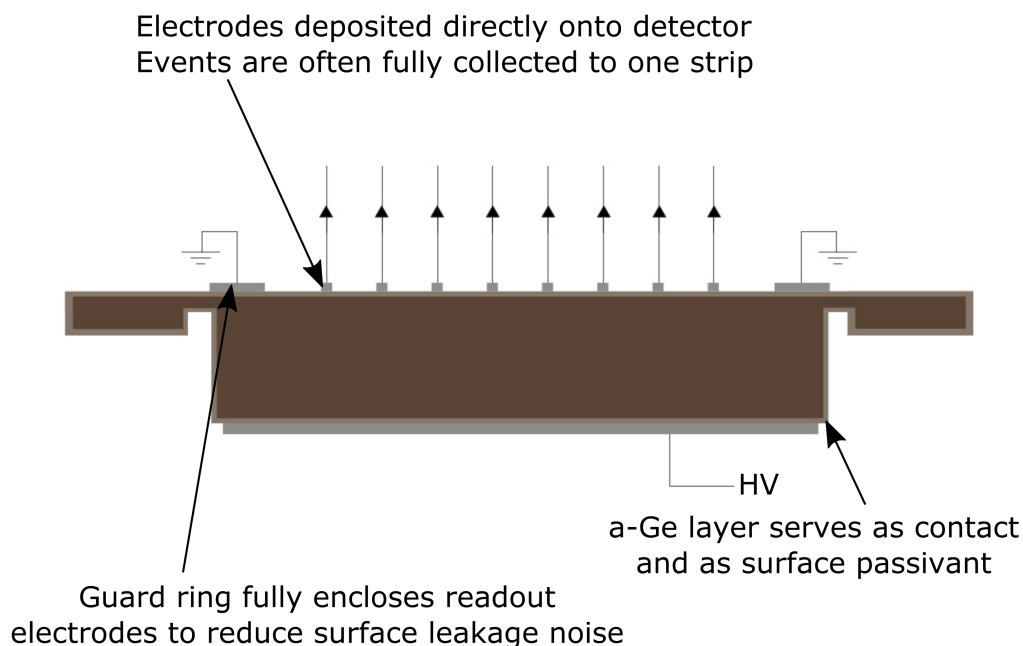


Figure 2.14: Single sided strip detector offering one dimensional position sensitivity with the strip pitch defining the position resolution. Amorphous semiconductor contact technology simplifies the fabrication of these types of detectors.

charge on many electrodes, the amount of which is given by the weighting potential of each electrode at the position of the charge. If the weighting potential is known, the charge induced on the electrodes can be used to extract the position and energy of the event. Using the weighting potentials, sub-electrode pitch position resolution can be achieved by using only the charge induced, or equivalently, the measured pulse height. Once the position is known, the energy of the event can be extracted using one pulse height and the same electrode's weighting potential at that position. After measurement, the charge can be conducted away to the grounded electrodes on either side of the proximity electrodes. These electrodes are referred to as the guard strip electrodes.

The amorphous germanium on the surface below the proximity electrodes serves an additional purpose to passivating the surface states. It allows for the conduction

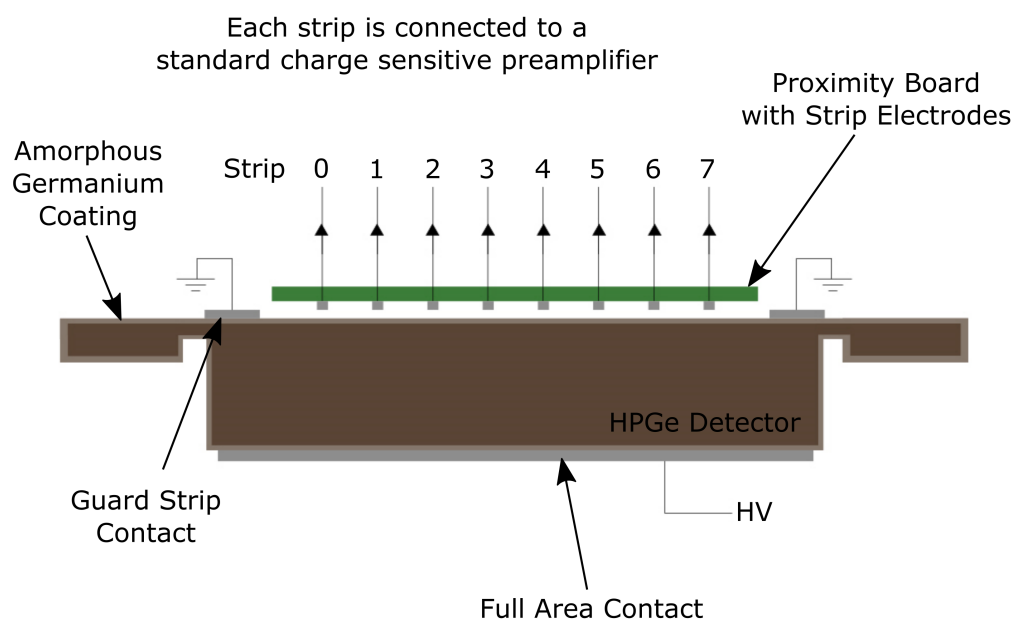


Figure 2.15: Position sensitive proximity charge sensing detector schematic. The detector is fabricated with amorphous germanium contacts, shown as the lighter outer layer. Aluminum electrodes are deposited on top of the amorphous germanium for high voltage (HV) application and charge removal, shown as the grounded electrodes on the top surface. The proximity electrodes sit a fixed distance from the surface of the detector. Each strip is individually connected to a charge sensitive preamplifier.

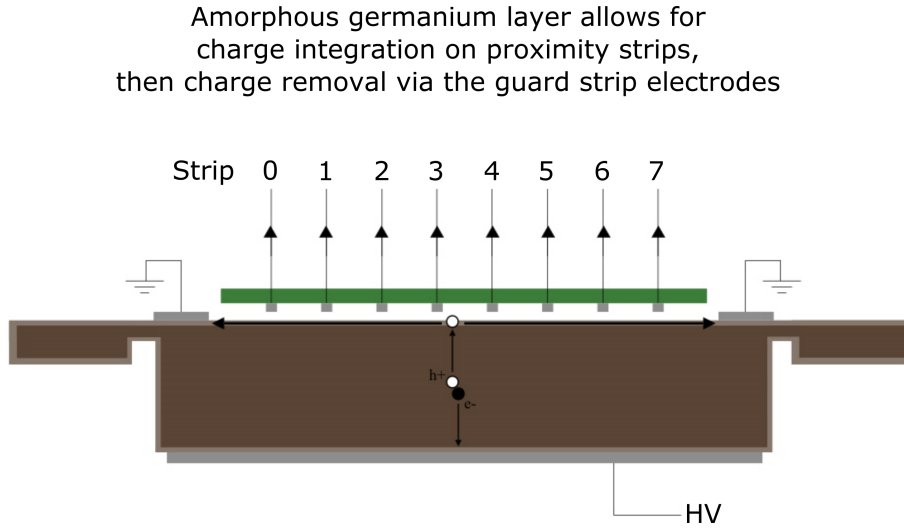


Figure 2.16: Position sensitive proximity charge sensing detector schematic showing radiation event charge transport and removal. Charge generated in a radiation interaction is transported in opposing directions to the HV contact and the proximity surface. The charge is measured by the proximity electrodes, then conducted along the amorphous germanium layer to the guard strip electrodes for removal.

of charge that is collected to that surface to the guard strip electrodes for removal as shown in Figure 2.16. To achieve this, the resistivity of the amorphous germanium layer must be low enough to allow for speedy removal of the charge. If the resistivity is too high, charge will build up and degrade the performance of the detector. However, if the resistivity is too low, the conduction electrons in the amorphous germanium will rearrange when the charge from an event is approaching, shielding the proximity electrodes from collecting that charge. The resistivity must be appropriate to account for both factors.

This method addresses many of the challenges with HPGGe strip detectors presented above. The ability to achieve sub-strip pitch position resolution means the

system needs fewer electrodes to instrument large detector areas. With fewer readout electrodes, fewer electronic channels are needed for instrumentation, reducing the cost and complication of the system. Because the electrodes do not need to be electrically connected to the detector crystal, they can instead be fabricated onto a printed circuit board (PCB). Using a PCB, electrode connections are simplified because the connections can be made away from the detector and without the prospect of damaging the detector or electrodes. Solder connections are also robust to cryogenic temperature operation. PCB technology also allows for multi-layer and other complicated electrode designs that would be difficult or impossible to fabricate onto the surface of a detector. This also allows for easy interchange of readout designs, without the need to re-fabricate the detector.

There have been several studies performed that have investigated similar readout mechanisms to the proximity charge sensing method presented here. In 1977, Kurz et. al. implemented proximity electrodes in a novel configuration to achieve position sensitive readout of HPGe detectors [73]. They were able to achieve 1 mm position resolution and 4.2 keV energy resolution with their system. This system required the periodic removal of charge to maintain depletion in the HPGe, as there were no connected electrodes for charge removal after a radiation event.

In 1978, Battistoni et. al. published on the merits of resistive cathode technology for position sensitive readout of proportional wire detectors [74]. The resistive cathode is adhered to the inner wall of the tube, and, at appropriate resistivities, is transparent to moving charge in the detector volume, but allows for the charge collected to the wall to be transported away. The position information is extracted from the delay in the signal between the two ends of the helical coil, and position resolution down to 1.6 cm was achieved with a tube length of 1 m. Also investigated in this work was the use of readout strips that were oriented orthogonally to the central anode wire. More recently, similar work was performed by Athanasiades et. al. [75].

In 1997, Luke et. al. used proximity electrodes to compensate for edge effects on the weighting potentials in coplanar-grid detectors [76]. Then, in 2009, Luke et. al. applied proximity electrodes to a Si(Li) detector crystal with a resistive amorphous silicon surface coating and two electrodes suspended above the crystal with a standoff distance of 60 μm . Signals were measured and used to map the relative signal height, or weighting potential, as a function of position, shown in Figure 2.17. The measured values agreed with calculated weighting potentials to a remarkable degree. This work paved the way for the current work, showing that position resolution could be much finer than the pitch of the electrodes [77].

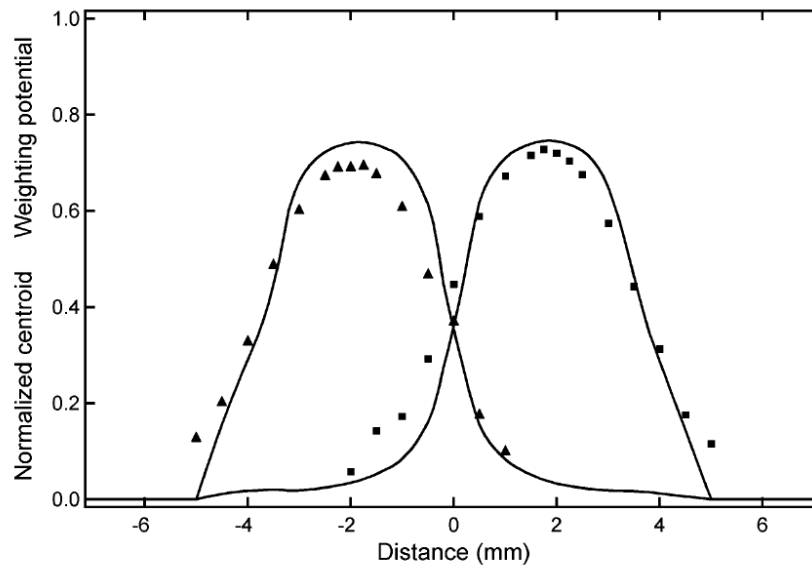


Figure 2.17: Measured (data points) and modeled (solid lines) weighting potentials for a two strip proximity electrode detector implemented on a Si(Li) detector. Each electrode was 2.9 mm wide with a separation of 0.75mm . The gap between the proximity electrodes and the detector surface was 0.060 mm. The detector was operated at room temperature. As reported in [77].

Chapter 3

Position and Energy Extraction Methods

Using the proximity charge sensing method, nonzero integrated charge on multiple electrodes provides the information needed to extract the position of the event with resolution much finer than the readout electrode segmentation. The pulse heights from a single event indicate the electrode under which the event occurred – the electrode with the largest pulse height – and on which side of that electrode the event was centered – towards the electrode with the second largest pulse height. Using this knowledge as a starting point for position extraction methods, we can develop methods to extract event positions with very fine position resolution. These methods rely on the weighting potentials for each readout electrode to extract both position and energy (see Section 2.2.4). The methods that have been explored throughout this work will be presented in this chapter.

3.1 Position and Energy Extraction Using Calculated Weighting Potentials

The first method investigated as part of this work utilizes calculated weighting potentials to localize and extract the energy of an event. The weighting potentials were calculated using the commercial software Maxwell 14.0 [78], assuming perfect knowledge of the detector as it was fabricated. Using Eq. 3.1, only one dimension must be reconstructed. A two-dimensional detector model is necessary for electrostatic modeling of the weighting potential, but only data from the crystal surface is written to a file for analysis. An example geometry is shown in Figure 3.1.

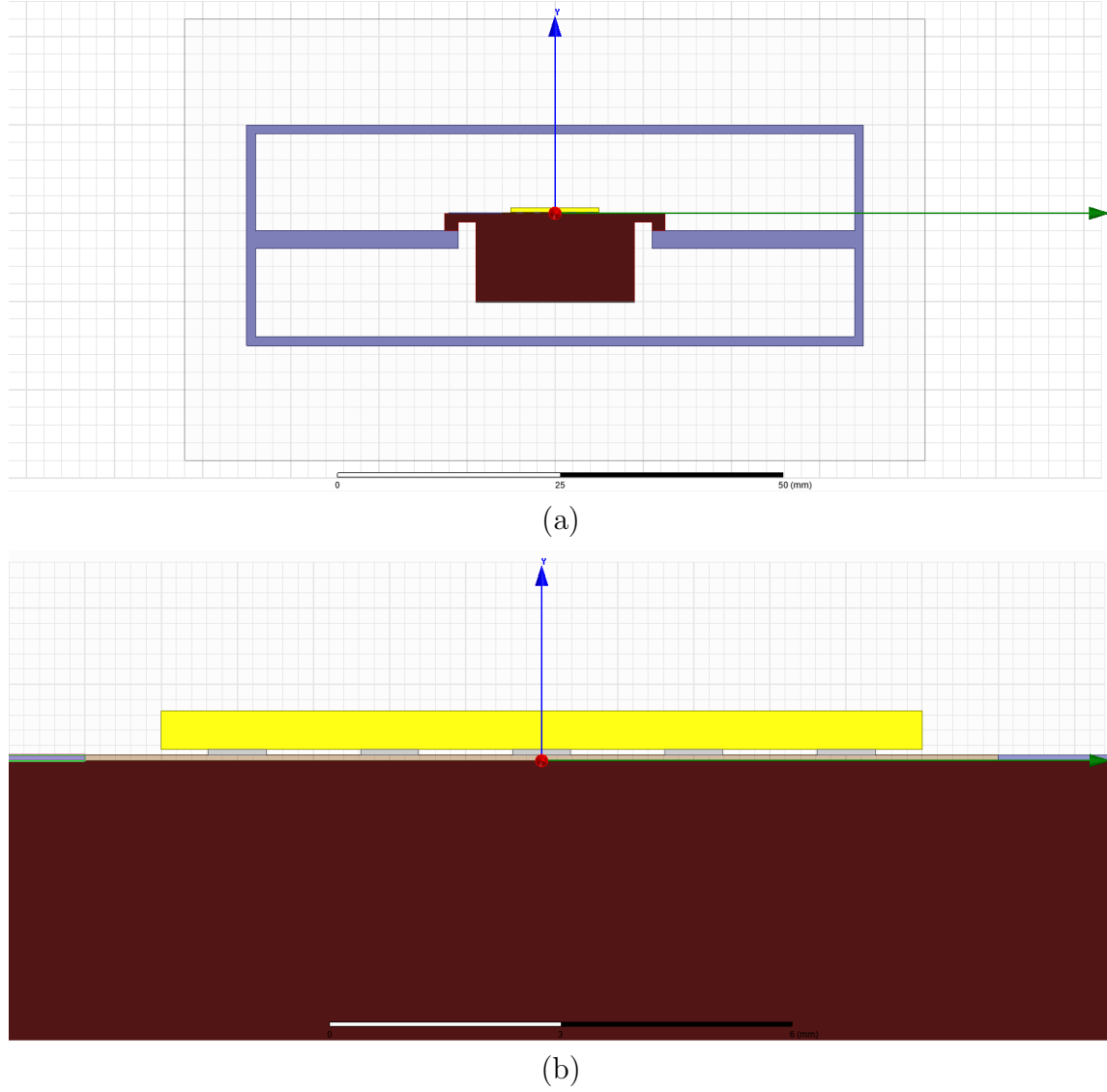


Figure 3.1: Screen capture showing an example geometry of a proximity detector, as modeled in Maxwell 14.0. This is the geometry of the small, proof of principle detector fabricated at LBNL. (a) shows the full geometry, with the detector crystal in the middle (in brown) with the proximity board on top. Surrounding the detector is a simplified version of the detector mount. The outer outer box shows the region of vacuum inside, which all non-model features are vacuum. The boundary condition at the outer edge requires the voltage to fall to zero at infinity. (b) shows a magnified image of the proximity electrode geometry. Five strips at a pitch of 2 mm with a width of 0.76 mm sit atop a Kapton layer, modeled in translucent yellow. The Kapton layer was 0.076 mm thick and modeled with dielectric constant $\epsilon_r = 3.0$. The guard strip electrodes are shown in gray at the edges of the Kapton layer.

Two further simplifications to the weighting potential equations presented in Section 2.2.4 were utilized in this work. Due to the planar nature of the detectors fabricated (more on detector design in Ch. 5), the dimensionality of $\vec{r}$ can be reduced. The weighting potential for planar detectors with one full area electrode falls to zero at the full area electrode regardless of position. Therefore, the induced charge on an electrode is proportional to the amount of charge and the weighting potential at the crystal surface opposite the full area electrode. This means the weighting potential dependence on the spatial dimension that describes detector depth (z) can be dropped, i.e. $\phi_{0,j}(x, y)$. The polarity of the induced charge will depend on the charge carriers collected to the proximity surface. The induced charge will be negative if holes are collected to that surface and positive if electrons are collected. Which charge carrier is collected is given by the applied high voltage. We also assume that the weighting potential does not vary along the length of the strip, which means that the weighting potential will only depend on the position perpendicular to the strip length, x . This leads to Eq. 3.1, where q is the charge collected to the crystal surface below the proximity electrodes .

$$Q_j = \pm q \phi_{0,j}(x) \quad (3.1)$$

The assumption that the weighting potential does not vary along the length of the strips allows us to reduce the model used to calculate the weighting potentials to two dimensions, representing a cross section of the detector. The equation describing the total induced charge for an event, Eq. 3.1, only relies on the weighting potential at the detector surface, which varies with the dimension x . The weighting potential will be peaked directly below the electrode and fall off away from the electrode on either side, with any other features given by the geometry of the neighboring electrodes and influenced by dielectric materials. The text following this introduction assumes a thorough knowledge of weighting potentials and the assumptions that were made in this work.

To generate the weighting potential data, 1V was applied to one electrode, with all other electrodes grounded (i.e. 0V), and the electric potential was iteratively solved in the space on a mesh defined by Maxwell with input ensuring the grid was fine enough. The data were written to a file for later analysis and the process repeated for each readout electrode. Plotted in Figure 3.2 is an example of a weighting potential for a single strip.

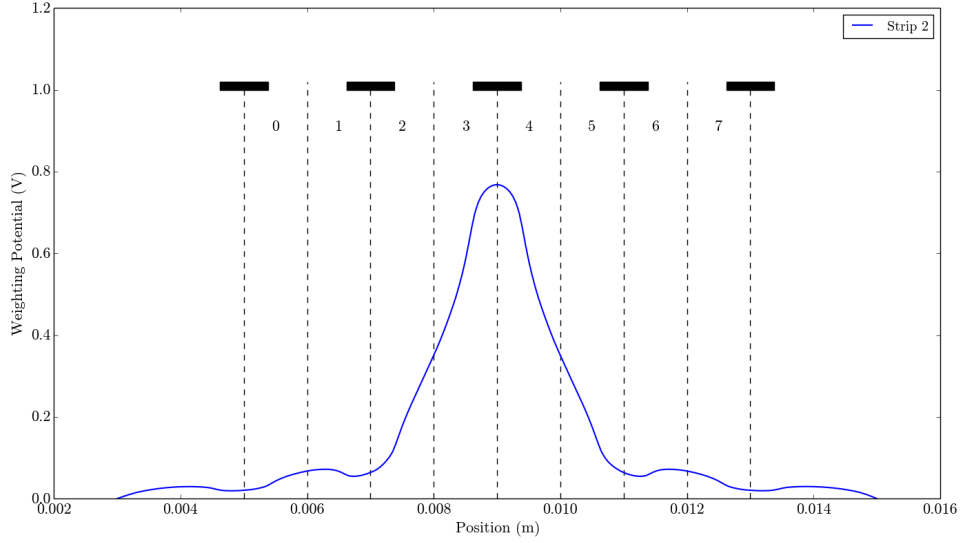


Figure 3.2: Single weighting potential for a strip in the middle of the detector plotted as a function of position along the surface of the germanium. Note the peaked nature directly below the strip, which is represented as a box at the top.

3.1.1 Position Extraction from Pulse Height Data

The advantage of the proximity sensing readout scheme is that the induced signal varies as a function of position. This, ultimately, is the variable that allows for sub-strip pitch position resolution. Considering the example weighting potential given in Figure 3.2, if an ionizing radiation event occurs within the vicinity of this electrode that deposits a known amount of charge, then the measured charge on this electrode is simply the deposited charge multiplied by the weighting potential at the position of the event. Measuring this induced charge hints at the position of the event, however the position would not be uniquely defined because this relation does not vary monotonically and because the energy deposited in the event is unknown. Multiple electrodes arranged in a regular pattern must be used to extract position. An example set of weighting potentials are given in Figure 3.3 for reference.

An ionizing radiation event that occurs between two electrodes will induce signals on both electrodes, with the pulse height on each electrode proportional to the respective weighting potentials at the position of the charge. Inspecting the amount of induced charge on each electrode will immediately indicate the electrode to which the event was closest. If the induced signals are equal, the event occurred halfway

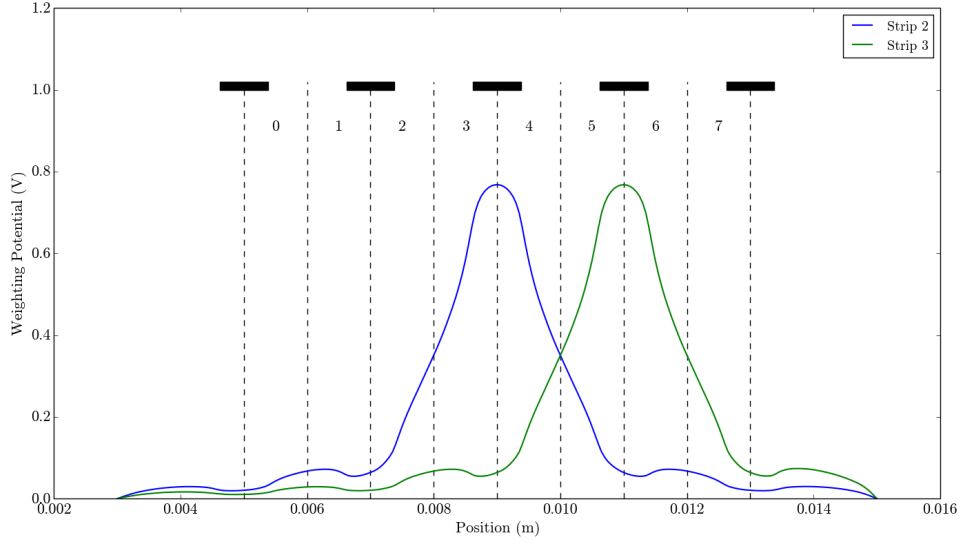


Figure 3.3: Two neighboring weighting potentials for strips near the middle of the detector, plotted as a function of position along the surface of the germanium.

between the two electrodes. Moving to the right or left from that position, one signal will increase while the other decreases.

The signals will also be energy dependent, and, without knowledge of the energy of the event, a method is needed to eliminate that dependence. By taking the ratio of one signal to another, the energy dependence will be eliminated and a relationship between the position and the pulse height ratios can be established. The ratio chosen for this work uses the larger signal as the numerator and the smaller of the two signals as the denominator. This relationship varies monotonically on the region between the strip center and half the distance to the next strip. For this reason, the position extraction space was subdivided into regions defined by these limits, and the weighting potentials and region definitions can be found in Figure 3.4.

The weighting potential ratios are calculated for each region and saved as a map between ratio and position. These ratios can be seen in Figure 3.5.

For an event between strips j and k , where strip j has the largest pulse height, p_j , and strip k has the second largest pulse height, p_k , the ratio of the pulse heights must be equal to the ratio of the two strip weighting potentials, $\phi_{0,j}$ and $\phi_{0,k}$. This is shown mathematically in Eq. 3.2.

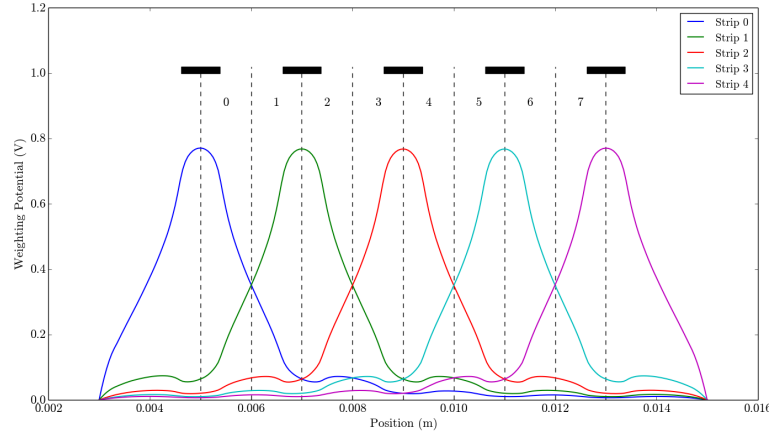


Figure 3.4: The proximity readout position extraction method requires regions to be defined in which the weighting potential ratio is monotonically increasing such that the ratio can be mapped to a position. The regions are defined between the dashed lines, and numbered as shown in the figure. Outside the series of dashed lines there is no way to extract a position, and events determined to have taken place there were ignored.

$$\frac{\phi_{0,j}}{\phi_{0,k}}(x) = \frac{p_j}{p_k} \quad (3.2)$$

Using the proper weighting potential ratio from above, the event can then be mapped to a position within the region using Equation 3.2. In this equation, $\phi_{0,j}$ corresponds to the weighting potential for the strip, j , with the largest pulse height, p_j . Similarly, $\phi_{0,k}$ corresponds to the strip, k , with the second largest pulse height, p_k .

3.1.2 Energy reconstruction

Using the larger of the two signals to minimize noise contributions, the signal is divided by the weighting potential at the extracted position, which removes the dependency of the pulse height on the weighting potential. This gives a quantity that is proportional to the event charge, and, therefore, the energy of the event. Then, multiplying by a calibration factor gives the energy of this event. This is described mathematically in Eq. 3.3.

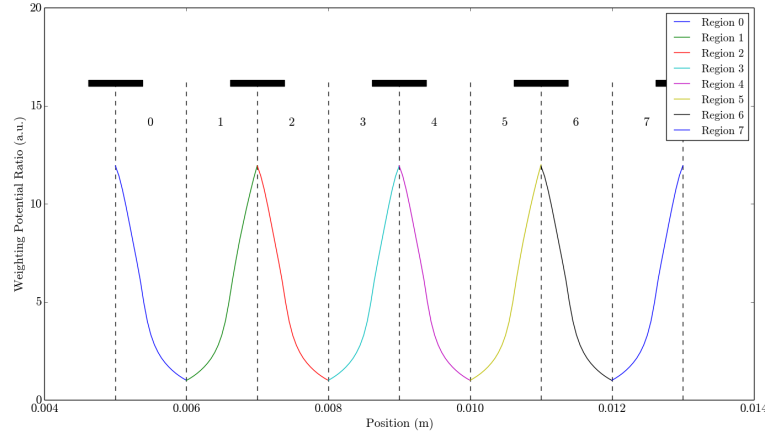


Figure 3.5: Weighting potential ratios for each region plotted as a function of position. These ratios are used to calculate the position of each interaction based on Equation 3.2.

$$E = \frac{p_j}{\phi_{0,j}(x)} C_2 \quad (3.3)$$

3.1.3 Method 1 Issues

This position and energy extraction method was used to analyze data measured with the proof of principle detector, which will be presented in Section 5.2.1. Flood field data measured with the detector should yield a flat position distribution, but this was not observed when extracting the position with this method. Event positions are skewed towards the beginning of each region, leaving a deficit beneath each strip, as seen in Figure 3.6. Inaccurate position extraction can result from weighting potentials that are calculated using erroneous readout electrode geometry or from factors involving the physics of charge transport and signal induction. The energy resolution also suffered as a result of weighting potentials errors. The energy resolution achieved with this method was 4.5 keV at 59.5 keV, whereas the flood field data method presented in the next section is able to achieve 2.9 keV at 59.5 keV.

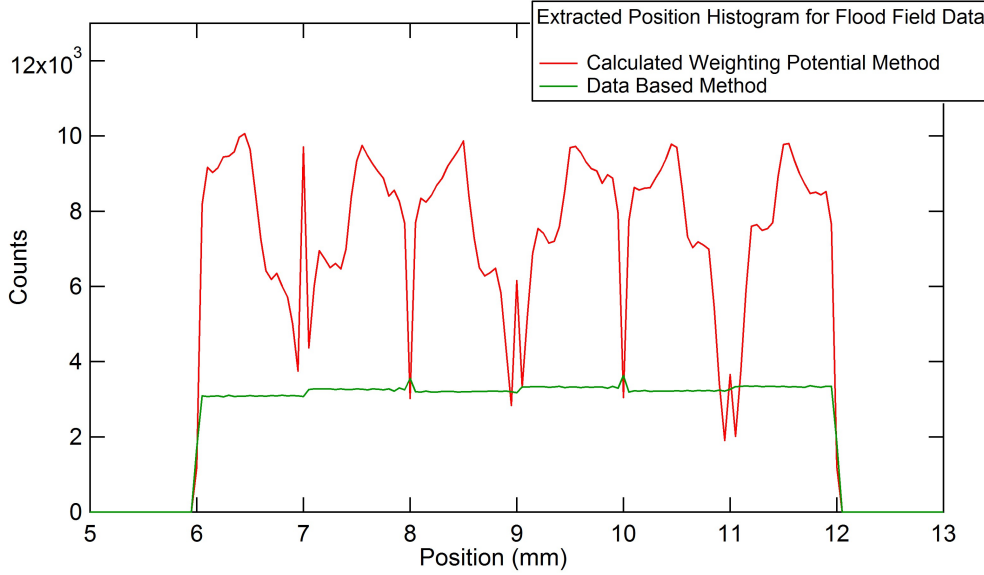


Figure 3.6: Extracted position histograms for flood field data showing the inaccuracies of the calculated weighting potential position extraction method. The extracted position distribution using the flood field data position extraction method is shown for comparison.

3.2 Position and Energy Extraction Using Flood Field Data

Considering the issues with the method described above, another reconstruction method needed to be investigated. As described in [72], a simple mathematical formulation allows for the reconstruction of position using measured data. This method more accurately reconstructs the event positions, and the method will be described below.

3.2.1 Description of the Method and Mathematics

The issues with the previous method likely stem from uncertainties in the geometry of the readout electrodes. Measured data can be used to extract the relation between the position and the weighting potential ratio as well as the weighting potential itself. The detector is evenly illuminated with γ -rays while data is being acquired. This type of measurement is referred to as flood field illumination, and is achieved by

positioning a point source far enough away from the detector such that the flux arriving at the detector can be assumed equal for all positions. It is expected that the extracted position histogram for all events should be flat for all positions when the detector is illuminated in this fashion. By requiring this to be true, the weighting potential ratios, which provide the mapping from ratio to position, can be extracted directly from the data.

Since the measured weighting potential likely includes detector physics effects, I will refer to this quantity as the pseudo-weighting potential, or $\tilde{\phi}_j$, where j denotes the electrode number. This quantity will be mapped as a function of position for each readout electrode, such that the position and energy extraction can be performed as in the previously described method.

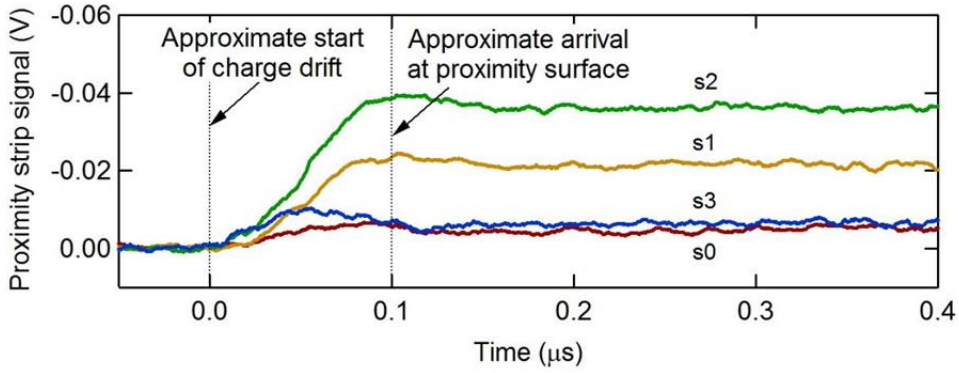


Figure 3.7: Example signal shape for a single event that occurred under strip two (s2) on the strip one (s1) side. The extracted pulse heights from these signals are used in this method to extract the position and energy of the event. This event is from a ^{137}Cs source.

Using flood field event data, first the pseudo-weighting potential ratios, or $\frac{\tilde{\phi}_j}{\tilde{\phi}_k}$, are calculated. As shown in the last section, this ratio is a monotonically varying function within a region. For the data-based method, the same region definitions will be used.

To begin, the ratio r is calculated as in Eq. 3.4 for each event:

$$r = \frac{p_j}{p_k} \quad (3.4)$$

In this equation, p is the pulse height measured on adjacent electrodes, j and k , where j denotes the electrode with the larger pulse height. Within a given region, this quantity ranges from $1 \leq r \leq r_m$, where

$$r_m \equiv \frac{\tilde{\phi}_i}{\tilde{\phi}_j} \left(x = \frac{d}{2} \right), \quad (3.5)$$

defined on the interval $0 \leq x \leq d/2$. For this equation, $x = 0$ represents half the strip pitch (i.e. $d/2$) away from strip j in the direction of strip k . The position $x = d/2$ is the center of strip j .

To derive an equation from which the positions can be determined, all flood field event ratios are entered into a histogram, $H(r)$, which takes on a characteristic shape that is indicative of the weighting potential ratio for that region. Equating the number of events in equivalent regions in the position histogram, which has an equal number of events per unit length, H_0 , and the pulse height ratio histogram yields Equation 3.6.

$$\int_0^x H_0 dx = \int_1^r H(r) dr \quad (3.6)$$

Carrying out the integral on the left over the full region yields the total number of events. Note the change in the limits for the integral on the right.

$$N = H_0 \frac{d}{2} = \int_1^{r_m} H(r) dr \quad (3.7)$$

By rearranging this equation, it is possible to replace N in Eq. 3.6 with known quantities to arrive at Equation 3.8, which is the equation used for all position extraction in this method.

$$x = \frac{d}{2N} \int_1^r H(r) dr. \quad (3.8)$$

This equation provides a direct mapping from event pulse height ratio to the event's position. All other quantities are known or measured: d is set by the strip pitch, N is the total number of events measured, r is the ratio for a particular event, and $H(r)$ is measured from flood illumination data, and can be considered a calibration of the detector.

After all flood field event positions have been extracted, the pseudo-weighting potentials can be extracted from the data. For a given region, all events that occurred within $x \pm \Delta x$ are gathered¹, and the larger of the two pulse heights for each event is entered into a histogram. The centroid of the peak in this histogram is

¹ Δx is chosen based on the desired granularity of $\tilde{\phi}_j$, with the limitation that there must be a peak present from the events contained in that range. If Δx is too small, there will not be sufficient events and a peak position cannot be extracted.

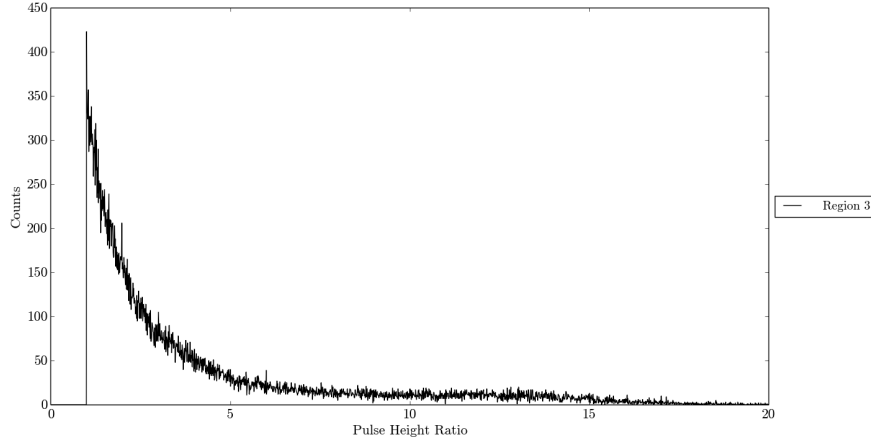


Figure 3.8: Ratio histogram from flood field data for region 3 in a $5 \times 5 \text{ cm}^2$ detector with eight proximity electrodes optimized for position resolution. The shape of this histogram encodes the position mapping for the region, based on Equation 3.8. Note that the histogram starts at one, where the weighting potentials are equal at the midpoint between two strips. The data-based method did not allow ratios above 20 for this detector geometry. Event ratios with a larger magnitude would be mapped directly under the strip.

taken to be proportional to the pseudo-weighting potential for that position, and the process is repeated for positions covering the range of the region. This produces one region's pseudo-weighting potential, so this extraction process must be repeated for all regions.

At this point, the pseudo-weighting potential magnitude reflects the ADC values of the digitizer. To scale $\tilde{\phi}_j$ properly, a measurement of maximum $\tilde{\phi}_j$ must be performed for each electrode. This can be done by instrumenting the electrodes that are electrically connected to the detector, or the guard strip electrodes used for charge removal from the detector. Using a preamplifier and measuring full energy γ -ray events, we can measure the gain of the system. By using this same preamplifier connected to each proximity electrode, in a separate measurement we can measure the pulse height deficiency from the proximity electrode by measuring the largest pulse height collected by that electrode. Taking the ratio of the proximity electrode pulse height to the guard strip pulse height gives the maximum weighting potential for that electrode. The pseudo-weighting potentials can be scaled by this measured

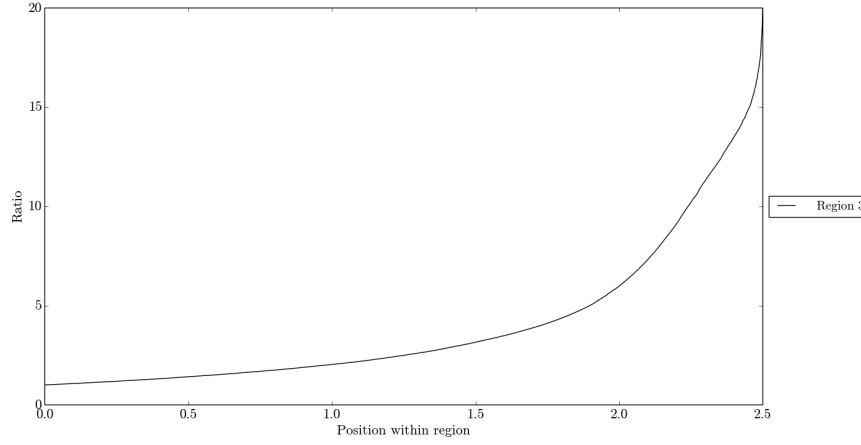


Figure 3.9: Applying the integration in Equation 3.8 to the histogram shown in Figure 3.8 yields the relationship between position and pulse height ratio shown here. This plot is a representative example of the relationship between position and pulse height ratio, but each region varies slightly.

quantity to reflect the true weighting potential.

Using the extracted pseudo-weighting potentials, the full energy of each event can be calculated. The measured signal is proportional to the weighting potential as given in Equation 3.1, and the full interaction energy can be extracted using the same method. A variation on Equation 3.1 provides the means for extracting the energy.

$$E = \frac{p_j}{\tilde{\phi}_j(x)} C_j \quad (3.9)$$

In Equation 3.9, p_j is the pulse height measured for an event on electrode j , $\tilde{\phi}_j$ is the pseudo-weighting potential for that electrode, and C_j is a calibration factor to convert ADC units to energy.

3.2.2 Method 2 Issues

This method performs substantially better than the calculated weighting potential method, as shown in Figure 3.6. However, due to low adjacent electrode signal pulse height (i.e. p_k) and electronic noise, issues can arise when reconstructing events

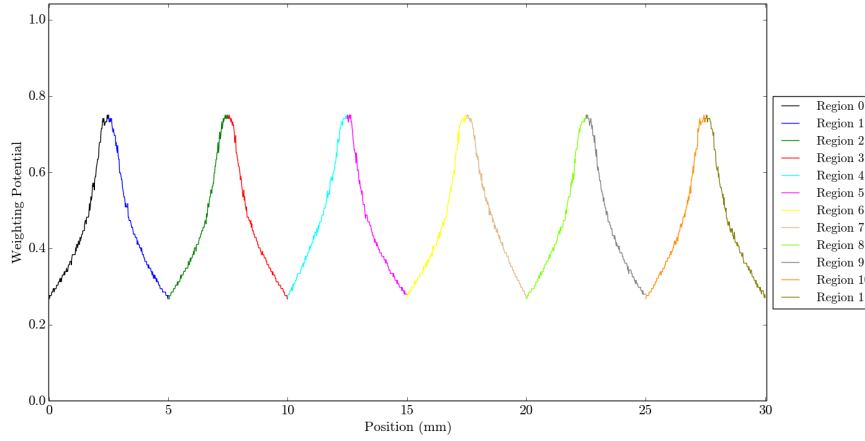


Figure 3.10: Using the position and pulse height information, the weighting potentials shown here can be extracted from the flood field data.

near the middle of the strips. For an event underneath a strip, this method relies on the small signal of the neighboring strip, which can be significantly affected by noise. Because this is used as the denominator of the ratio, it can significantly affect the resulting ratio. In addition, the weighting potentials of both the strip with the largest signal as well as the second largest signal are relatively flat, such that small amounts of noise can shift the reconstructed position by a significant margin.

3.3 Possible Other Methods

While only the methods above have been thoroughly investigated, other methods are still possible and may give better results than those above. One method that was considered mapped the position as a function of the arctangent of the ratio of one signal to an adjacent signal. This method has the advantage of being able to extract event positions on the full strip pitch, marginally simplifying the reconstruction. The method was not pursued because it gave similar position resolution to the data-based method above, which was the basis of all software we had developed. Other methods could utilize the signals from more than two electrodes, which could possibly enhance the reliability of position extraction.

Chapter 4

Strip Electrode Optimization

4.1 Optimization Goals and Methods

Because the induced charge signals are highly dependent on the electrode geometry, ability to extract the position and energy accurately should depend highly on the readout electrode geometry. For this reason, we performed a study that aimed to optimize the geometry for position resolution and energy resolution. This will help to probe the limitations of this method when competing with more standard detector electrode schemes.

There are many geometric and dielectric factors that will affect the resulting weighting potentials of a proximity charge sensing system, including but not limited to: electrode width, electrode pitch, electrode depth, dielectric spacer thickness, dielectric spacer permittivity, electrode PCB thickness, and electrode PCB permittivity. These factors will all affect the shape and magnitude of the resulting weighting potentials, some with greater influence than others. We chose to use eight strips to read out charge from a $5 \times 5 \text{ cm}^2$ detector crystal. To cover this active area while avoiding edge effects, we chose the pitch of the strips to be 5 mm. Then, through thought experiments and modeling, we decided to focus on the effects of the strip width and the distance between the strips and the crystal surface, i.e. dielectric spacer thickness. We chose these two parameters as variables for this study, while holding other geometric parameters constant. The dielectric constant of the dielectric spacer will also have a large impact on the induced signal, but we chose to hold this constant to simplify the calculations.

We employed two separate methods by which to calculate the position and energy. This way, we had results that we could compare to ensure accuracy. The first method was a semi-analytic method. The second approach was a Monte Carlo method that

simulated event pulse heights, then extracted the position and energy from those pulse heights using the method presented in Section 3.1. As an input for both methods, the electronic noise of the system was measured. The quantity used for all calculations was 1.5 keV, or 0.01 sigma for 59.5 keV γ -rays. These methods, the results, and what the results dictate for detector design are presented in this chapter.

4.2 Semi-Analytic Method

The semi-analytic calculation of uncertainties uses the standard approximation of uncertainty propagation [79] as applied to the position and energy extraction method presented in Section 3.1. Through error propagation, we are determining the impact that electronic noise has on the resolutions. The derived analytic expressions for the resolutions depend on the proximity readout electrode weighting potentials. Because we lack an equation for the form of the weighting potentials, Maxwell 14.0 and numerical calculations were used where a mathematical equation was absent.

4.2.1 Definition of System

To produce the necessary weighting potentials, we adjusted the geometry of the model in a stepwise fashion, calculated the weighting potentials, wrote them to file, then used those weighting potentials to calculate the uncertainty for that geometry. Strip widths used were 0.5 mm, 1 mm, 2 mm, and 4 mm. Dielectric (Kapton) thicknesses used were 0.025 mm, 0.5 mm, and 0.1 through 0.8 mm in 0.1 mm steps. Not all Kapton thicknesses were used with all strip widths, if it was observed that the position and energy resolution were not improving. The dielectric constant of the Kapton layer was set to 3.0. All other factors were held constant. A screen shot of the design can be found in Figure 4.1.

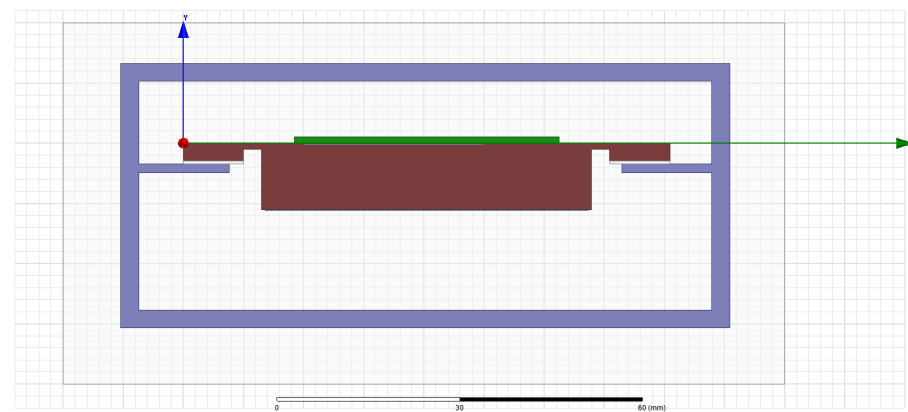


Figure 4.1: Model geometry as shown in Maxwell 14.0 for the optimization study. Shown is the HPGe crystal in brown with the proximity board atop, surrounded by a simplified detector mount. See Figure 4.2 for more proximity board and Kapton layer details.

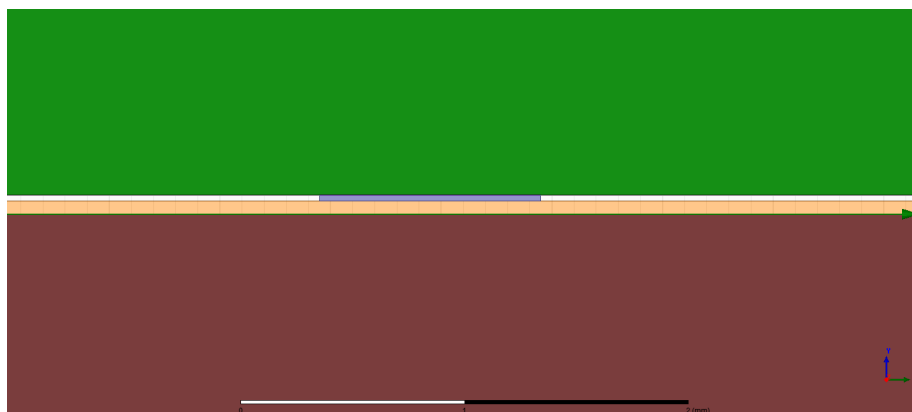


Figure 4.2: Model geometry detail as shown in Maxwell 14.0 for the optimization study. The Kapton layer that sets the standoff distance between the detector surface and the proximity strips can be seen in yellow, with one of the 1 mm strips in gray atop. The gray section to the left of the Kapton layer is the guard strip electrode. For the optimization, the Kapton layer thickness and the strip width were adjusted and the position and energy uncertainty were analyzed.

4.2.2 Mathematics of Error Propagation

The propagation of error for this system begins with the definition of the position extraction function, as introduced in Equation 3.2. As a reminder, $\phi_{0,j}$ is the weighting potential for strip j , $\phi_{0,k}$ is the weighting potential for strip k which is adjacent to strip j , and p_j and p_k are pulse heights measured from strips j and k , respectively, for the same event.

$$\frac{\phi_{0,j}}{\phi_{0,k}}(x) = \frac{p_j}{p_k} \quad (4.1)$$

Treating $\frac{\phi_{0,j}}{\phi_{0,k}}$ as an invertible function, we can simply invert this equation as shown in Eq. 4.2.

$$x = \left(\frac{\phi_{0,j}}{\phi_{0,k}} \right)^{-1} \left(\frac{p_j}{p_k} \right) \equiv x \left(\frac{p_j}{p_k} \right). \quad (4.2)$$

This function will provide the basis for the propagation of uncertainty [79]. Using the standard error propagation approximation, we can calculate an expression for position uncertainty. In this equation, σ_{p_j} and σ_{p_k} are the electronic noise contributions for strips j and k , respectively. The noise is assumed to be uncorrelated.

$$\sigma_x^2 = \left(\frac{\partial x}{\partial p_j} \right)^2 \sigma_{p_j}^2 + \left(\frac{\partial x}{\partial p_k} \right)^2 \sigma_{p_k}^2, \quad (4.3)$$

We can use the partial derivative chain rule to translate this equation into terms that we can calculate from the weighting potentials. The chain rule expansions are shown in Equations 4.4 and 4.5.

$$\frac{\partial x}{\partial p_k} = \frac{\partial x}{\partial p_j/p_k} \frac{\partial p_j/p_k}{\partial p_k} \quad (4.4)$$

$$\frac{\partial x}{\partial p_j} = \frac{\partial x}{\partial p_j/p_k} \frac{\partial p_j/p_k}{\partial p_j} \quad (4.5)$$

By substituting Equations 4.4 and 4.5 into Eq. 4.3 and carrying out the differentiation, we obtain the equation with which we calculate the position uncertainty. Here, we have assumed that the individual channel noise is uncorrelated but equal, i.e. $\sigma_{p_j} = \sigma_{p_k} = \sigma_e$.

$$\sigma_x^2 = \left(\frac{\partial x}{\partial p_j/p_k} \frac{\partial p_j/p_k}{\partial p_k} \right)^2 \sigma_{p_j}^2 + \left(\frac{\partial x}{\partial p_j/p_k} \frac{\partial p_j/p_k}{\partial p_j} \right)^2 \sigma_{p_k}^2 \quad (4.6)$$

$$\sigma_x = \frac{1}{p_k} \left(1 + \left(\frac{p_j}{p_k} \right)^2 \right)^{1/2} \frac{\partial x}{\partial p_j/p_k} \sigma_e \quad (4.7)$$

To carry out the calculation, the pulse height for strip j , p_j , is set equal to the weighting potential for strip j at the event position x_i . The same holds for strip k .

$$p_j = \phi_{0,j}(x_i) \quad (4.8)$$

This calculation must be carried out numerically. The simplest way to do so is to invert this quantity, as shown in Equation 4.9. Note that we have used Equations 4.1 and 4.8 to arrive at Equation 4.9. This differentiation is easily carried out using calculated weighting potentials.

$$\frac{\partial x}{\partial p_j/p_k} = \left(\frac{\partial p_j/p_k}{\partial x} \right)^{-1} = \left(\frac{\partial p_j/p_k}{\partial x} \right)^{-1} = \left(\frac{\partial \phi_{0,j}/\phi_{0,k}}{\partial x} \right)^{-1} \quad (4.9)$$

This same mathematics can be applied to the propagation of error for the energy extraction method used in this work. The definition of the functional form for energy extraction is shown in Equation 4.10, which was presented in Section 3.1

$$E = \frac{p_j}{\phi_{0,j}(x(p_j/p_k))} C_j \quad (4.10)$$

It is assumed that the calibration factor, C_2 , is without error. The error propagation approximation equation is similar, with the independent variables being p_j and p_k .

$$\sigma_E^2 = \left(\frac{\partial E}{\partial p_j} \right)^2 \sigma_{p_j}^2 + \left(\frac{\partial E}{\partial p_k} \right)^2 \sigma_{p_k}^2 \quad (4.11)$$

The derivation is more intensive because the equation for energy extraction relies on the position extraction. Taking the terms one at a time, and utilizing the partial derivative chain rule as we did above, we are able to translate again into terms which are calculable from the weighting potentials.

$$\frac{\partial E}{\partial p_j} = \frac{\partial E}{\partial p_j} \frac{\partial p_j}{\partial p_j} + \frac{\partial E}{\partial \phi_{0,j}} \frac{\partial \phi_{0,j}}{\partial p_j} \quad (4.12)$$

$$\frac{\partial E}{\partial p_j} = \frac{1}{\phi_{0,j}} - \frac{p_j}{\phi_0} \frac{\partial \phi_{0,j}}{\partial p_j} \quad (4.13)$$

Similarly, for the second term in Equation 4.11, we can expand into calculable terms.

$$\frac{\partial E}{\partial p_k} = \frac{\partial E}{\partial p_j} \frac{\partial p_j}{\partial p_k} + \frac{\partial E}{\partial \phi_{0,j}} \frac{\partial \phi_{0,j}}{\partial p_k} \quad (4.14)$$

$$\frac{\partial E}{\partial p_k} = -\frac{p_j}{\phi_{0,j}^2} \frac{\partial \phi_{0,j}}{\partial p_k} \quad (4.15)$$

The weighting potential derivatives can be further expanded, as shown here.

$$\frac{\partial \phi_{0,j}}{\partial p_j} = \frac{\partial \phi_{0,j}}{\partial x} \frac{\partial x}{\partial p_j} \quad (4.16)$$

$$\frac{\partial x}{\partial p_j} = \frac{\partial x}{\partial p_j/p_k} \frac{\partial p_j/p_k}{\partial p_j} = \frac{\partial x}{\partial p_j/p_k} \frac{1}{p_k} \quad (4.17)$$

In the same way, we can calculate the weighting potential derivative with respect to p_k .

$$\frac{\partial \phi_{0,j}}{\partial p_k} = \frac{\partial \phi_{0,j}}{\partial x} \frac{\partial x}{\partial p_k} \quad (4.18)$$

$$\frac{\partial x}{\partial p_k} = \frac{\partial x}{\partial p_j/p_k} \frac{\partial p_j/p_k}{\partial p_k} = -\frac{\partial x}{\partial p_j/p_k} \frac{p_j}{p_k^2} \quad (4.19)$$

The results of inserting the expanded terms into Equations 4.13 and 4.15 are:

$$\frac{\partial E}{\partial p_j} = \frac{1}{\phi_0} - \frac{p_j}{\phi_0^2} \frac{1}{p_k} \frac{\partial \phi_0}{\partial x} \frac{\partial x}{p_j/p_k} = \frac{1}{\phi_0^2} \left[\phi_0 - \frac{p_j}{p_k} \frac{\partial \phi_0}{\partial x} \frac{\partial x}{\partial p_j/p_k} \right] \quad (4.20)$$

$$\frac{\partial E}{\partial p_k} = \frac{p_j}{\phi_0^2} \frac{\partial \phi_0}{\partial x} \frac{\partial x}{\partial p_j/p_k} \frac{p_j}{p_k} = \frac{p_j/p_k^2}{\phi_0} \frac{\partial \phi_0}{\partial x} \frac{\partial x}{\partial p_j/p_k} \quad (4.21)$$

Using Equations 4.20 and 4.21, we can solve for the energy uncertainty. To do this, we will assume that the electronic noise is the same between the two electrodes, i.e. $\sigma_j = \sigma_k = \sigma_e$, where σ_e is the electronic noise of the system.

$$\sigma_E^2 = \left[\left(\frac{1}{\phi_0^2} \left[\phi_0 - \frac{p_j}{p_k} \frac{\partial \phi_0}{\partial x} \frac{\partial x}{\partial p_j/p_k} \right] \right)^2 + \left[\left(\frac{p_j/p_k}{\phi_0} \right)^2 \frac{\partial \phi_0}{\partial x} \frac{\partial x}{\partial p_j/p_k} \right]^2 \right] \sigma_e^2 \quad (4.22)$$

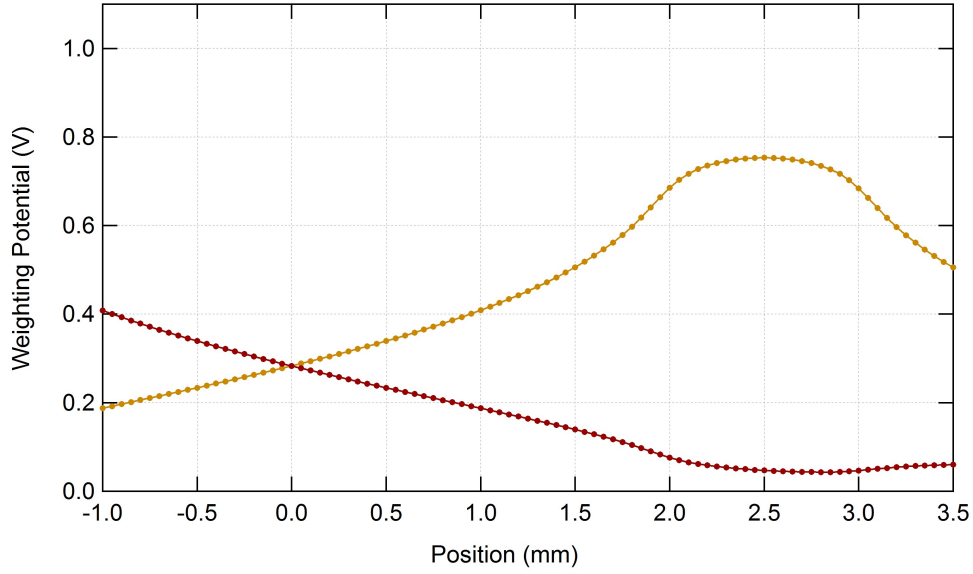


Figure 4.3: Calculated weighting potentials for 1 mm width strips and 100 μm Kapton thickness

4.2.3 Results and Discussion

Sample calculated weighting potentials for 1 mm and 4 mm strips with a Kapton thickness of 100 μm are given in Figures 4.3 and 4.5, respectively. From these weighting potentials, the weighting potential ratios can be calculated simply by taking $\phi_{0,j}(x_i)/\phi_{0,k}(x_i)$ for all x_i in the region. The granularity is set by the weighting potential output grid. Example weighting potential ratios corresponding to the weighting potentials in Figures 4.3 and 4.5 can be found in Figures 4.4 and 4.6, respectively. The derivative terms are calculated using these weighting potential ratios.

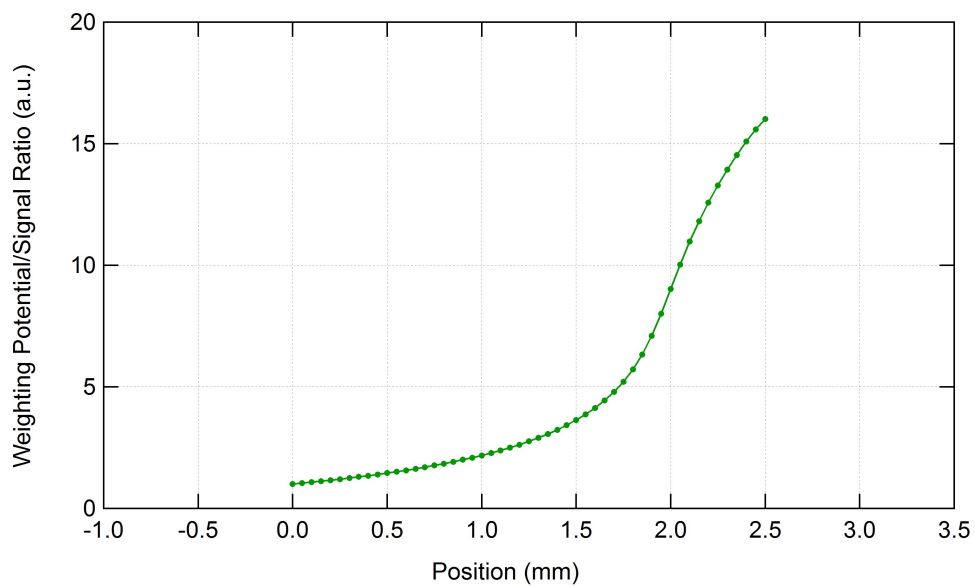


Figure 4.4: Calculated weighting potential ratios for 1 mm width strips and 100 μm Kapton thickness

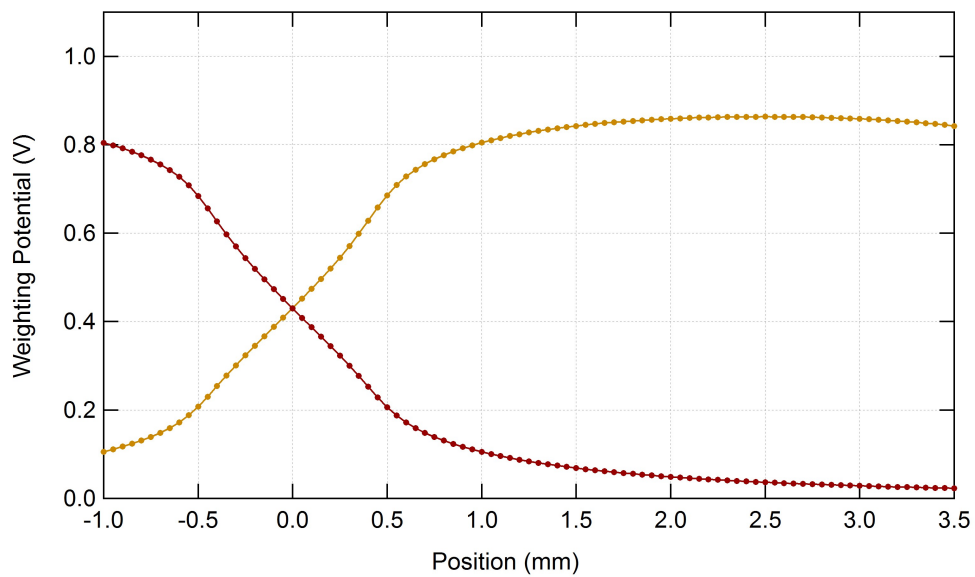


Figure 4.5: Calculated weighting potentials for 4 mm width strips and 100 μm Kapton thickness

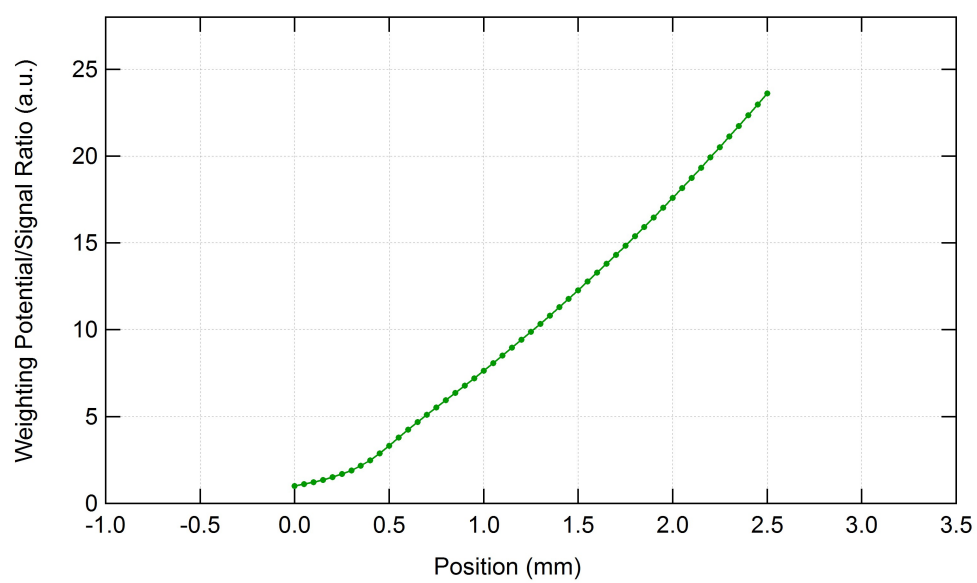


Figure 4.6: Calculated weighting potential ratios for 4 mm width strips and 100 μm Kapton thickness

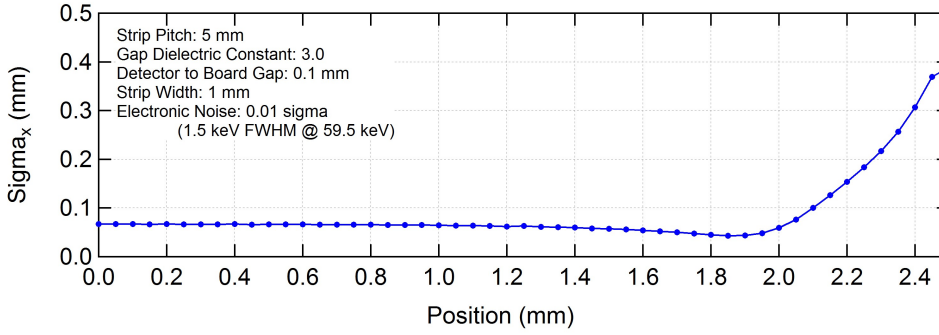


Figure 4.7: Position uncertainty as a function of position for 1 mm strip width and 100 μm Kapton thickness, as calculated analytically by the method derived above.

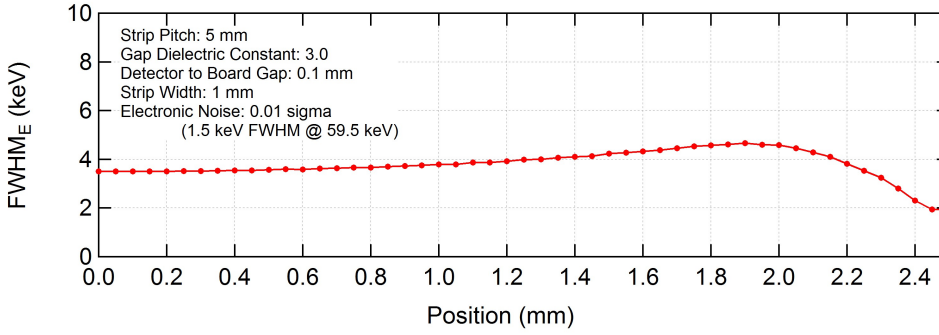


Figure 4.8: Energy uncertainty as a function of position for 1 mm strip width and 100 μm Kapton thickness, as calculated analytically by the method derived above.

Example results of this method for these two geometries are shown in Figures 4.7, 4.8, 4.9, and 4.10. As can be seen from the results, the energy and position uncertainty vary as a function of position. This is an expected result based on the shape and amplitude of the weighting potentials and weighting potential ratios.

For each geometry, the arithmetic mean was taken of the position and energy uncertainties, like those shown in the examples given in Figures 4.7 through 4.10. The mean serves as a figure of merit for the electrode geometry's position and energy uncertainty by which it can be compared against other geometries. The summary of these results can be seen in Figures 4.11 and 4.12.

From these results, we can see that thinner strip widths provide better average position resolution. This can be explained using Equation 4.7. The inverse pro-

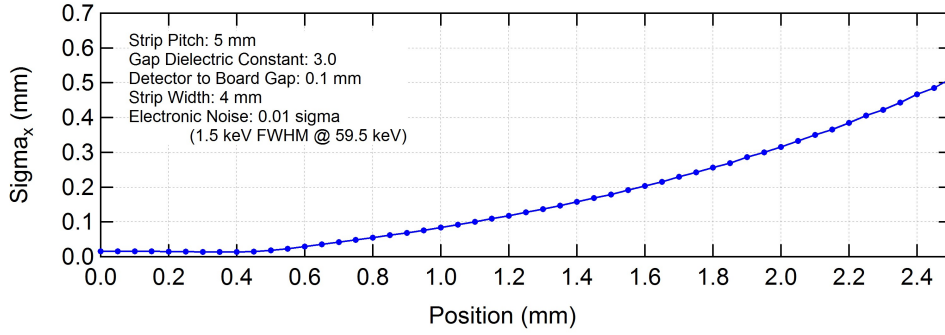


Figure 4.9: Position uncertainty as a function of position for 4 mm strip width and 100 μm Kapton thickness, as calculated analytically by the method derived above.

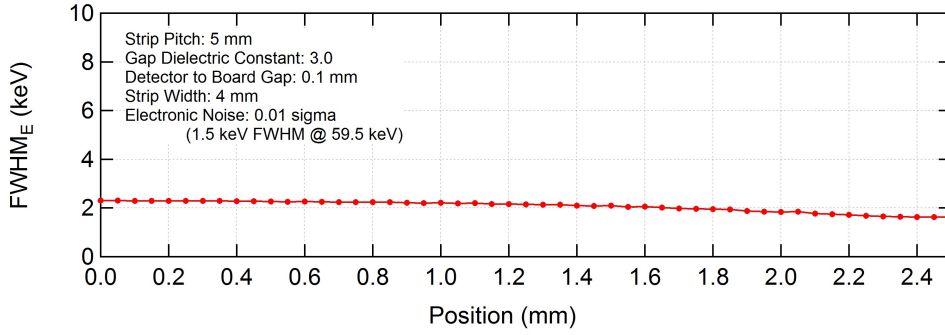


Figure 4.10: Energy uncertainty as a function of position for 4 mm strip width and 100 μm Kapton thickness, as calculated analytically by the method derived above.

portionality to p_k , the neighboring strip pulse height, contributes to better position resolution when p_k is large. As the strip width is reduced, p_k increases and is larger over more of the region. Conversely, if the strip width is larger, the neighboring pulse height is small over more of the region, leading to degraded position resolution. The position resolution also varies linearly with the pulse height ratio. From this, we should expect that the position resolution would tend to be better where the pulse height ratio is low. The ratio is always lowest at the midpoint between strips, where the strip weighting potentials are equal, and the ratio is highest at the center of the strip. From Figures 4.7 and 4.9 we can see that the position resolution at the midpoint between strips (0.0 mm) is always better than the resolution at center strip (2.5 mm). The last factor is the inverse of the pulse height ratio derivative with

respect to position. We can see that the weighting potential ratio, and therefore the pulse height ratio, for wide strips varies approximately linearly with position from Figure 4.6. The contribution to the position resolution is approximately constant across the region. With thinner strips, the derivative will vary as a function of position. Examining Figure 4.4, between 1.75 mm and 2.25 mm the derivative is larger than for the rest of the region. The inverse of the derivative is therefore small, and likely accounts for the improved position resolution in the same region, seen in Figure 4.7. The trend towards better position resolution with decreasing strip width can also be seen in Figure 4.11. From this plot, we can also see that, as the strip width decreases, the strips must be closer to the detector surface to maintain sufficient pulse height magnitudes and therefore position resolution. This result ignores any physical limitations in controlling the geometry. As the readout electrodes get closer to the detector surface, the fractional tolerance error increases. Because we assume a uniform stand-off distance, any deviation results in erroneous position and energy extraction. The error is more pronounced for smaller distances. For this reason, it is important to choose a larger stand-off distance for the detector design.

The energy resolution follows a different trend. In this case, better resolution is achieved with wider strips. Examining Equation 4.22, we see that energy resolution improves if the weighting potential does not vary highly with position since the variance depends on the square of the derivative of the weighting potential with respect to position. The energy uncertainty also varies as the inverse square of the weighting potential magnitude, such that strip configurations with larger weighting potential magnitudes will give better resolution. Since wider strips give higher weighting potentials over a larger span of the region, the average energy resolution for wider strips will be better than that of thinner strips. Energy resolution also depends on the inverse square of the derivative of the weighting potential ratio. This seems to have only a minor effect on the energy resolution despite a seemingly strong dependence, as its effects are not apparent in the resulting resolutions shown in Figures 4.8 and 4.10. The final dependence is on the square of the pulse height ratio. In the case of the 1 mm strip width, at the midpoint between strips, the effects of the pulse height ratio and the weighting potential seem to cancel, resulting in a fairly constant energy resolution as a function of position. The increase in uncertainty at positions >1.2 mm can be seen as the result of increasing derivatives in Equation 4.22. The decrease in uncertainty at positions >2.0 mm results from the derivatives decreasing and the weighting potential magnitude increasing. Similar conclusions can be drawn for the 4 mm strip width results in Figure 4.10. The contributions of the individual terms effectively cancel each other in this case, resulting in a fairly constant energy resolution across the full region.

These trends can also be seen in the region averaged uncertainties shown in Fig-

ures 4.11 and 4.12. For each strip width shown in the different trend lines, the uncertainty is plotted for varying distances between the strips and the detector surface (also referred to as board to detector gap or Kapton thickness). For each strip width, there is an optimal Kapton thickness for the position uncertainty and the energy uncertainty. Uncertainties are minimized in both cases with a small Kapton thickness. The position uncertainty improves as the strip width decreases. The energy uncertainty improves as the strip width increases.

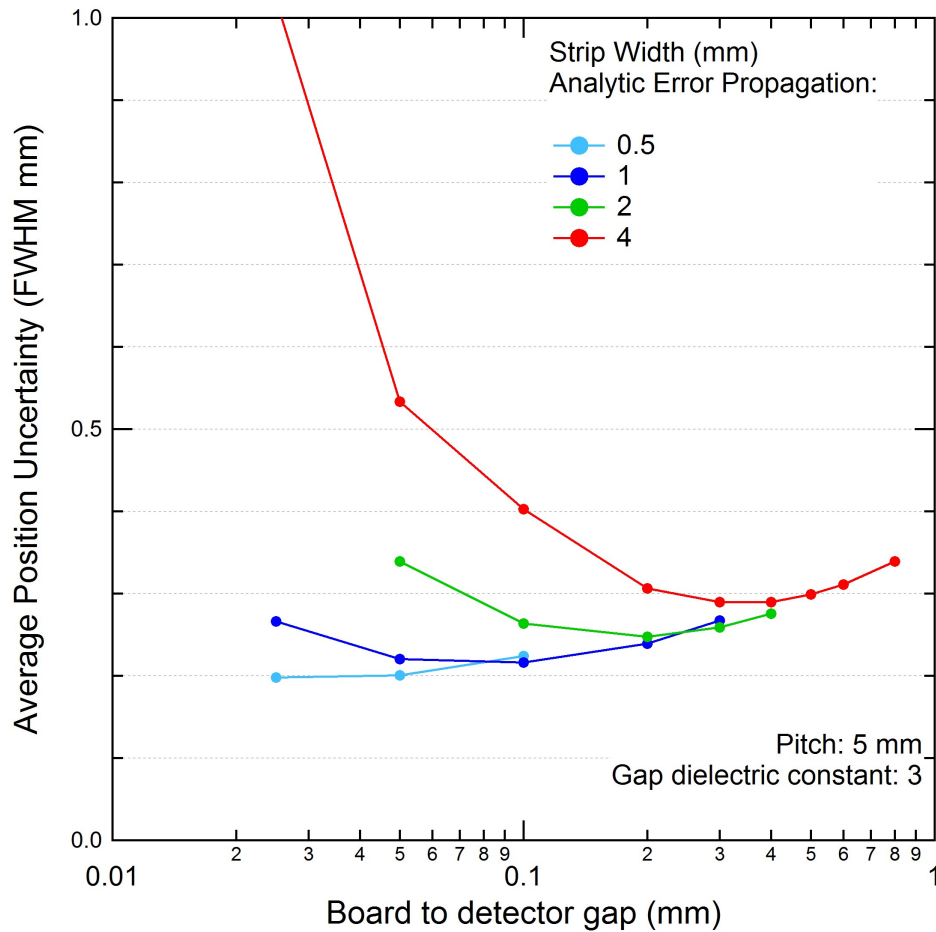


Figure 4.11: Results of the semi-analytic uncertainty propagation optimization method for position uncertainty. These results were obtained by averaging the results of one region for the readout electrode geometry given by the curve and the board to detector gap in the figure. The general trend shows that thinner strips that are closer to the detector crystal surface give better position resolution.

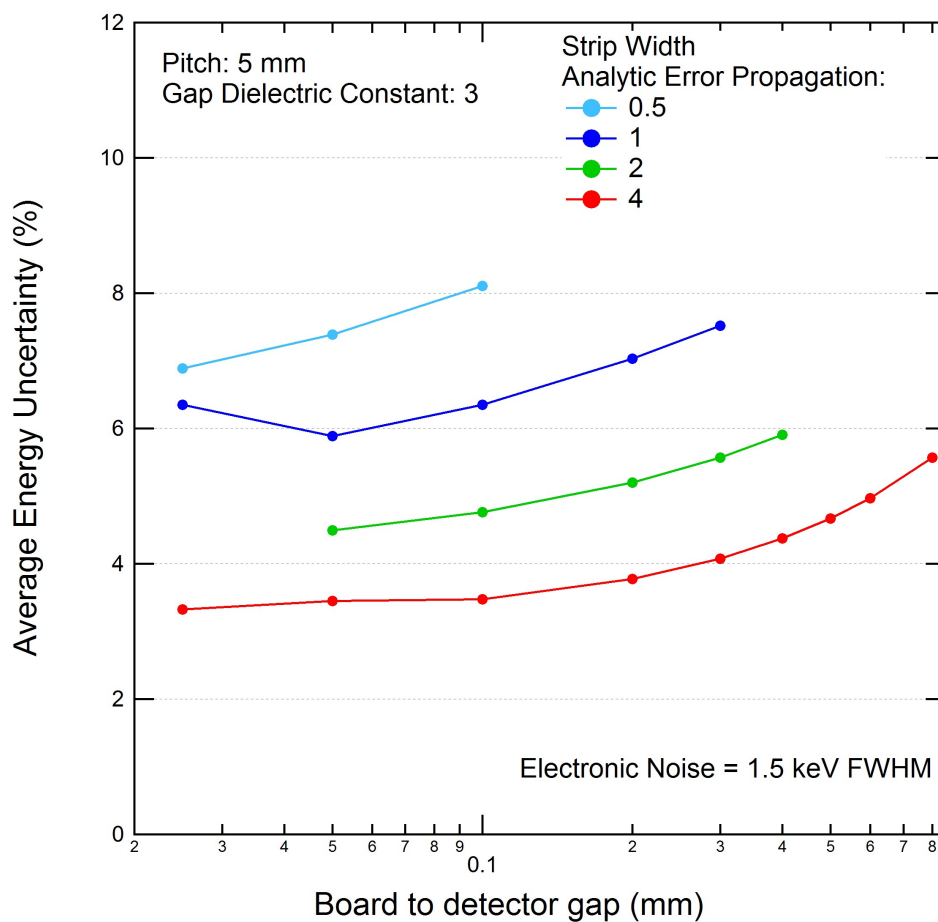


Figure 4.12: Results of the semi-analytic uncertainty propagation optimization method for energy uncertainty. These results were obtained by averaging the results of one region for the readout electrode geometry given by the curve and the board to detector gap in the figure. The general trend shows that wider strips that are closer to the detector crystal surface give better energy resolution.

4.3 Monte Carlo Method

The analytic method presented in the previous section provides approximations of the position and energy uncertainties, which give physical insight into the dependence of the uncertainties on the geometry of the strips. However, because the analytic calculation is an approximation, it will not be accurate for all geometries. For this reason, we pursued a Monte Carlo method to validate the results of the analytic method. In this method, the weighting potentials were used to generate simulated events that were then reconstructed using the method presented in Section 3.1. The resulting distributions were analyzed and the results were used to compare the performance of each geometry.

4.3.1 Method of Event Propagation

Using the same weighting potentials that were employed for the analytic method, the pulse heights, p_j and p_k , were set using the weighting potentials $\phi_{0,j}(x_i)$ and $\phi_{0,k}(x_i)$, respectively, for each x_i on an equally spaced grid spanning one region. One million events per grid position were generated using the weighting potential, and separately seeded Gaussian noise equal to the electronic noise of the system was added to each event such that the event was representative of a real detector event. The fabricated pulse heights were then propagated through the reconstruction method described in Section 3.1. The resulting distributions were analyzed and the results were recorded for comparison. This error propagation method should give the best performance limits since it assumes perfect knowledge of the system when reconstructing the data.

Examples of weighting potential positions, pulse heights, extracted positions, and extracted energies are given in Figures 4.13 through 4.20. The three example positions are 0.0 mm (the midpoint between strips j and k), 1.25 mm (measured from the midpoint), and 2.5 mm (directly below strip j).

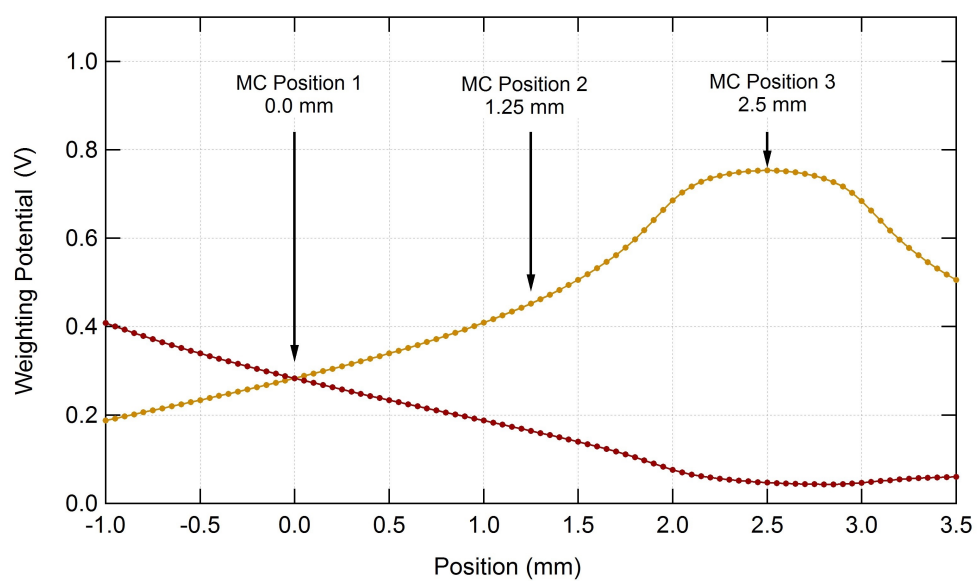


Figure 4.13: Example weighting potentials used for Monte Carlo electrode optimization. The positions indicated show the weighting potential positions used for the data shown in Figs 4.14 through 4.16.

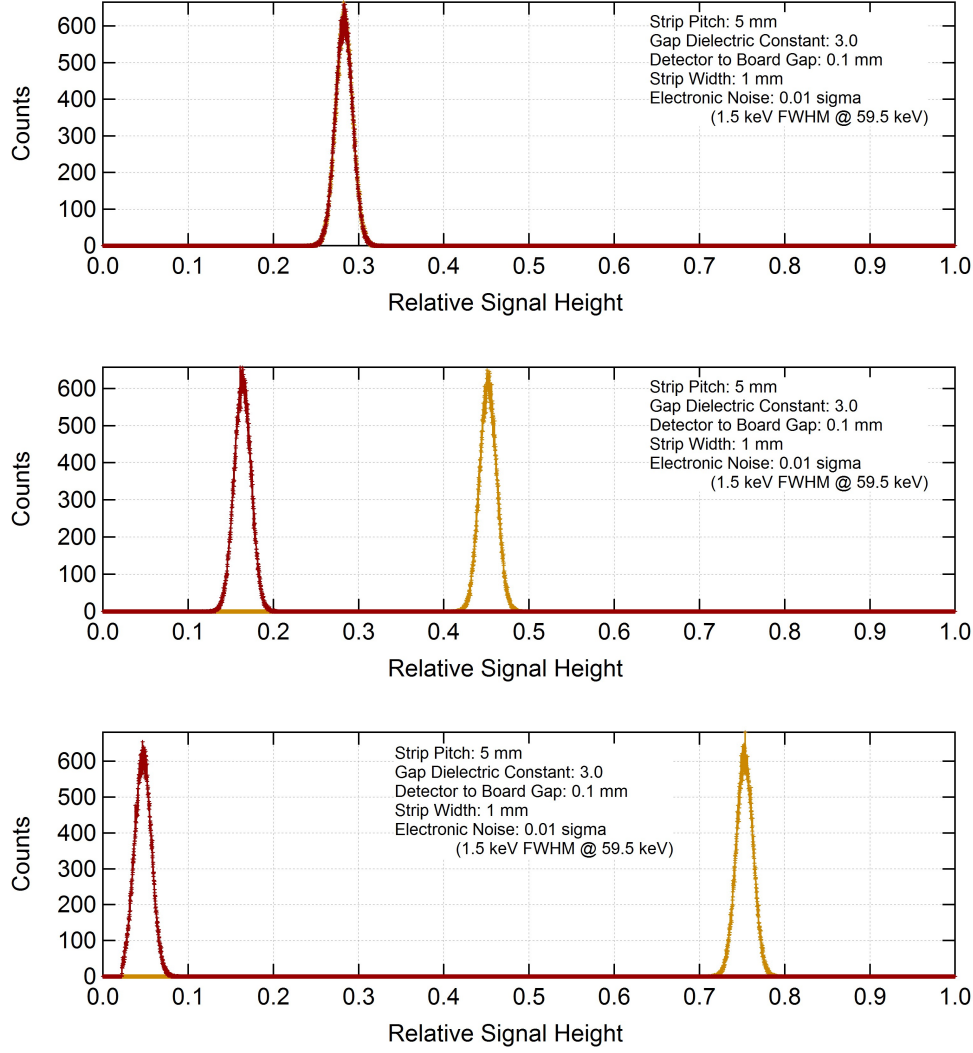


Figure 4.14: Pulse height histograms from the three example positions indicated in Figure 4.13. The pulse heights are representative of the weighting potential for each strip (p_j in yellow and p_k in red) at the position of the events. The example positions are 0.0 mm, 1.25 mm and 2.5 mm, measured from the start of the region, which is at the midpoint between strips. The pulse height units are volts based on the weighting potentials.

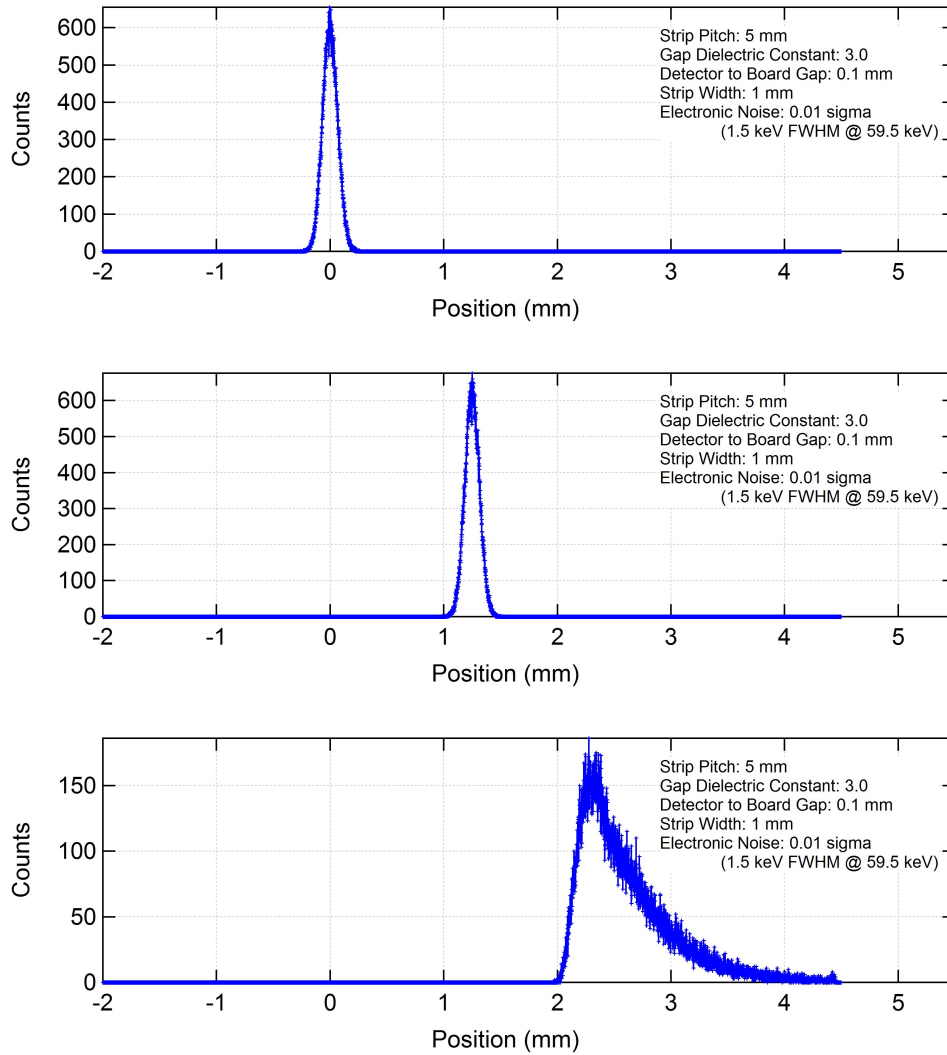


Figure 4.15: Extracted position histograms at three example positions: 0.0 mm (top), 1.25 mm (middle) and 2.5 mm (bottom). The position of each event was extracted using the method presented in Section 3.1. The resolution was measured by calculating the variance of each distribution.

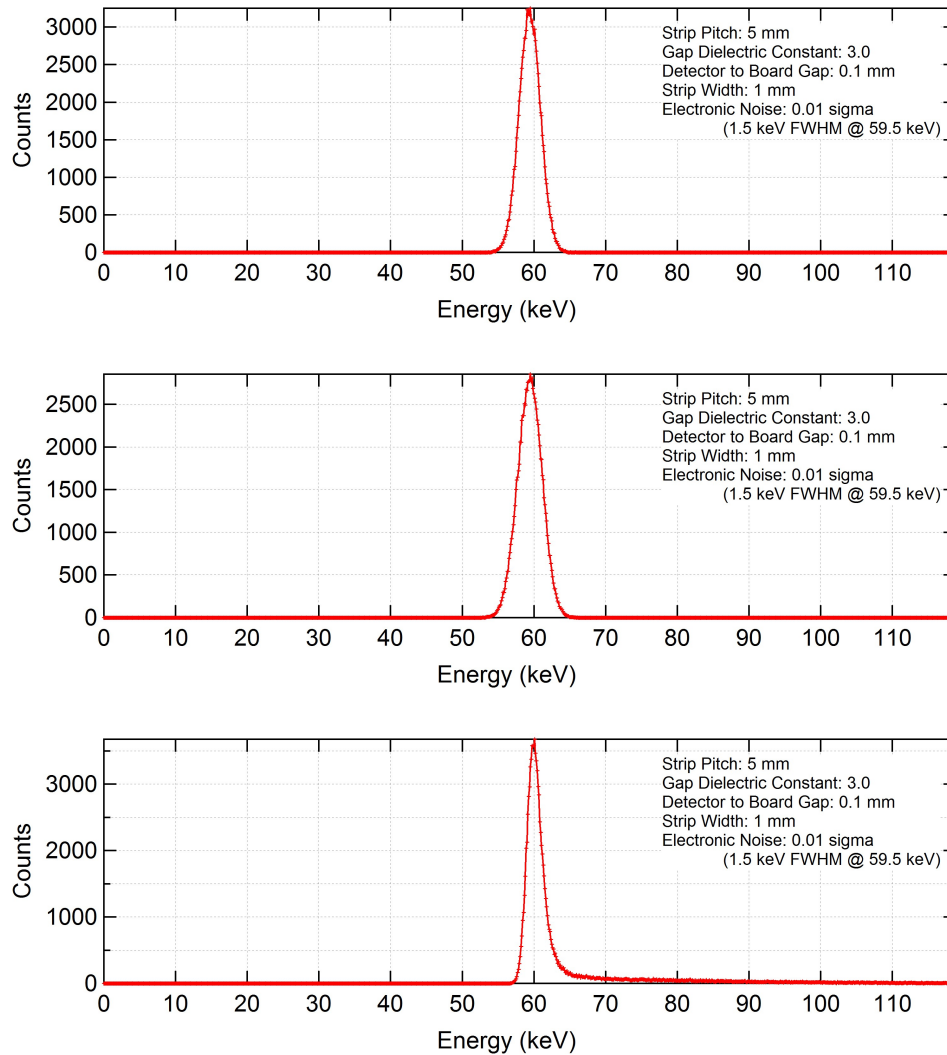


Figure 4.16: Extracted energy histograms at three example positions: 0.0 mm (top), 1.25 mm (middle) and 2.5 mm (bottom). The energy of each event was extracted using the method presented in Section 3.1. The resolution was measured by calculating the variance of each distribution.

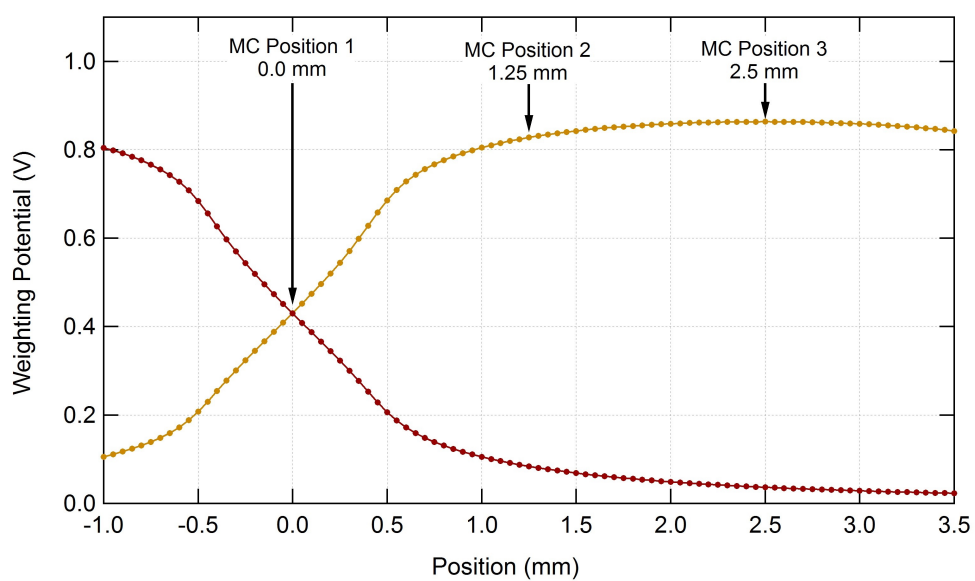


Figure 4.17: Example weighting potentials used for Monte Carlo electrode optimization. The positions indicated show the weighting potential positions used for the data shown in the next nine figures.

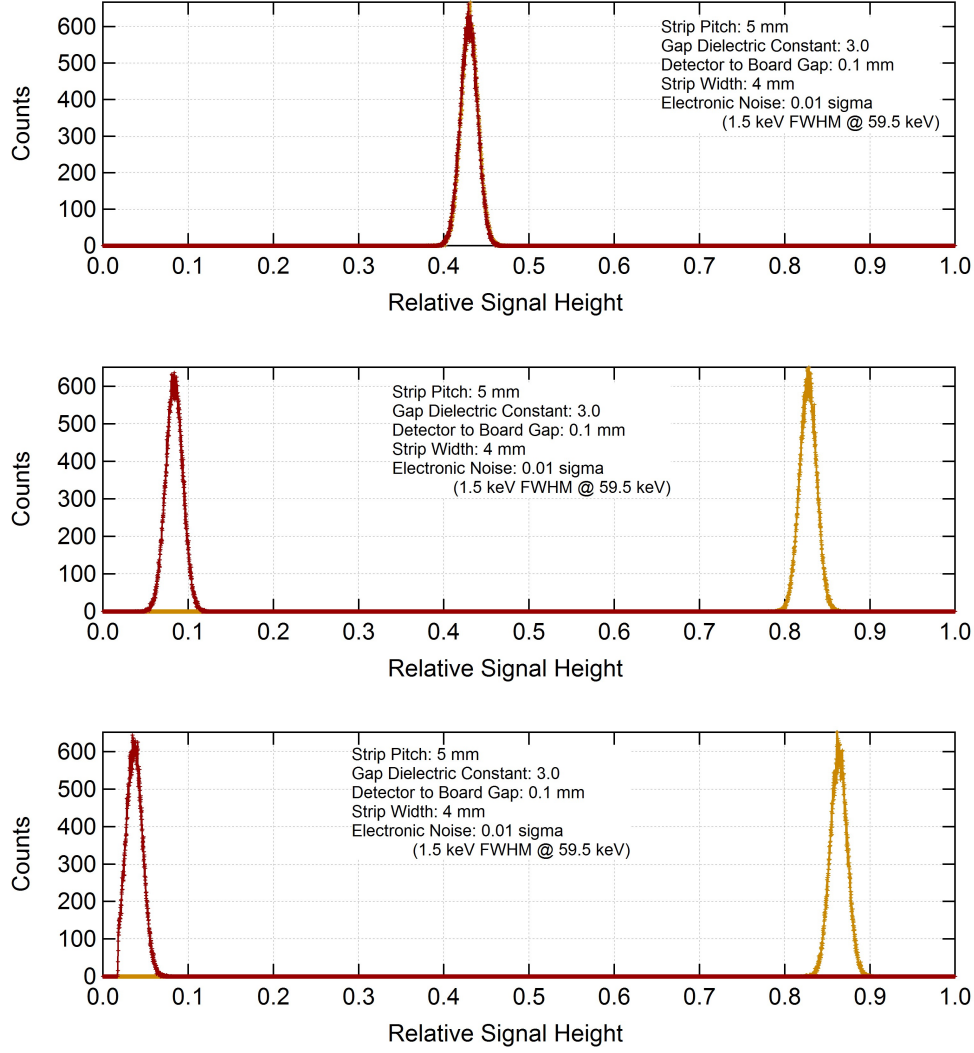


Figure 4.18: Pulse height histograms from the three example positions indicated in Figure 4.17. The pulse heights are representative of the weighting potential for each strip (p_j in yellow and p_k in red) at the position of the events. The example positions are 0.0 mm, 1.25 mm and 2.5 mm, measured from the start of the region, which is at the midpoint between strips. The pulse height units are volts based on the weighting potentials.

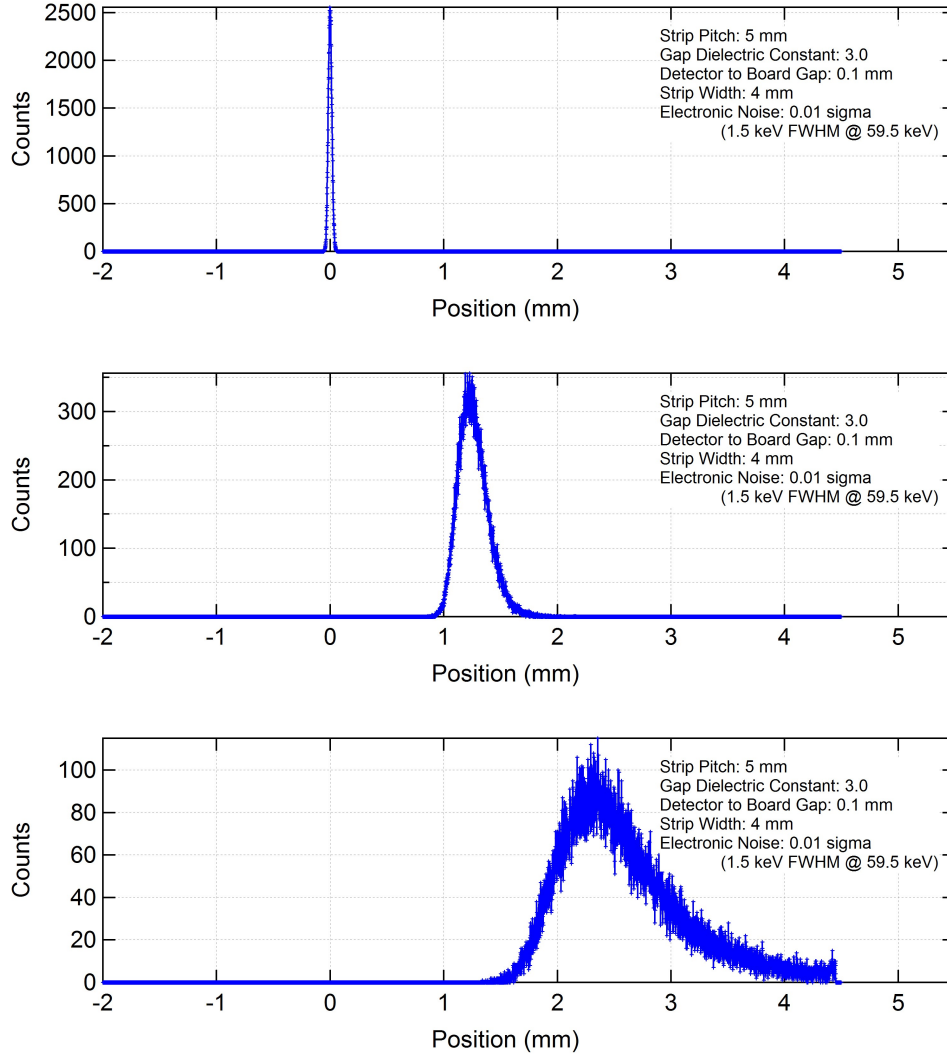


Figure 4.19: Extracted position histograms at three example positions: 0.0 mm (top), 1.25 mm (middle) and 2.5 mm (bottom). The position of each event was extracted using the method presented in Section 3.1. The resolution was measured by calculating the variance of each distribution.

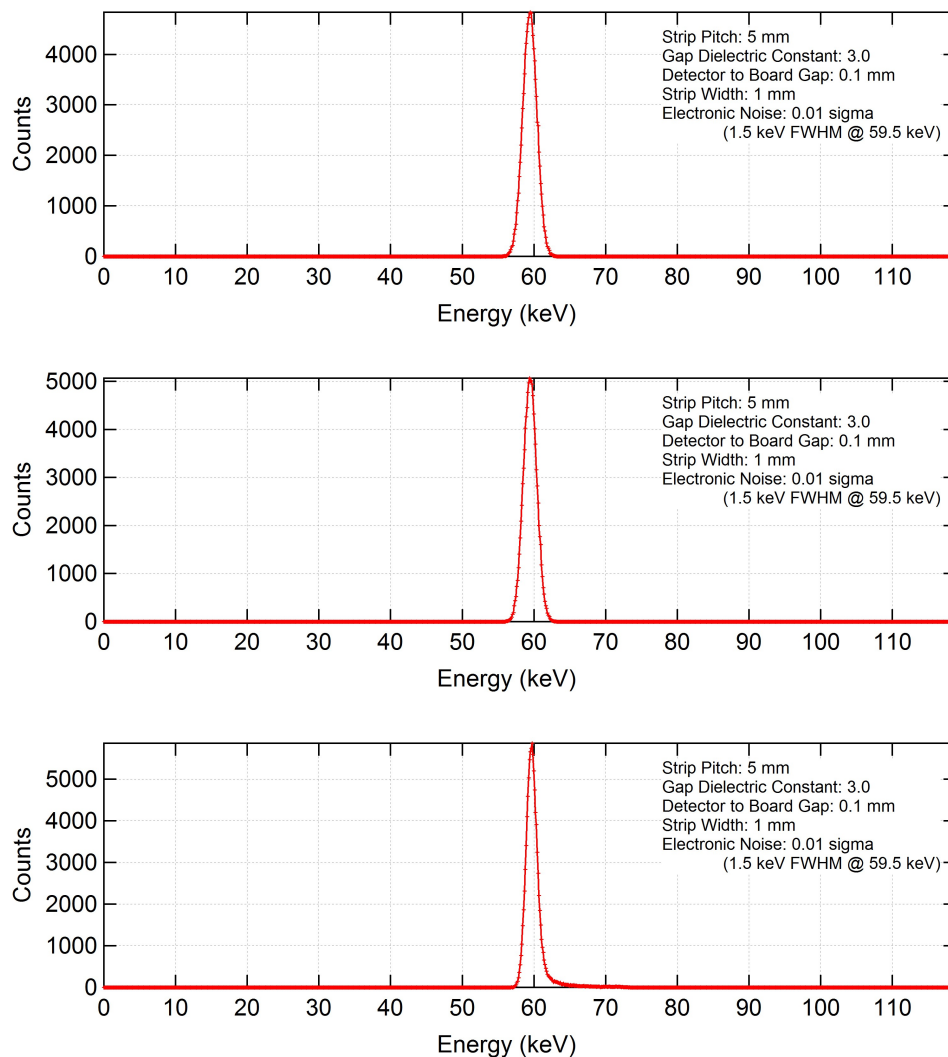


Figure 4.20: Extracted energy histograms at three example positions: 0.0 mm (top), 1.25 mm (middle) and 2.5 mm (bottom). The energy of each event was extracted using the method presented in Section 3.1. The resolution was measured by calculating the variance of each distribution.

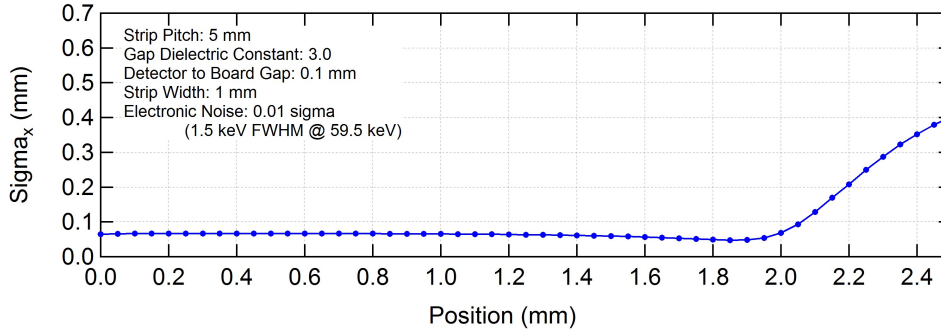


Figure 4.21: Extracted position uncertainty as a function of position for 1 mm strips with 100 μm Kapton thickness using the position extraction method presented in Section 3.1. This curve was calculated using simulated events and propagating them through the position extraction method.

4.3.2 Results and Discussion

Results from the Monte Carlo method are very similar to the semi-analytic method, which demonstrates that the results can be verified. The distinguishing difference is the result of the propagation of position uncertainty to the energy uncertainty close to the middle of the strip. This is highly pronounced in the 1 mm strip width, 100 μm Kapton thickness results shown in Figure 4.21. Between 0.0 mm and 2.0 mm, the energy uncertainty follows the same trend as the analytic results shown in Figure 4.8. While less pronounced, it is still present close to the center of the 4 mm strips.

The summary of these results is shown in Figures 4.25 and 4.26. As was done for the analytic method, the results were distilled down to the average position and energy uncertainties per region. The shapes of the results match those of the analytic method, which gives confidence that each method can be taken to represent the physical system uncertainty. The magnitude of the summarized Monte Carlo results is larger than the analytic results, which can be attributed primarily to the increased uncertainties close to the middle of the strips.

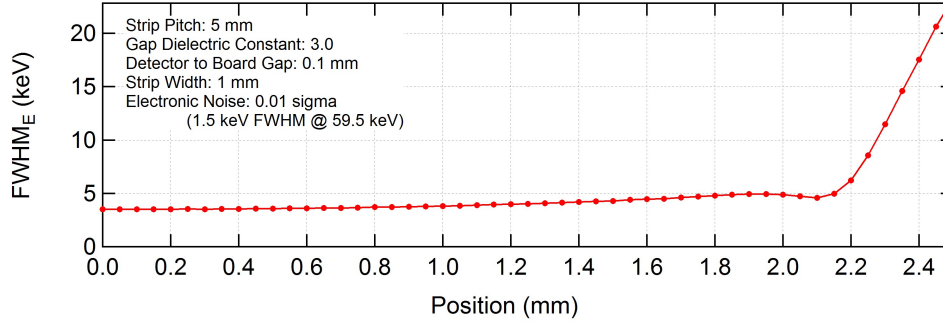


Figure 4.22: Extracted energy uncertainty as a function of position for 1 mm strips with $100\ \mu\text{m}$ Kapton thickness using the energy extraction method presented in Section 3.1. This curve was calculated using simulated events and propagating them through the energy extraction method.

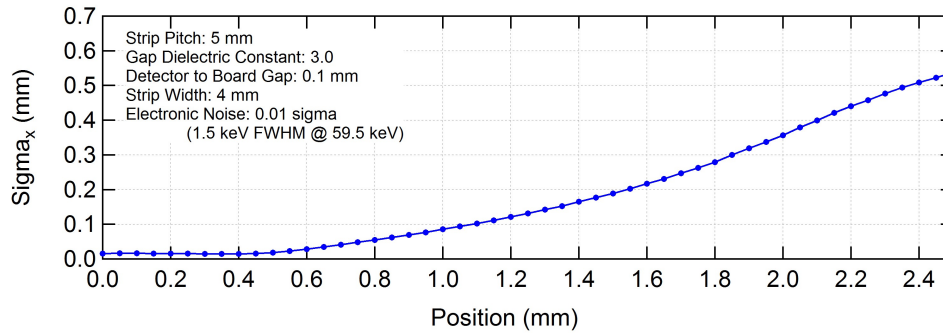


Figure 4.23: Extracted position uncertainty as a function of position for 4 mm strips with $100\ \mu\text{m}$ Kapton thickness using the position extraction method presented in Section 3.1. This curve was calculated using simulated events and propagating them through the position extraction method.

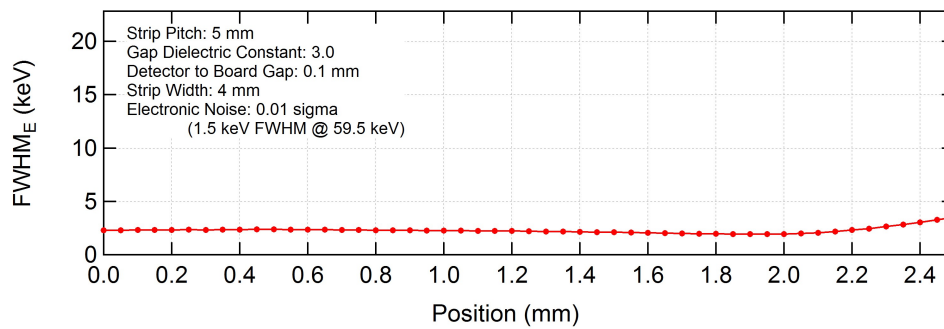


Figure 4.24: Extracted energy uncertainty as a function of position for 4 mm strips with 100 μm Kapton thickness using the energy extraction method presented in Section 3.1. This curve was calculated using simulated events and propagating them through the energy extraction method.

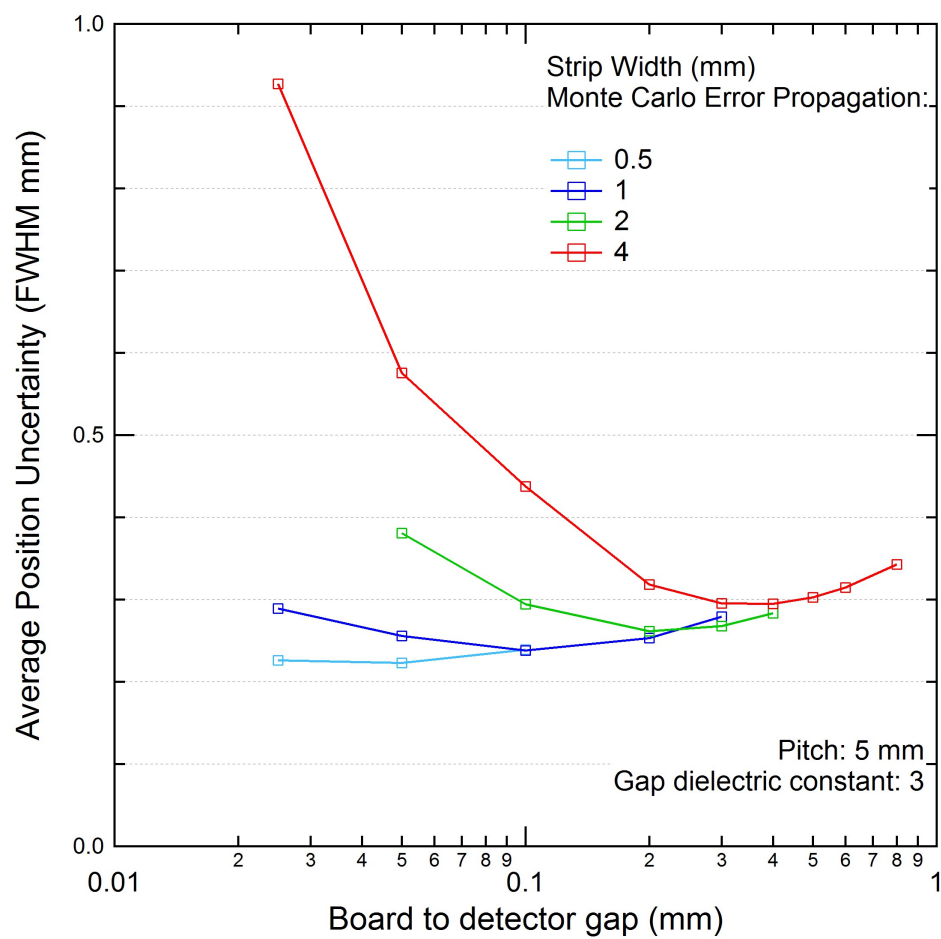


Figure 4.25: Summary of position uncertainty results from the Monte Carlo error propagation method.

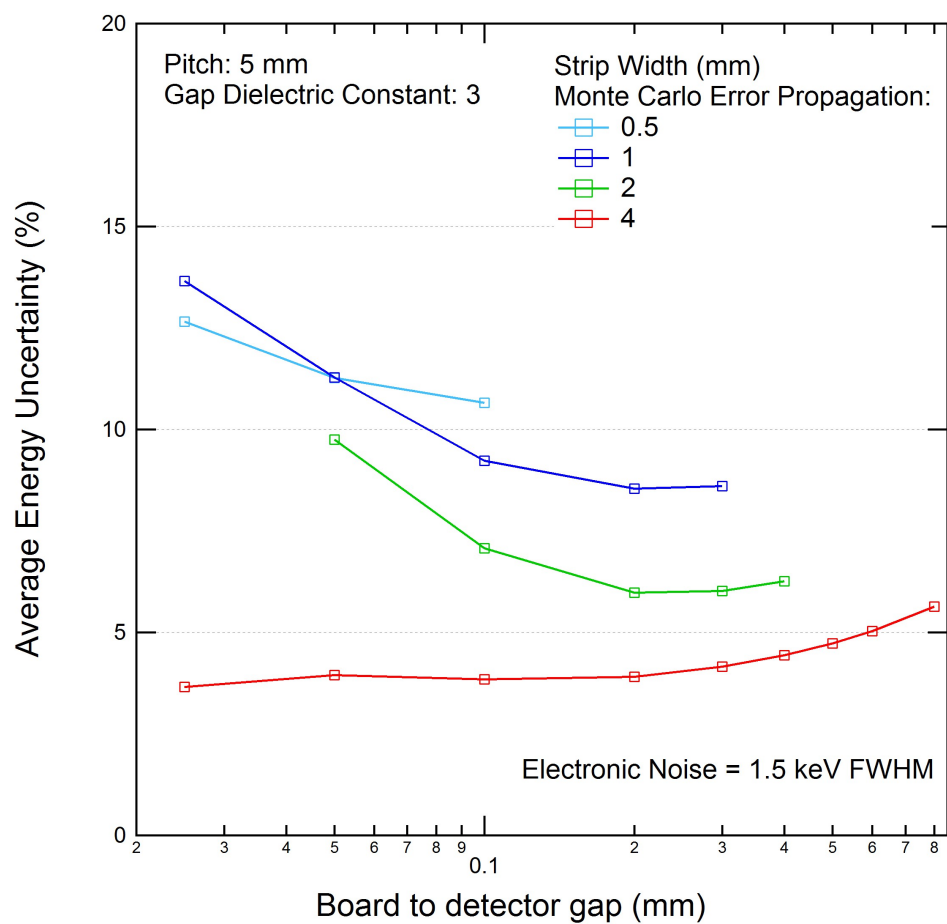


Figure 4.26: Summary of energy uncertainty results from the Monte Carlo error propagation method.

4.4 Comparison of Results and Conclusions

Figures 4.27 and 4.28 summarize the results from the analytic and the Monte Carlo methods. The results show that the position uncertainty improves with decreasing strip width combined with a thinner Kapton film thickness. The energy uncertainty also improves with thinner Kapton thickness, but improves instead with wider strips. This presents a trade-off between energy and position uncertainty optimization. To optimize for position uncertainty, thinner strips are desired. To optimize for energy uncertainty, the strips should be wider.

Another result to note is the significant discrepancy between the analytic method and the Monte Carlo method at thin Kapton thicknesses. Part of this can be attributed to the breakdown of the standard error propagation approximations. It is also due to significant tailing in the extracted position and energy distributions when using the Monte Carlo method. This is the result of the limitations of the position and energy extraction method used for this calculation, for which we assumed a linear extension of the weighting potential ratio for events with a ratio that fell outside the region bounds. This could have been better handled by using the data-based position and energy extraction method presented in Section 3.2.

4.4.1 Selection of Electrode Geometry

The goal of this optimization was to inform our selection of the geometry of a printed circuit board to be used for an optimized proximity readout detector. Because of the trade-off presented above, we chose one geometry to optimize for position resolution and another to optimize for energy resolution. To optimize position resolution while maintaining the ability to control the detector geometry, we chose the 1 mm strip width with a board to detector gap of 100 μm . We chose this thick Kapton film to reduce resolution degradation caused by thickness variation. While a thinner Kapton layer with a smaller strip width would provide better position resolution according to the results presented here, we chose larger features to better control the geometries involved.

For optimal energy resolution, we chose a 4 mm strip width matched with the 100 μm Kapton thickness. This combination provides substantial charge induction on the electrodes, minimizing noise effects, making this an intuitive choice when optimizing for energy resolution. See Figures 4.29 and 4.30 for pictures of the fabricated boards.

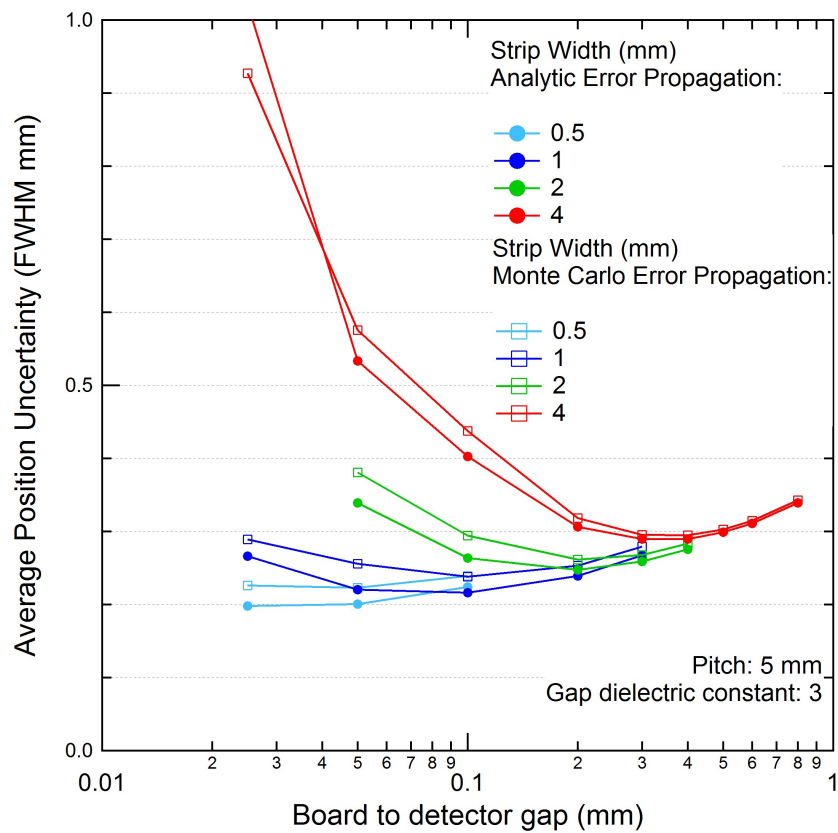


Figure 4.27: Position uncertainty averaged over one region as a function of Kapton thickness and plotted for different strip widths.

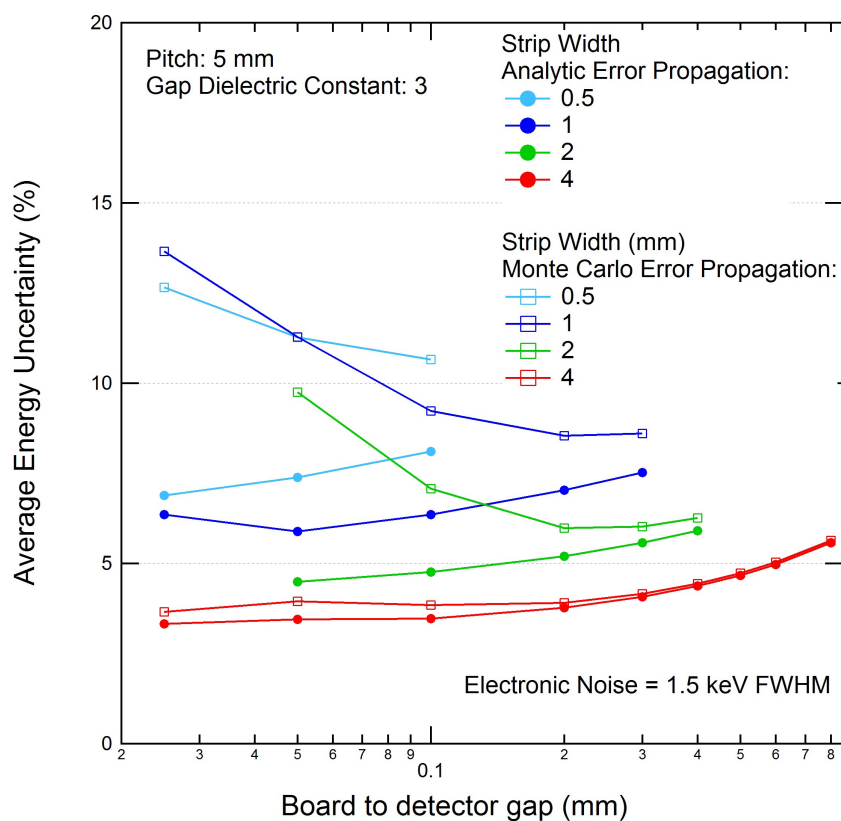


Figure 4.28: Energy uncertainty averaged over one region as a function of Kapton thickness and plotted for different strip widths.

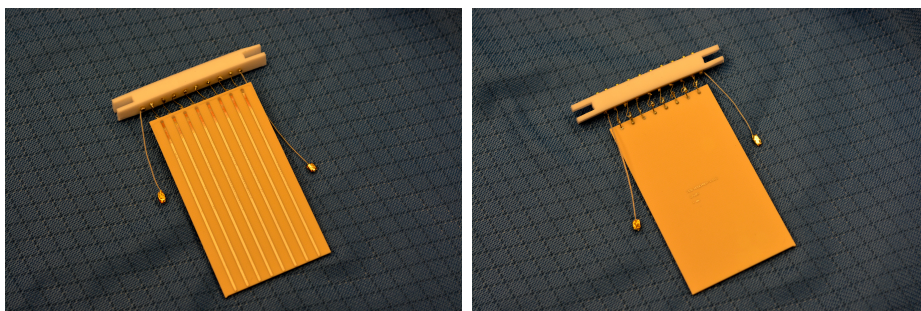


Figure 4.29: Board design that optimizes for position resolution. The strip width is 1 mm. This board will be pressed down on top of a Kapton layer such that the electrodes are approximately $100\ \mu\text{m}$ away from the surface of the HPGc crystal.

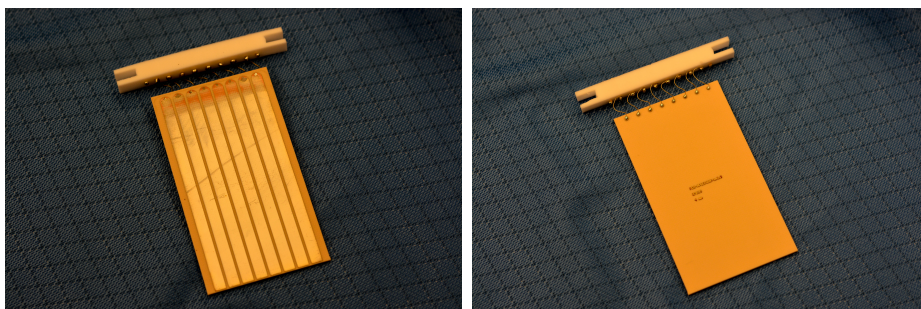


Figure 4.30: Board design that optimizes for energy resolution. The strip width is 4 mm. This board will be pressed down on top of a Kapton layer such that the electrodes are approximately $100\text{ }\mu\text{m}$ away from the surface of the HPGe crystal.

Chapter 5

Fabricated Detectors and Experimental Equipment

We fabricated two detectors at LBNL in the Semiconductor Detector Laboratory. The first was a small prototype detector for demonstrating the proximity electrode readout technique on an HPGe detector and evaluating the position and energy extraction methods introduced in Chapter 3. The second detector was a larger crystal with an optimized proximity readout geometry to test the limitations of this technology. I will present the characteristics of these detectors, the fabrication techniques that were important for this technology, and the associated hardware and software in this chapter. I will also present the setup of the collimators used for scanning measurements.

5.1 Detector Design, Materials, and Fabrication Techniques

All detectors fabricated for this work followed the same design principles and differed only in geometry. HPGe crystals were fabricated into detectors using established fabrication techniques, an example of which is given in Appendix A. We deposited amorphous germanium (a-Ge) films onto all sides of the HPGe crystal to protect the surface from contaminants, passivate dangling bonds at the surface of the crystalline HPGe, provide bipolar blocking where contacts are present, and to provide a resistive layer underneath the proximity electrodes that can transport charge away after it is measured. The a-Ge films were deposited using RF sputtering, and the sputter gas was chosen based on the desired qualities of the film to be deposited. On the high voltage contact surface and the sides of the detector, a high resistivity a-Ge

film was deposited. The conduction mode in a-Ge is variable range hopping between localized states, as presented in Section 2.2.3. Defects in the film including unsatisfied bonds on Ge atoms (“dangling bonds”) act as localized states available for this type of conduction. Single hydrogen atoms can bond with these dangling bonds, making them unavailable for variable range hopping conduction and increasing the resistivity of the film. Hydrogen gas was added to the otherwise inert sputter gas, and the hydrogen gas bond is broken in the plasma, making the hydrogen atoms free to bond with dangling bonds. The sputter gas mixture used for the higher resistivity surfaces was argon with 7% hydrogen.

To achieve the lowest possible resistivity that is needed for the surface below the proximity electrodes, pure argon was used as the sputter gas. Lower resistivity is needed here to allow for the removal of charge from the surface after it has been measured. Inability to remove this charge causes charge buildup and electric field bending or detector failure. It also must be resistive enough to avoid shielding the readout electrodes from charge that is liberated by a radiation event. By crudely modeling this surface as the resistor in an RC circuit, where the capacitance is associated with the electrodes on and near the detector (~ 10 pF), we can derive the resistance of the a-Ge film that gives a reasonable charge dissipation time. A dissipation time of order 1 ms is acceptable, which gives $R_s = 10^8 \Omega/\square$, where R_s is the surface sheet resistance, assuming the readout surface is square. We used this number as our target sheet resistance throughout this project.

All detector iterations have three electrical contacts: a full area, high voltage contact and two grounded electrodes on the opposing surface that establish a uniform electric field and remove charge from the surface below the proximity electrodes (“guard strip” electrodes). These are all aluminum electrodes that are deposited by thermal evaporation with a shadow mask, which occludes the areas where aluminum is not desired and allows for deposition where the contacts will be.

The proximity electrodes are fabricated onto a printed circuit board. The board itself must be made of a low dielectric loss material, for which we chose Rogers 4003. The electrodes are copper, with later iterations immersion plated with silver. By using this design, we hoped to be able to control the geometry of the readout board so that there would be little variation in weighting potential between electrodes or along the length of an electrode.

To establish the correct distance between the readout electrodes and the surface of the detector, we used thin Kapton film. The film is simply placed on the detector surface between the guard strip electrodes, and then the readout board is pressed down onto the film by spring wires that are attached to the detector mount.

Figures 5.1 and 5.2 show simplified schematics of the two detector geometries we used. The schematic in Figure 5.1 shows the proof of principle detector, which had

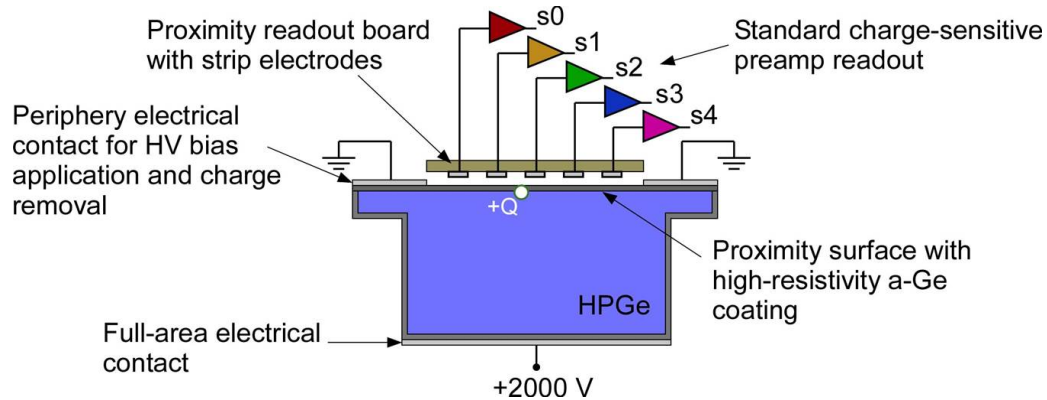


Figure 5.1: Schematic representation of the proof of principle detector design.

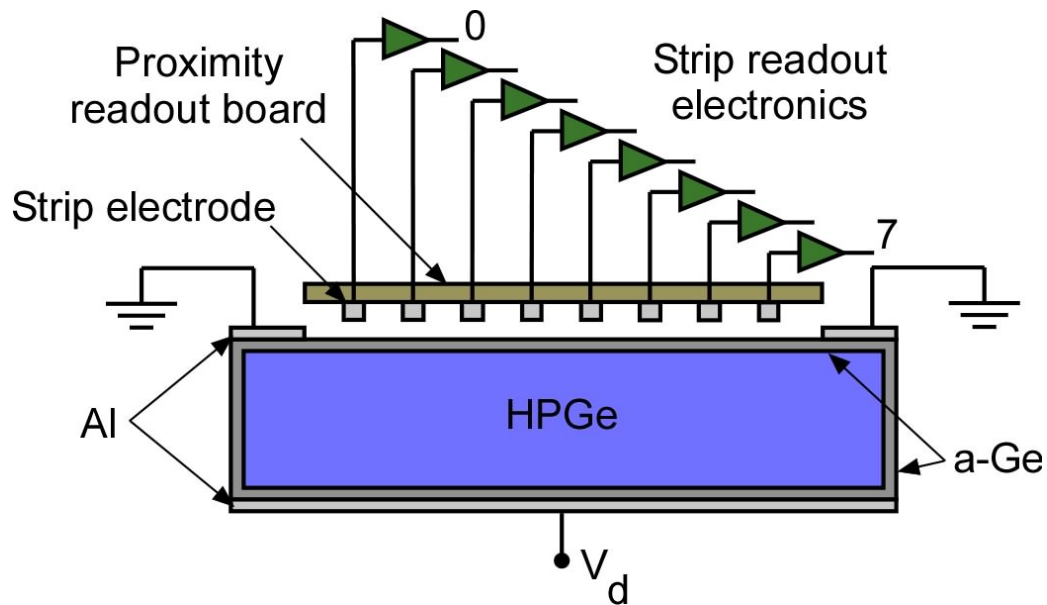


Figure 5.2: Schematic representation of the optimized detector design.

five proximity readout electrodes, each of which was connected to a charge sensitive preamplifier. The design details for this detector will be discussed in the next section. Figure 5.2 shows the layout of the optimized detector with eight individually instrumented proximity electrodes. Both detector designs have a-Ge contacts and passivated surfaces. Two guard strip electrodes straddle the proximity electrodes, and the full-area high voltage contact is deposited on the opposite surface.

5.2 Fabricated Detectors

5.2.1 Proof of Principle Detector

For a prototype detector aimed at demonstrating the proximity electrode signal readout method, we chose a detector geometry that we often use for testing fabrication methods because we have a number of HPGe crystals in this geometry, the crystal handling hardware exists, and the fabrication process is well documented. The geometry of the active volume of the detector is $18 \times 18 \text{ mm}^2$ in cross sectional area and 10 mm thick. The depletion voltage for the crystal used is $\sim 250 \text{ V}$, and the detector was operated at 1000 V. There are inactive “wing” regions that facilitate handling during detector fabrication. The wings remain undepleted during operation because there is no field penetration into this region, and therefore any damage to these regions will not result in additional leakage current. The wings are also used for detector mounting and as the thermal contact points for cooling.

The proximity readout board for this detector had five strips with a 2 mm pitch. Each strip was 0.76 mm wide. The board was pressed down on two 0.076 mm thick Kapton films for a total stand-off distance of approximately $150 \mu\text{m}$.

5.2.2 Optimized Detector

The second detector we fabricated used the uncertainty propagation results presented in Section 4.4 to choose a board design to best optimize for position resolution. I will refer to this detector as the optimized detector. The HPGe crystal used for the optimized detector measures $54 \times 54 \text{ mm}^2$ active area and 11 mm thick. The depletion voltage is $\sim 900 \text{ V}$, and the operating voltage was 1000 V for all measurements. The crystal has a circular wing that measures 81 mm in diameter.

We designed a readout board and had it fabricated based on the results of the optimization presented in Chapter 4. We used 1 mm width strips at a 5 mm pitch set approximately $100 \mu\text{m}$ from the crystal surface to optimize for position resolution. To achieve this standoff, two 0.002 in (0.051 mm) thick Kapton layers were placed between the crystal and the readout board. The proximity readout board is pressed down on top of the Kapton layers. It is difficult to say how uniform the standoff distance is due to the challenge to measure this distance. Quantifying uncertainty is difficult for this reason. The board has metal plated vias at the end of each strip electrode that allow for soldered connections to readout wires. These wires are then connected to a teflon feed through to pass through the mount wall. Secondary wires then go to a cryostat wall feed through, and then to the preamplifier inputs.

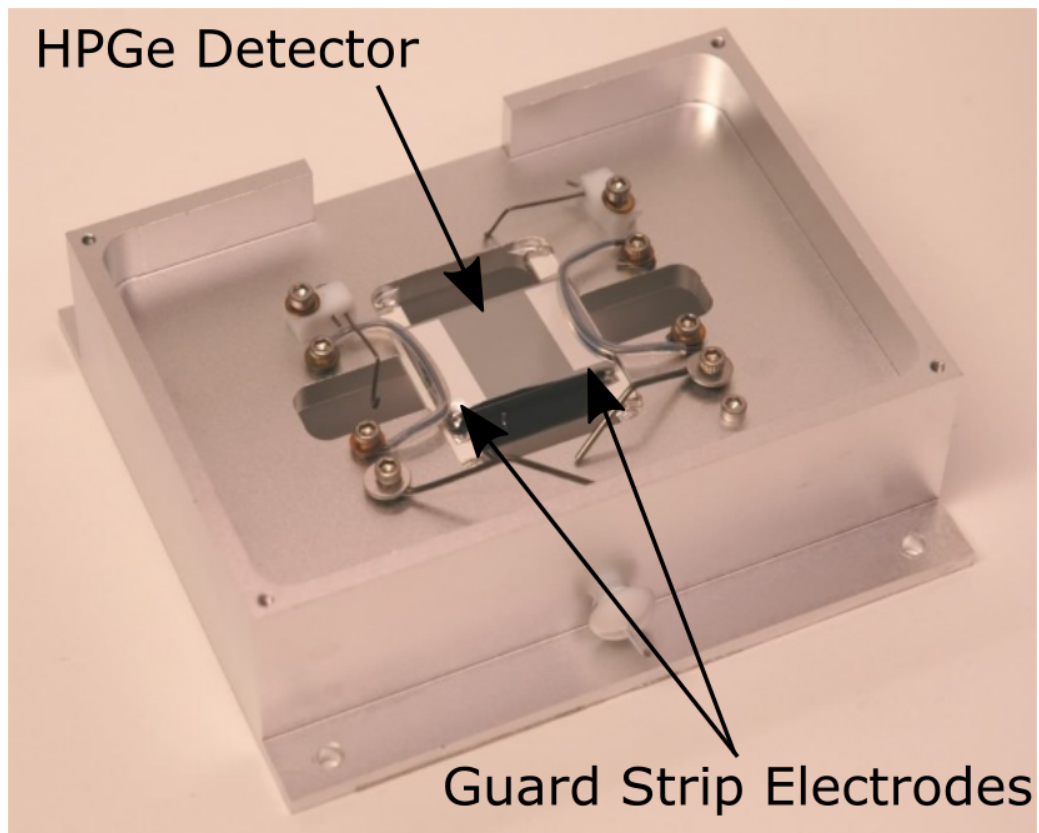


Figure 5.3: Proof of principle detector in the detector mount and without the proximity readout board mounted.

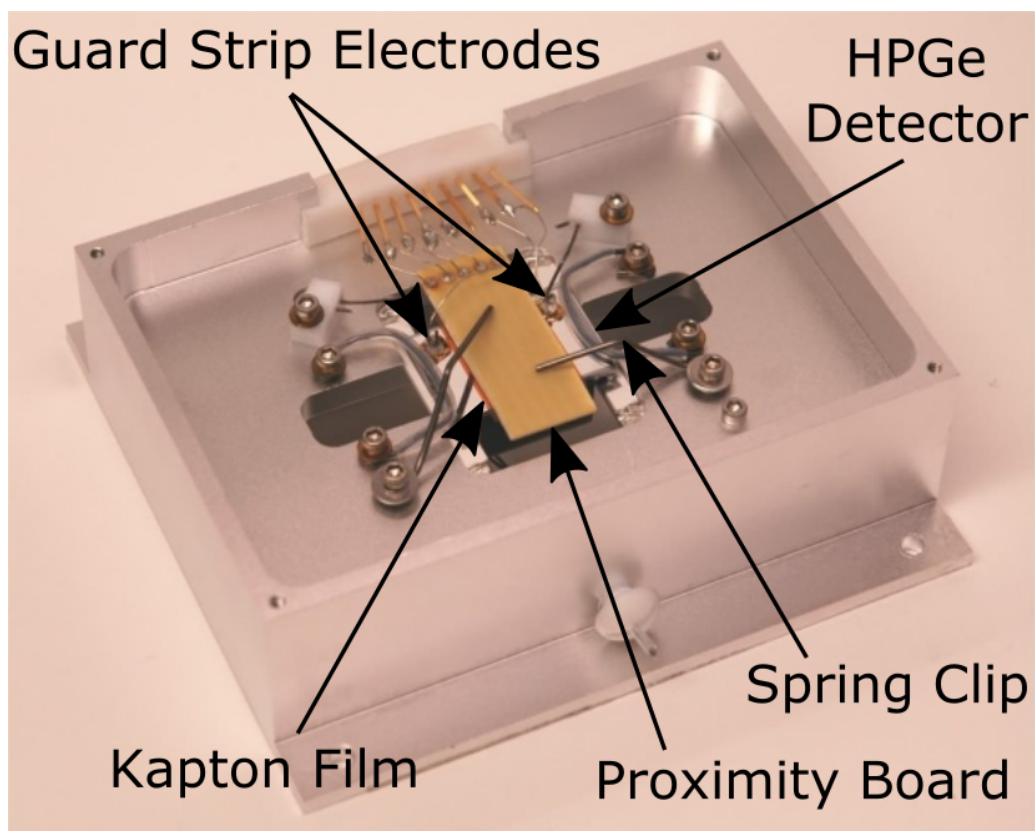


Figure 5.4: Proof of principle detector with the proximity readout board mounted.

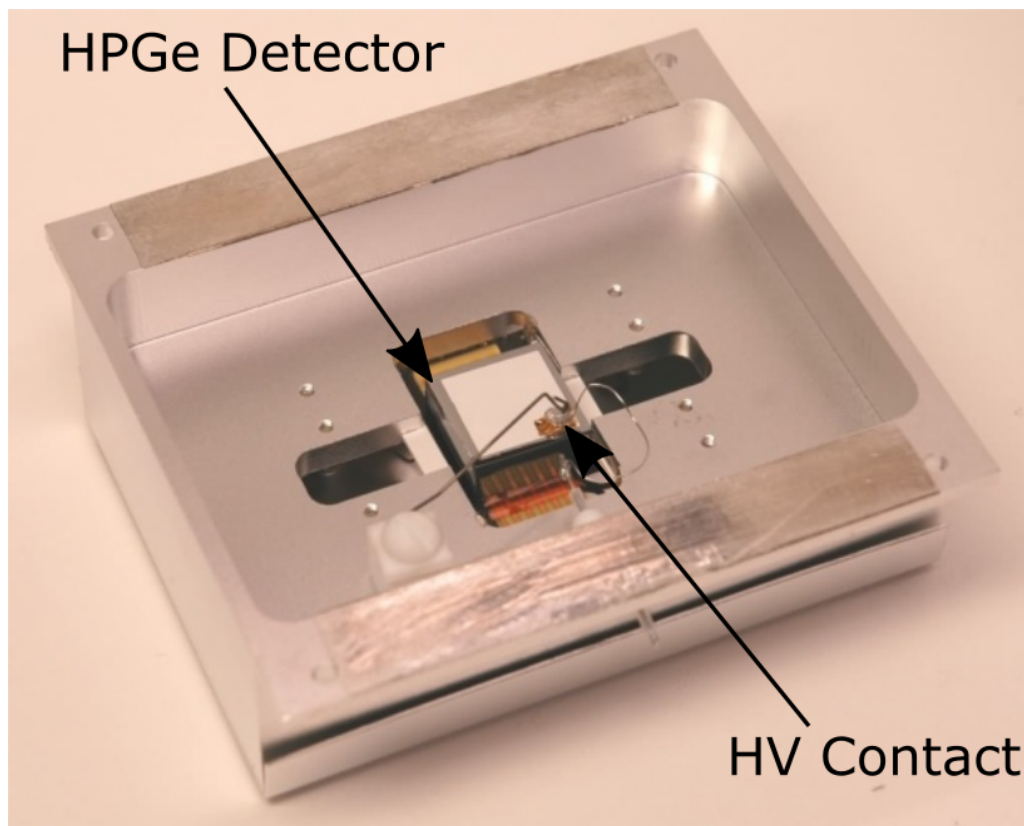


Figure 5.5: Proof of principle detector in the detector mount showing the high voltage side.

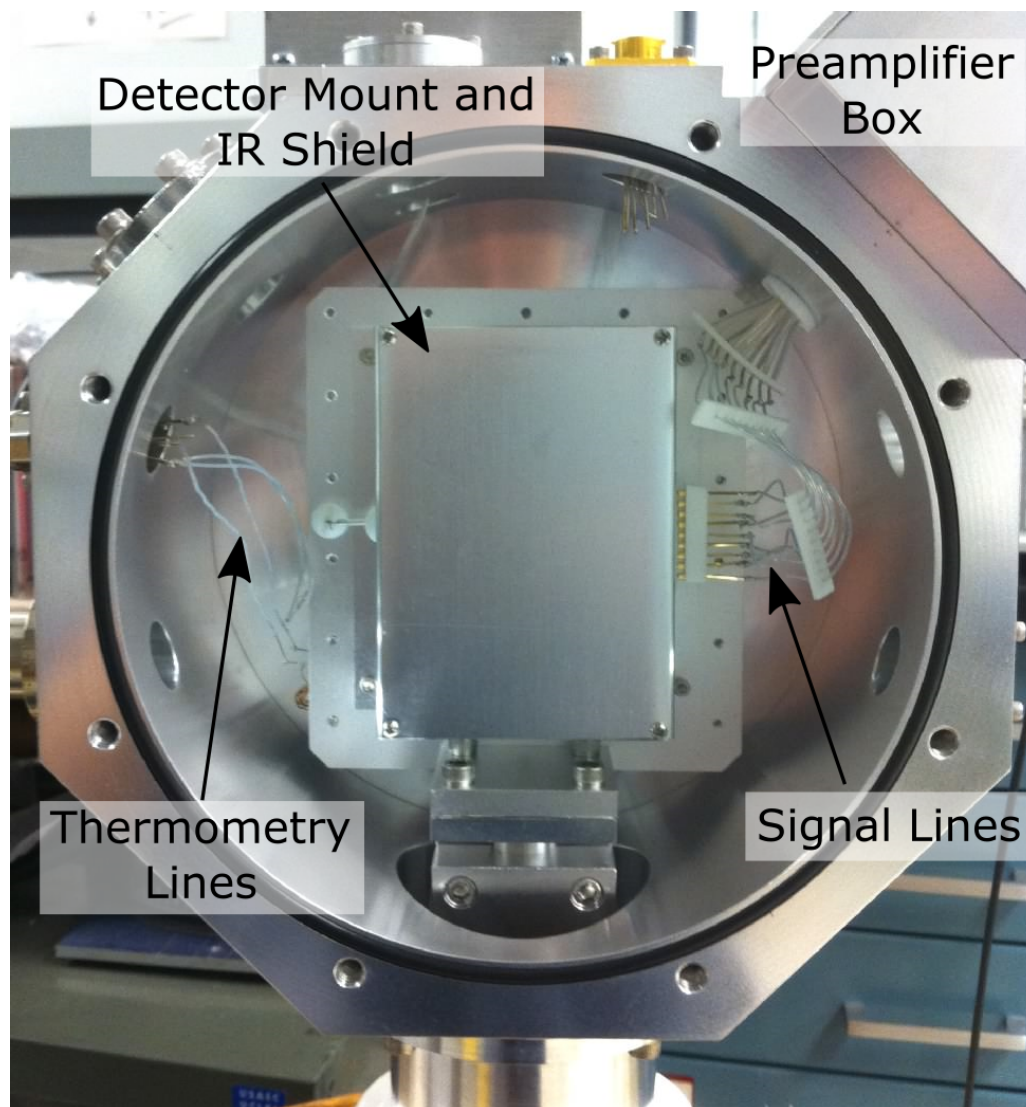


Figure 5.6: Proof of principle detector mounted into the cryostat. Each strip is connected to a wire that runs to a charge sensitive preamplifier, which are located in the box in the upper right. Covering the detector is the IR shield.

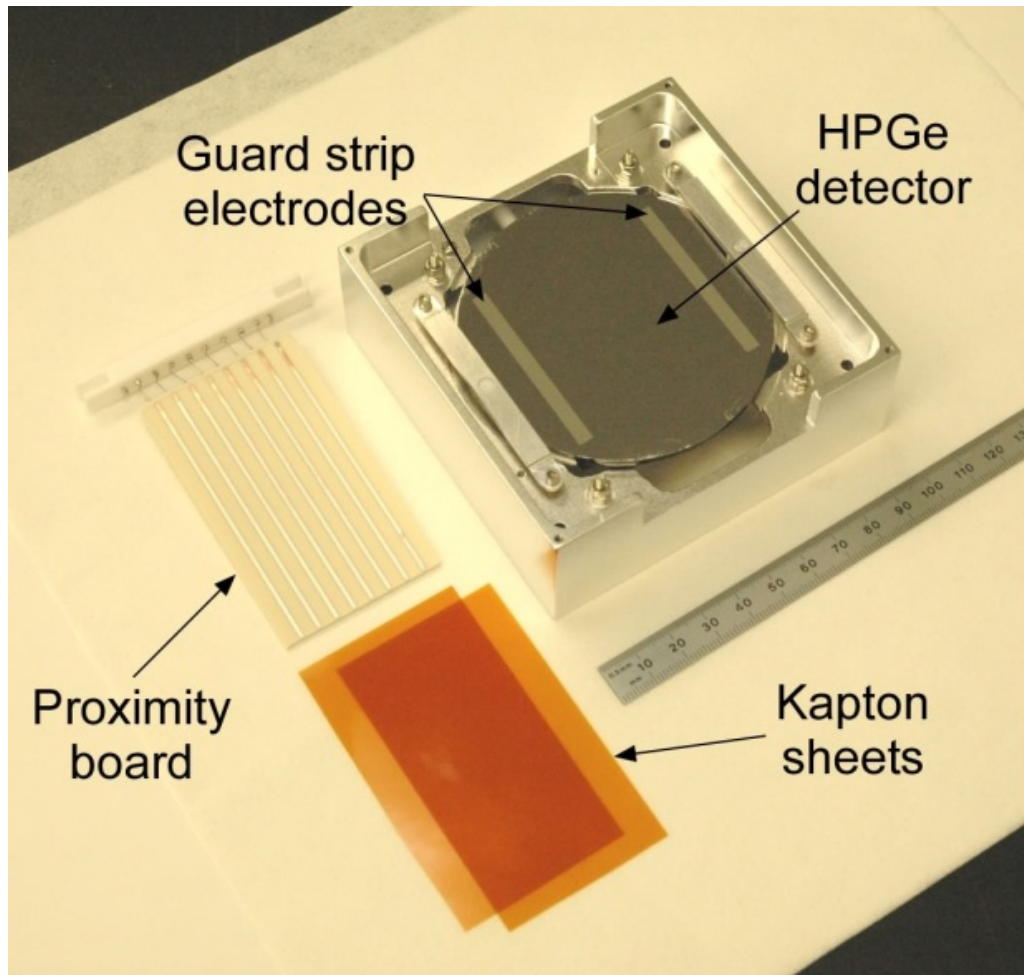


Figure 5.7: Optimized detector crystal fabricated to operate with proximity charge sensing readout. The 1 mm strip width readout board is to the left of the detector crystal, with the Kapton films used to set the distance between the board and the crystal surface.

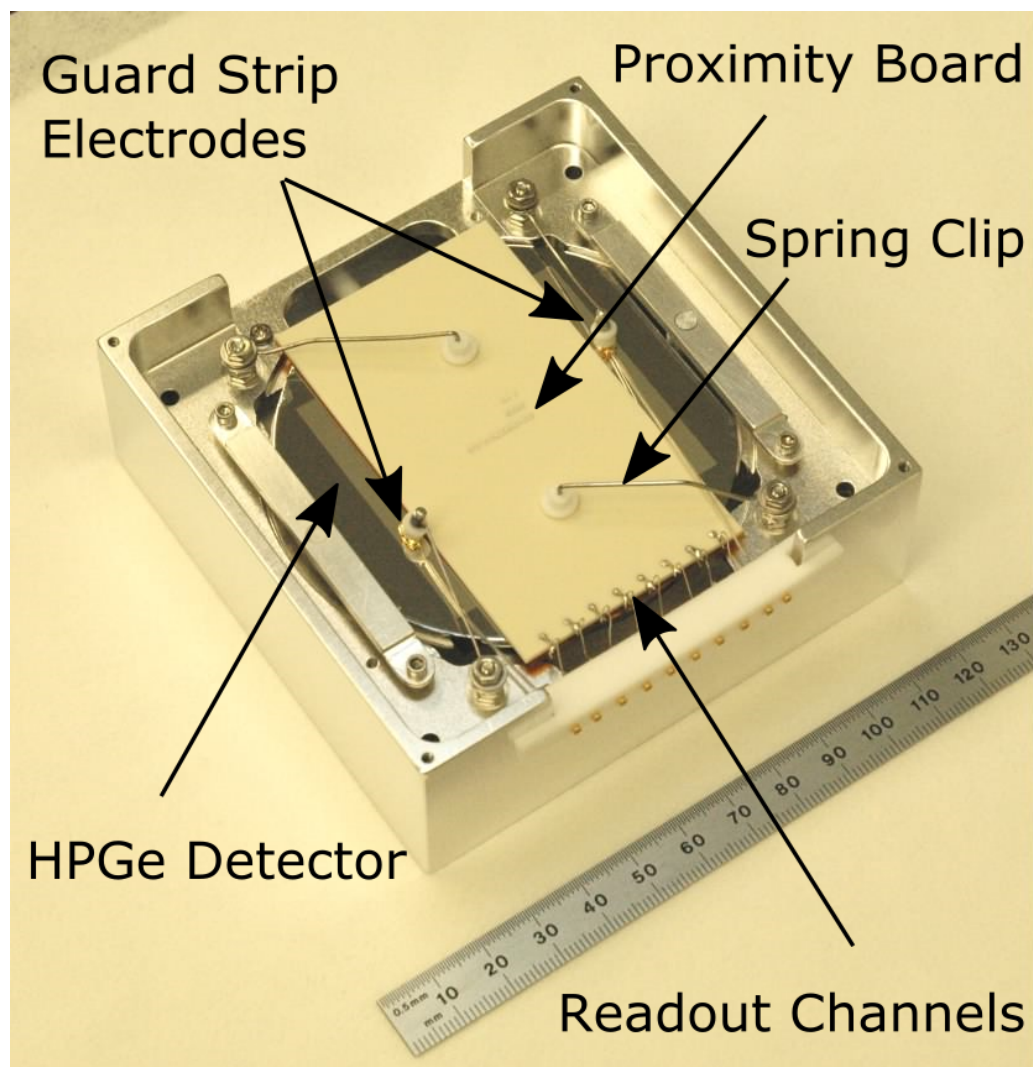


Figure 5.8: Optimized detector crystal fabricated to operate with proximity charge sensing readout with the 1 mm strip width readout board mounted onto the detector crystal, with the Kapton films used to set the distance between the board and the crystal surface (not visible in this picture). The electrical contacts that are pressed down on either side of the board to the guard strip electrodes allow for high voltage application and charge removal from the proximity surface.

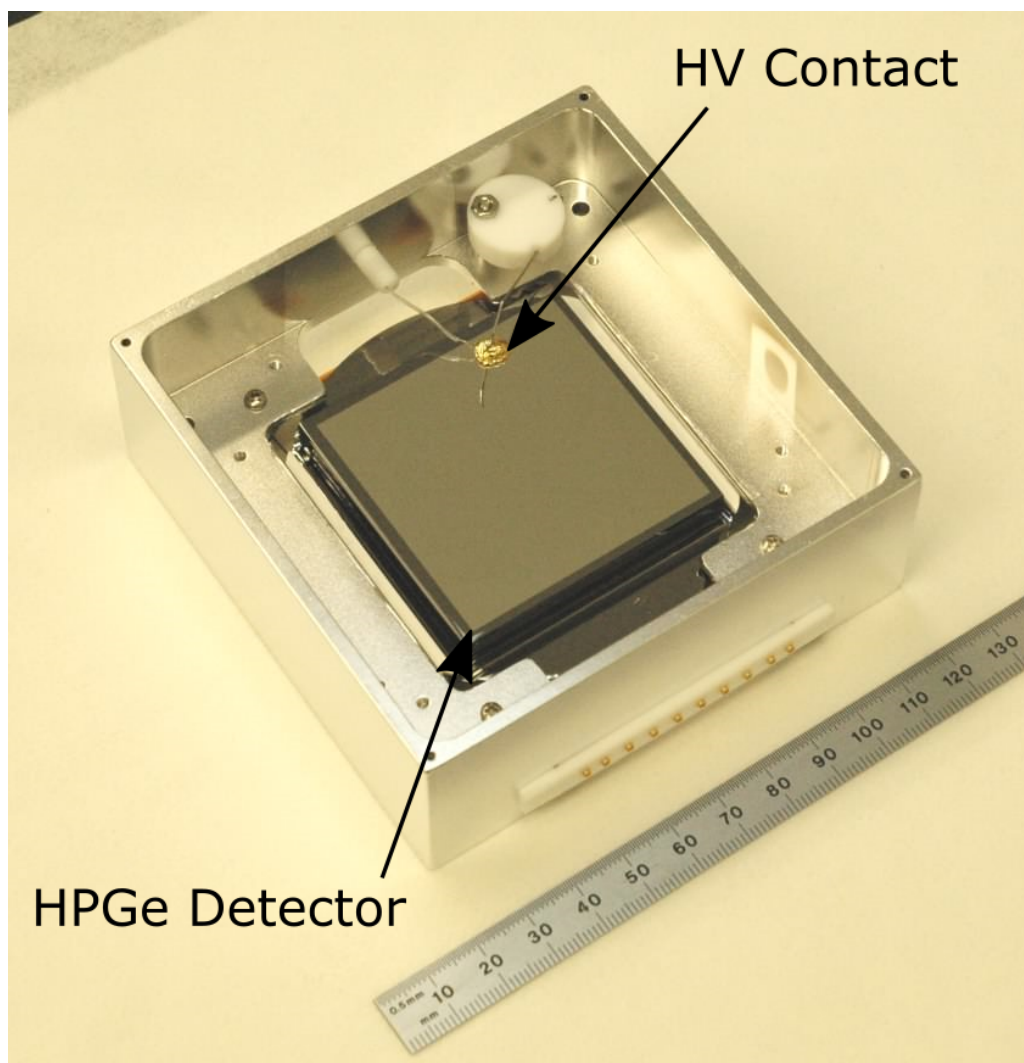


Figure 5.9: Optimized detector showing the full area, high voltage contact. The bias voltage is carried in on the line connected to the gold electrical contact, then pressed onto the detector with the spring wire from the corner of the mount.

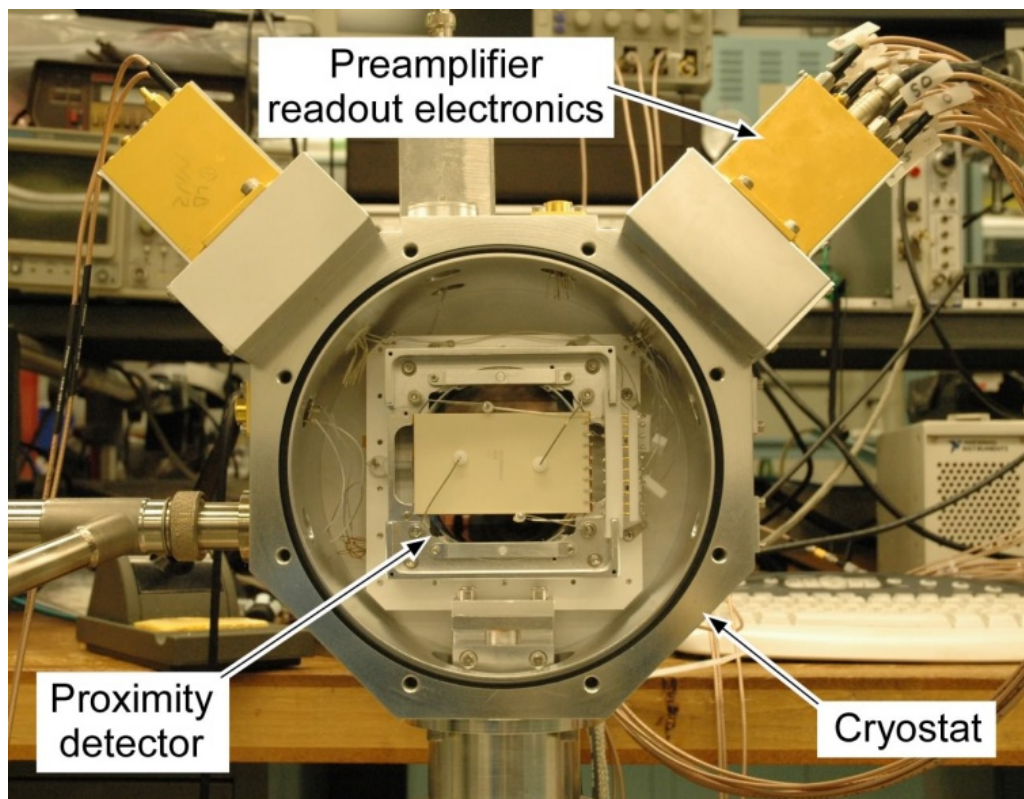


Figure 5.10: Optimized detector mounted into the cryostat. Each strip is connected to a wire that runs to a charge-sensitive preamplifier, which are located in the box in the upper right.

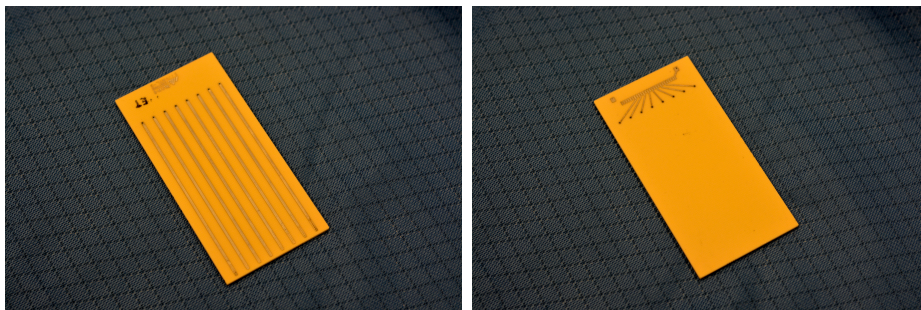


Figure 5.11: Re-designed proximity readout board for use with flexible connector.

In the configuration shown in Figures 5.7 through 5.10, the system was prone to microphonic noise. This noise source is caused by vibrations of the signal lines with respect to electrically conductive surfaces or vice versa, and can significantly degrade detector performance. We believed the vibrations to be in the signal wires, and we re-designed the readout board to connect to a flexible printed circuit that would keep the signal lines stationary with respect to each other and less prone to vibrations with respect to grounded surfaces. The new board design can be seen in Figure 5.11. The decision to use a flex circuit for signal transmission required redesigning the cryostat and detector mount. The fully assembled system can be seen in Figure 5.12.

Measurements on the redesigned system revealed that the microphonic noise source remained, and a systematic study of the possible sources revealed that the main contributor was the readout strips extending over the undepleted wing regions of the detector. This high capacitance system with the added complication of vibrations of the board itself was leading to significant noise. To address this issue, we reduced the board length such that the strips no longer extended over the wings. This solution reduced the noise contributions of the board, but there was still microphonic noise apparent in oscilloscope traces.

To try to address this issue, we designed a proximity readout board that used flex circuit technology as opposed to rigid boards. We thought that this may reduce the oscillation frequency of the readout strips. Lower frequency oscillations would reduce the impact of the noise source on detector signals, thereby improving detector performance. The results of this effort were the opposite of expectations, and the noise frequency was increased and was closer to the bandwidth of signals. The resulting signals could not be used for position or energy extraction, so we abandoned this method.

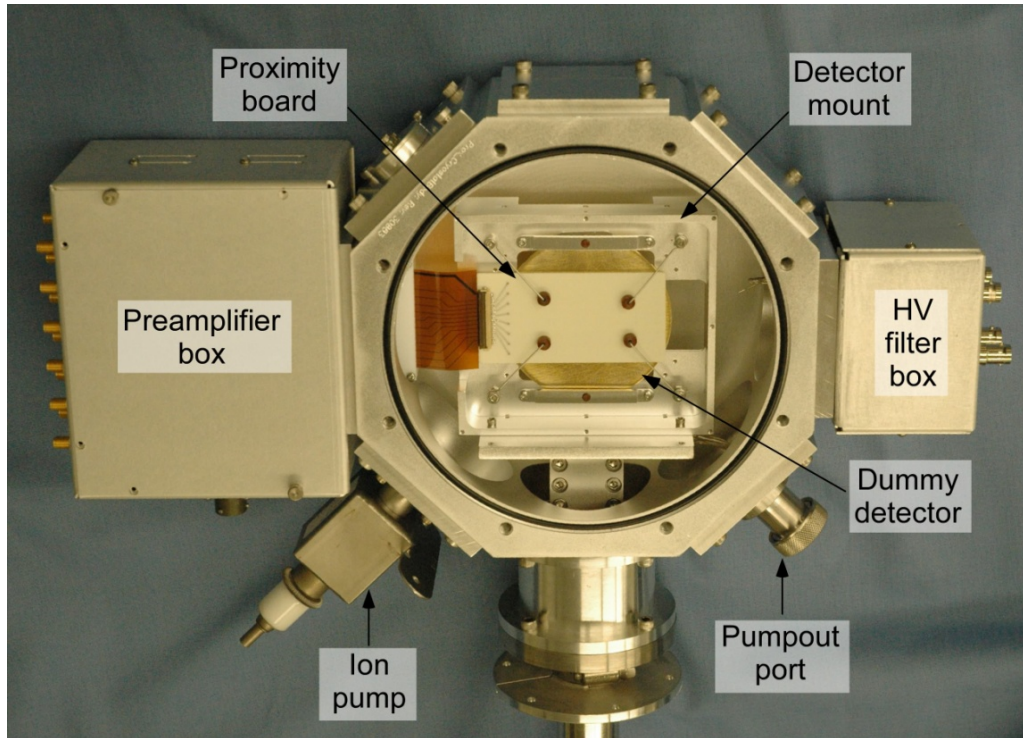


Figure 5.12: Optimized detector (metal detector blank) mounted into the cryostat. The flexible circuit can be seen to the left of the detector. It runs through the cryostat wall to the preamplifier mother board.

5.2.3 Two Dimensional Proximity Readout Design

Applications such as γ -ray imaging often require three dimensional position sensitivity in HPGe detectors. This can be achieved in planar detector geometries by implementing two dimensional readout in plane and analyzing drift time to measure interaction depth. A common conventional two dimensional readout implementation on planar HPGe detectors is orthogonal readout strips deposited on opposing faces of the detector crystal. Unfortunately, the proximity charge sensing method introduces complications that makes two dimensional readout difficult and we are unable to easily implement double sided orthogonal strips as in the conventional method. We considered several implementations, including double sided orthogonal strips, single sided orthogonal strips, and interlocking triangular strips.

We chose to pursue a single-sided orthogonal strip design. We made this choice so that we could use the full-area conventional contact for energy readout. We designed

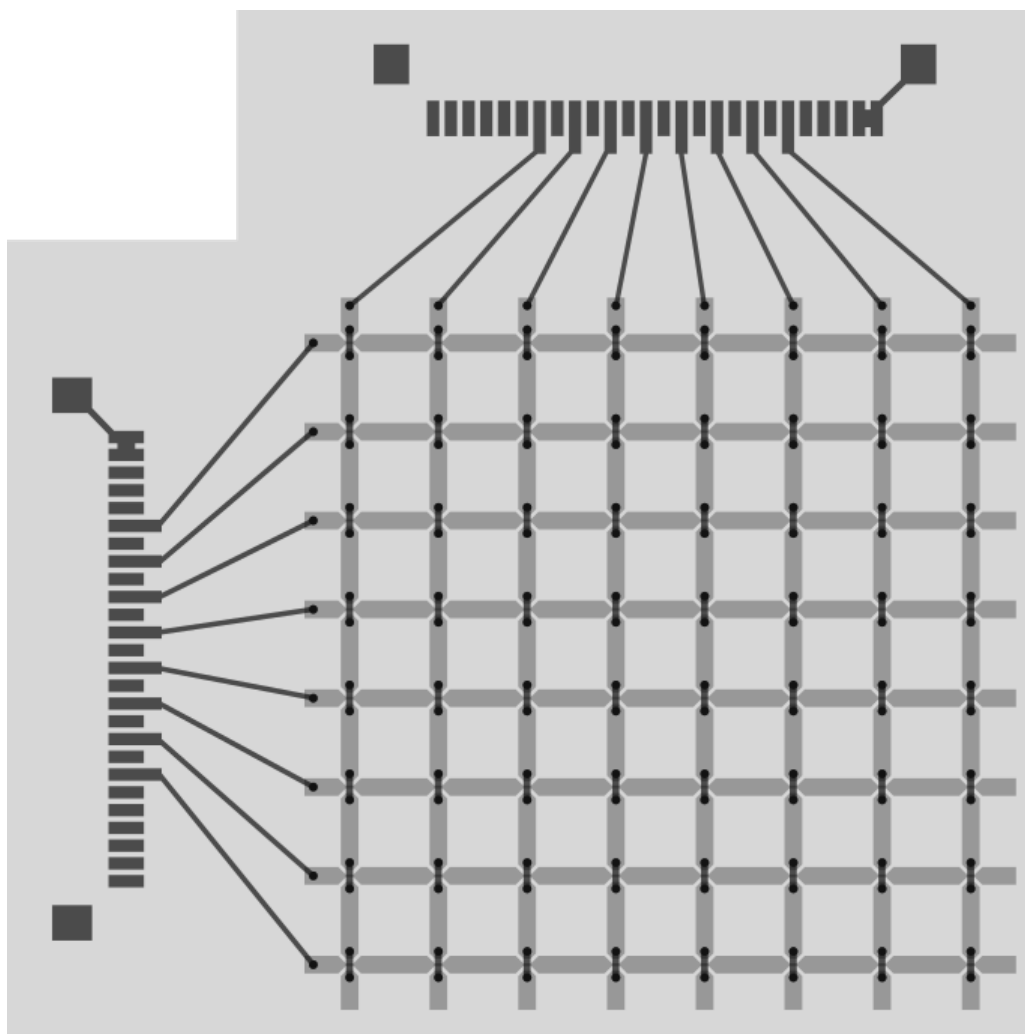


Figure 5.13: Two dimensional readout board design. Note that the darker features reside on the back plane while the lighter features reside on the front plane. The light gray outline represents the extent of the board.

a two dimensional proximity charge sensing board using the same design parameters as the optimized one dimensional board. The strip pitch and width remained 5 mm and 1 mm, respectively, to optimize for position resolution. There are eight strips in either direction for a total of 16 strips.

As can be seen in Figure 5.13, each strip is broken into sections that are connected either through the front or back plane. The electrodes in one dimension are connected

via a thin section that passes between the sections of the crossing strips, while the other set of strips connect through a backplane and metal plated vias.

This readout board was not implemented due to time constraints, but included in the future work for this project is to assess the feasibility of two dimensional readout using proximity electrodes.

5.3 Data Acquisition and Processing

5.3.1 Cryostat Design

The cryostat we used is a standard dip-stick design and has a cylindrical vacuum enclosure capped on either side with a thin window flange. The octagonal outer surface facilitates the attachment of electronics and vacuum equipment, as well as the cold finger feed-through. Attached to these surfaces are the preamplifier circuitry and housing, a high voltage filter and housing, a pump port, a connector for thermometry, and, later in the project, an ion pump. We instrumented the cryostat with temperature measurement and control, but was often operated at the lowest achievable temperature, ~ 85 K. The vacuum level was often in the 10^{-6} - 10^{-7} Torr range (when cold). A desiccant was present in the base of the dip stick, improving the base pressure when cold.

Inside the cryostat, there were several mechanical design iterations that facilitated the mounting of the detectors fabricated. Several examples of cryostat design are shown in Figures 5.6, 5.10 and 5.12.

5.3.2 Preamplifiers

The preamplifiers for this system were small, low noise, charge sensitive preamplifiers with resistive feedback. We used two designs over the course of this work, and both were LBNL designed. The second set of preamplifiers offered better matching between detector and FET capacitance to reduce noise.

5.3.3 XIA Pixie Data Acquisition System

The data acquisition cards used throughout this work were the X-ray Instrumentation Associates (XIA) LLC Pixie-4 cards. These are four channel, 14 bit, 75 MHz data acquisition cards that are operated in a National Instruments PXI crate either with or without a crate controller. Our system was operated by a controller in the crate that was running the Pixie controller software, which is run within Igor Pro, a data

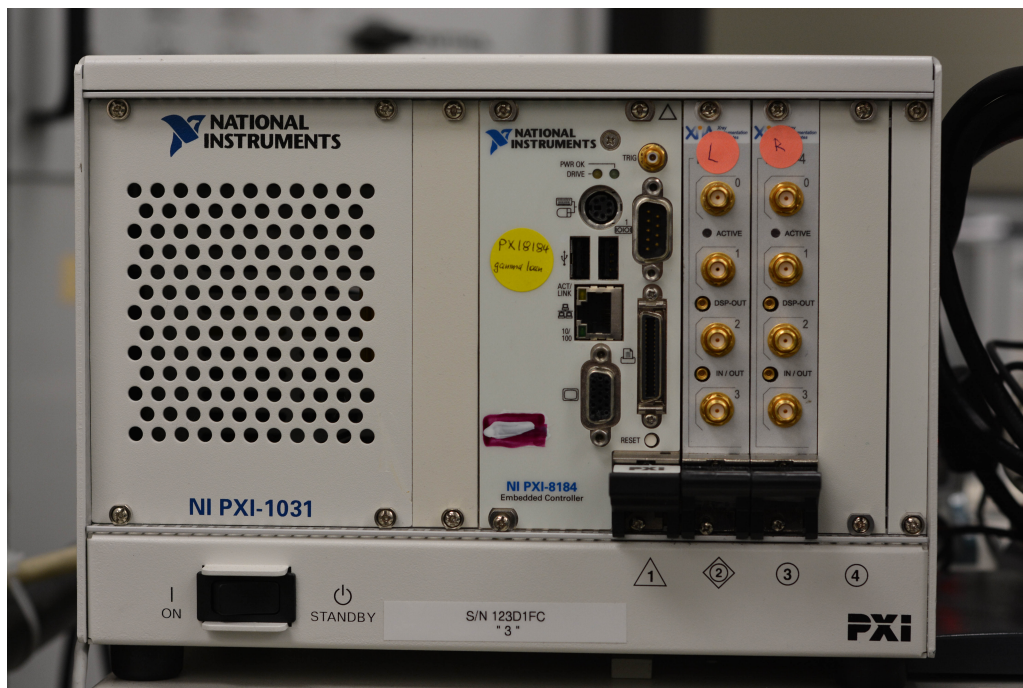


Figure 5.14: XIA Pixie-4 data acquisition setup used for the proximity readout signal digitization and processing. Two Pixie-4 cards were needed for both detectors, which needed five and eight channels, respectively. The controller is a National Instruments PXI-8184 embedded controller running Windows XP.

analysis program. Two Pixie-4 cards were required to instrument the five strip proof of principle detector and the eight strip optimized detector. We arranged the cards in a master-slave configuration, such that when one channel registered an event all channels would be read so that the reconstruction algorithms presented in Chapter 3 could be applied. All data was saved to disk for later analysis. Most data we saved was limited to energy and time data, and full trace data was typically not saved. The Pixie data acquisition hardware uses a trapezoidal filter to shape the preamplifier signals, and the filter parameters were set to the longest available peaking and gap times, $13.227 \mu\text{s}$ and $0.32 \mu\text{s}$, respectively. Because the strips are not connected to the detector, this system should not be as susceptible to current noise, and long shaping times should give the best performance.

Before any scan acquisitions, we adjusted the gain on each proximity electrode readout channel to ensure equal gain across all channels. This was done by injecting a known amount of charge via a pulser and an accurately measured capacitor into

the input of the preamplifiers, and then measuring the resulting peak position in the data acquisition software. We then adjusted the digital gain to align the peak with a chosen channel. We repeated this process for each channel so the total gain of each channel was equal.

5.3.4 Data Analysis

We performed a majority of the data analysis in Igor Pro 6. We wrote data processing scripts to implement the position and energy extraction methods presented in Chapter 3 and to analyze the results. I then translated these scripts into a python framework to enhance modularity and ease of use. All of the python code can be found at github.com/appriest/proximity.

5.4 Collimator Setup and Scanning

For coarse collimation, we used a set of circular aperture collimators to collimate the γ -ray beam. The collimators we used are made of a tungsten alloy with varying thicknesses and pinhole diameters. The collimator pieces are circular and fit into a precisely machined mounting bracket, which fits into a stage that holds the collimator pieces at precise distances from each other. For these measurements, a 1 mm diameter aperture, we placed a 10 mm thick collimator insert directly in front of the source. We placed a 0.5 mm diameter aperture, 5 mm thick collimator insert 22 mm in front of the source to achieve a smaller spot size. The source to detector distance was 76 mm. We estimated the spot size to be approximately 1 mm, FWHM, based on the geometry of the collimator.

We attached the collimator setup to a linear motion stage, oriented for motion in the x and y directions (perpendicular to the strips and along the strip length, respectively). Using this stage, the source was scanned across the strips in small steps (0.2 mm for the proof of principle detector scan and 0.5 mm for the first optimized detector scan) and, at each position, data was taken for a fixed period of time. For each event that surpassed the event threshold, we saved the pulse height and timing information for all strips in the system. In this way, we ensured that the information necessary to extract position and energy information was saved for analysis. For all scans, the step size was much smaller than the source width, so all events could be summed to produce a pseudo-flood field dataset. We expect that the summed distribution is approximately uniform as a function of position. The summed data are used to implement the position and energy extraction methods presented in Section 3.2.

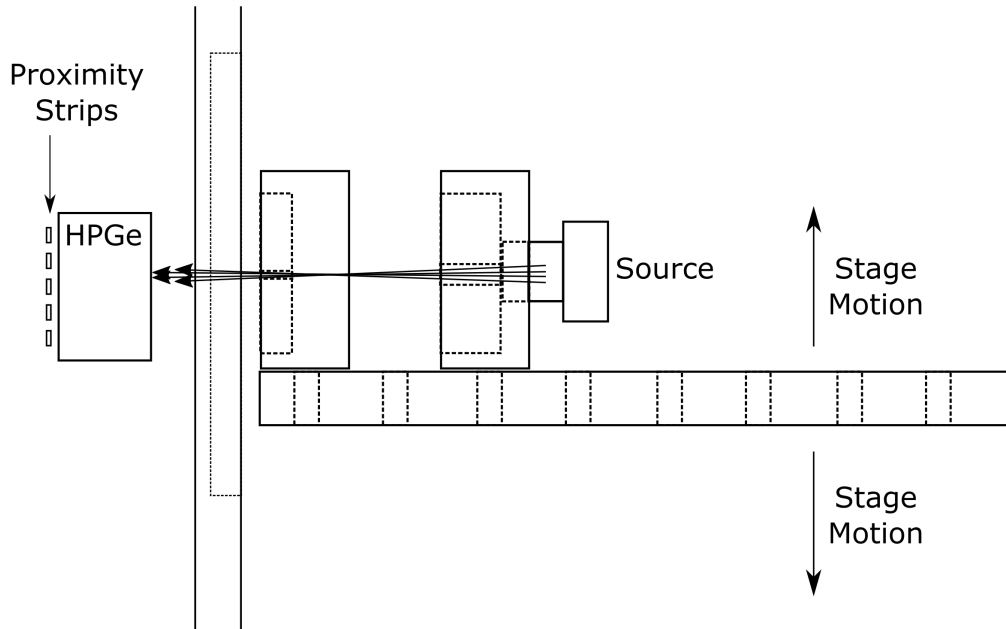


Figure 5.15: Setup of the coarse collimator. The detector to source distance is 76 mm. The source adjacent aperture is 1 mm in diameter, and the thickness is 10 mm. The other aperture is 0.5 mm in diameter and 5 mm thick, placed 22 mm in front of the source. The collimator holders are mounted into a stage that has 100 μm resolution motion capability in the vertical direction.

After we implemented the proximity readout board modifications presented in Section 5.2.2, we made measurements with a different collimator setup that was meant to collimate to a beam size closer to the position resolution limit of the system. This setup uses two tungsten bricks stacked on top of one another, separated by a thin Kapton layer that was placed at either end of the bricks. This left a gap of approximately 0.075 mm for γ -rays to pass through, producing a pseudo-fan beam source. To investigate the position and energy resolution of the optimized system, we aligned the source with the strip length and scanned in the direction perpendicular to the strips. To investigate strip non-uniformity, we turned the source ninety degrees such that it spanned the strips, then scanned along the strip length. For these measurements, we used two Kapton films, making the gap about 150 μm . This was done to increase signal and reduce measurement time. Schematics of the fine collimator setup can be found in Figures 5.16 (top view) and 5.17 (side view).

The other finely collimated scans were aimed at probing the position and energy

resolution of the system. Because the beam width was approximately 0.075 mm, well below the projected position resolution of the system (which should be approximately 260 μm as predicted for the optimized detector by the analysis in Chapter 4), the resulting distribution of events for a given scan position can be assumed to represent the practical resolution of the system. Because this source was a fan beam, it was important that the beam was properly aligned with the length of the strip. A 0.3 degree misalignment would result in an effective source width of 200 μm , which is on the order of the expected position resolution. To achieve this alignment, we performed angular measurements on the collimator surface and the top of the cryostat, and the collimator was adjusted to match the cryostat angle. We made small angle perturbations to the collimator and data were taken at a set position, then we measured the resulting peak width of the raw data. The best alignment is where the peak width was minimal. This should hold true despite performing no position or energy extraction¹.

This collimator was too heavy for the scanning stage used for the coarse collimator, so we used the translation stage of a mill in our lab for scanning. The source was stepped in 0.127 mm (0.005 in) steps, and we took data for 5 minutes at each position. We used the summed distributions to implement the position and energy extraction method presented in Section 3.2.

¹Certainly a better method for aligning the collimator with the strips would be to make a series of measurements in which the angle of the collimator slit was varied through a range of angles. The position resolution could be extracted for each data set, then plotted as a function of the angle. These data would reveal a minimum position resolution where the angle of the slit aligned with the strip length. We did not pursue this method because our data analysis code at the time would not have allowed for quick turnaround and would have prolonged the measurements by a considerable amount of time.

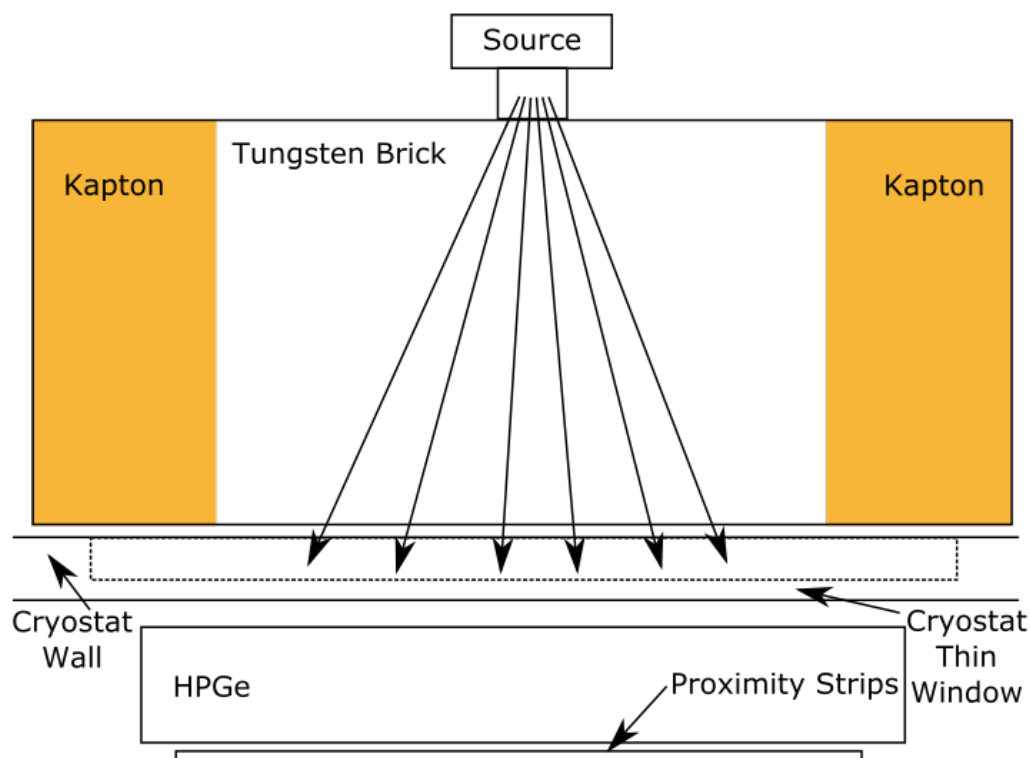


Figure 5.16: Top view of the collimator setup for very fine collimation of 59.5 keV γ -rays from ^{241}Am , oriented to investigate position and energy resolution as a function of position. Two large tungsten bricks were used, one stacked on top of the other, with a thin Kapton separator at either end of the bricks. This leaves a very thin gap for γ -rays to pass through in a fan-like beam. The beam slit shown here is oriented to align with the proximity strips, but it was also oriented orthogonally for measurements of strip non-uniformity.

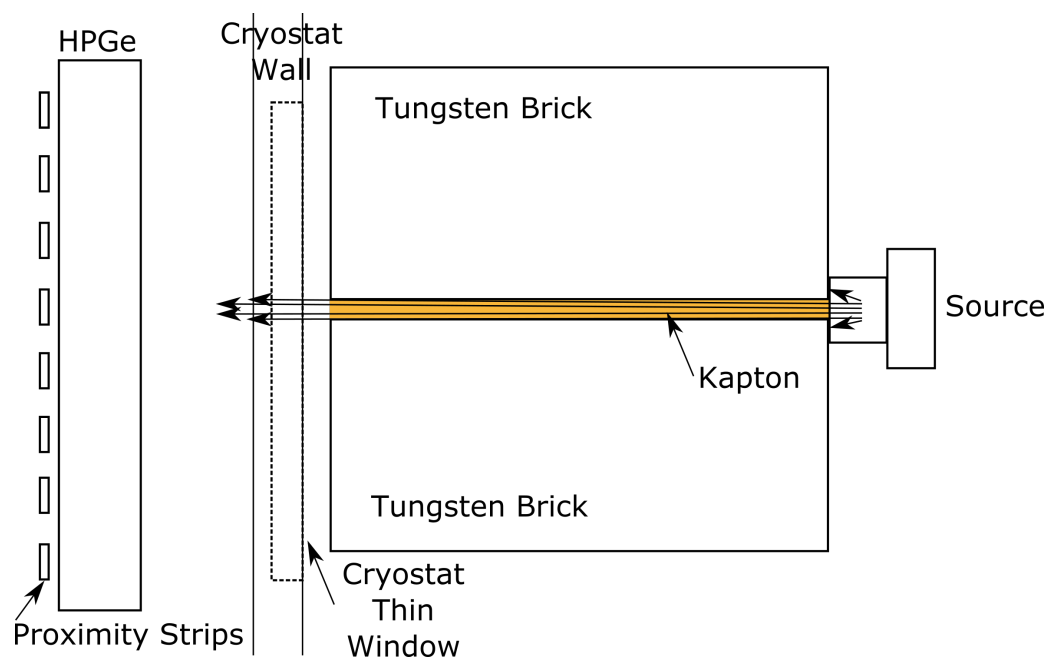


Figure 5.17: Side view schematic of the collimator setup for very fine collimation of 59.5 keV γ -rays from ^{241}Am . We scanned the source vertically for this configuration, which probed the position and energy resolution of the system.

Chapter 6

Measurements, Results, and Discussion

We performed scanning measurements on the fabricated detectors to test the performance of the proximity electrode signal readout method. We performed all measurements with the 59.5 keV γ -rays from a 1 mCi ^{241}Am source, which was collimated using the collimator setups described in Section 5.4. The measurements, results, and a discussion of the results will be presented here.

6.1 Proof of Principle Detector Measurements

To recap, the proof of principle detector active area measures $18 \times 18 \text{ mm}^2$ and 10 mm thick. The readout strips are 0.76 mm wide with a 2 mm pitch. For all detectors, events that occurred under the two outermost strips were not processed because it is impossible to decipher on which side of the strip the event occurred. This is why two fewer strips than the total number are shown for each detector implementation. The results of this scan, including the detector calibration, are shown in Figures 6.1 through 6.7.

The coarse collimation setup was used for this measurement and was scanned in 0.2 mm steps. The centroid positions of the extracted position distributions show that this step size is accurately extracted for each distribution. This can be seen in Figure 6.5, where we fit the data from two scan positions and the centroids are separated by $40 \text{ }\mu\text{m}$, which is in agreement with two steps of the collimator. This can also be seen in Figure 6.7 in the top plot. This plot shows the difference between the extracted position centroid and the stage position. Additionally, this shows that the residual is approximately zero across the width of the active area, indicating that

the extracted centroids are accurate.

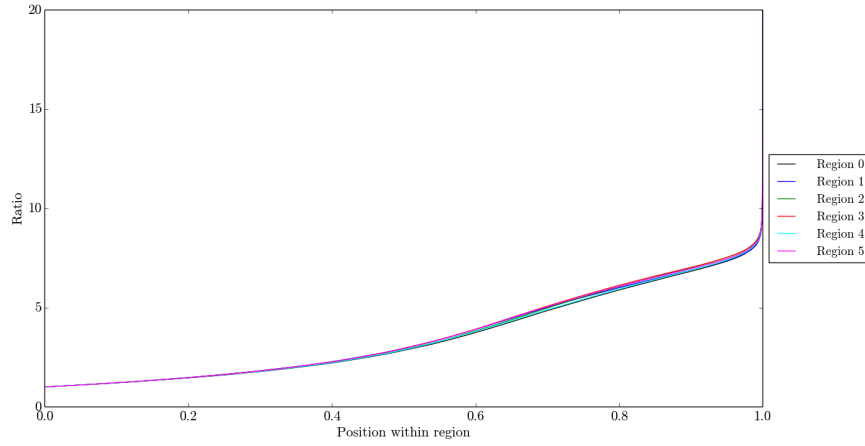


Figure 6.1: Mapping showing the relationship between pulse height ratio, p_j/p_k , and position. Each region spans the distance between the midpoint between two strips and the center of a strip. This means that, for regions 1, 3 and 5, the position is mapped backwards from the midpoint between strips. All regions are plotted here.

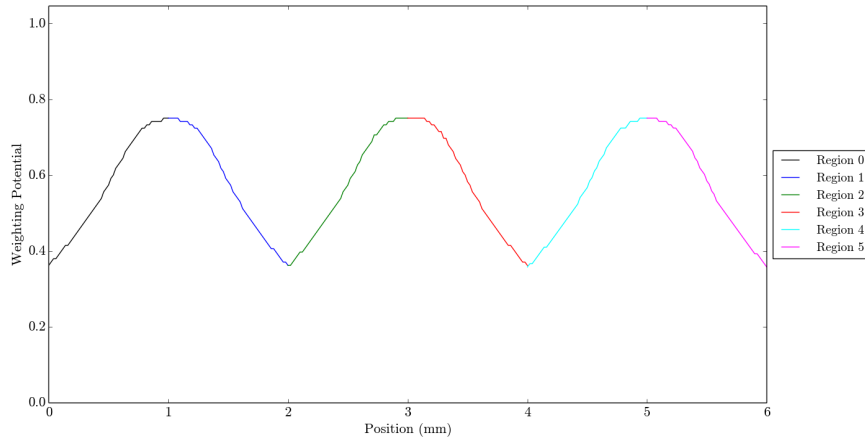


Figure 6.2: Proof of principle detector weighting potentials extracted from flood field data.

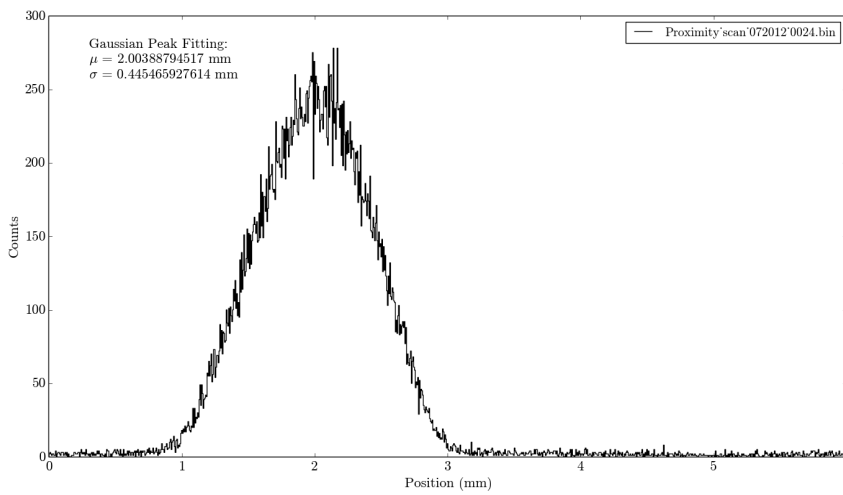


Figure 6.3: Extracted position histogram example from one scan position for proof of principle detector. Gaussian fit results are printed in the upper left hand corner. The data file name is shown in the upper right hand corner.

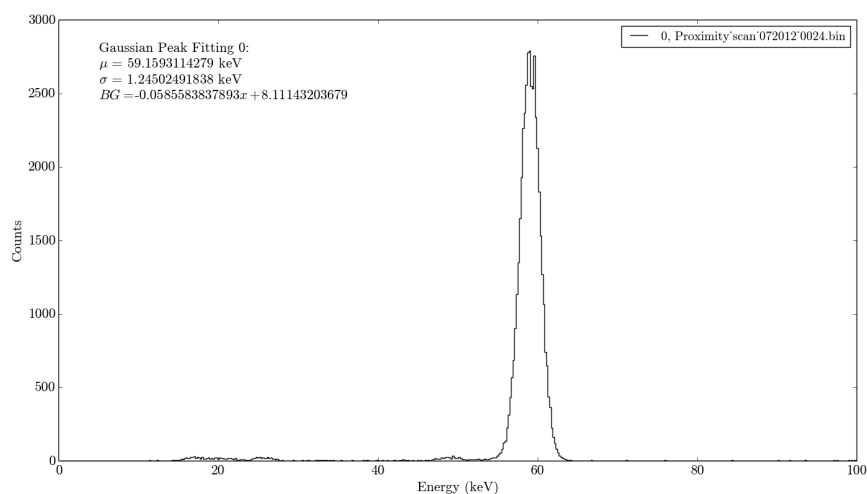


Figure 6.4: Extracted energy histogram example from one scan position for proof of principle detector. Gaussian fit with linear background results are printed in the upper left hand corner. The data file name is shown in the upper right hand corner.

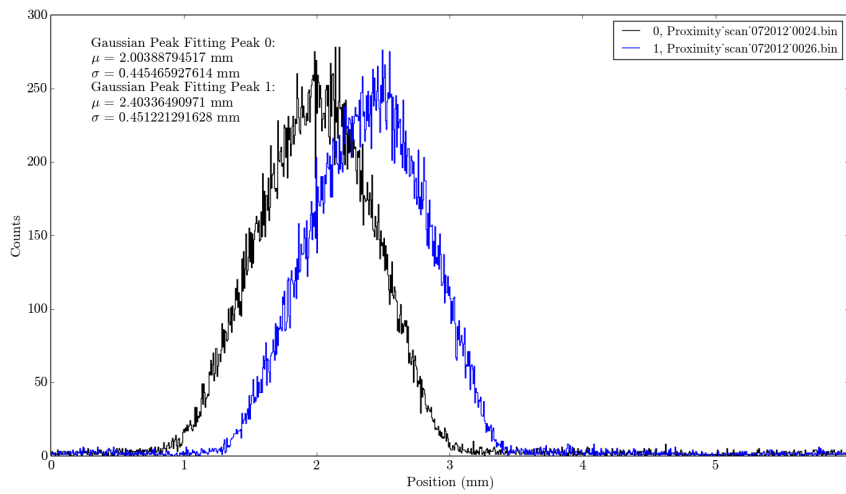


Figure 6.5: Extracted position histogram examples from adjacent scan positions for proof of principle detector. Gaussian fit results are printed in the upper left hand corner. The data file names are printed in the upper right hand corner, showing that these data correspond to two scan positions that are 0.4 mm from each other. This is in agreement with the fits.

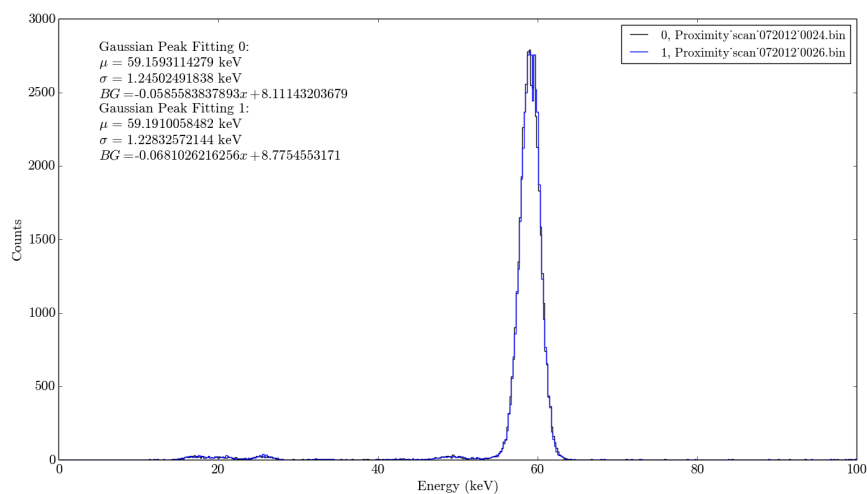


Figure 6.6: Extracted energy histogram examples from adjacent scan positions for proof of principle detector. Gaussian fit results are printed in the upper left hand corner.

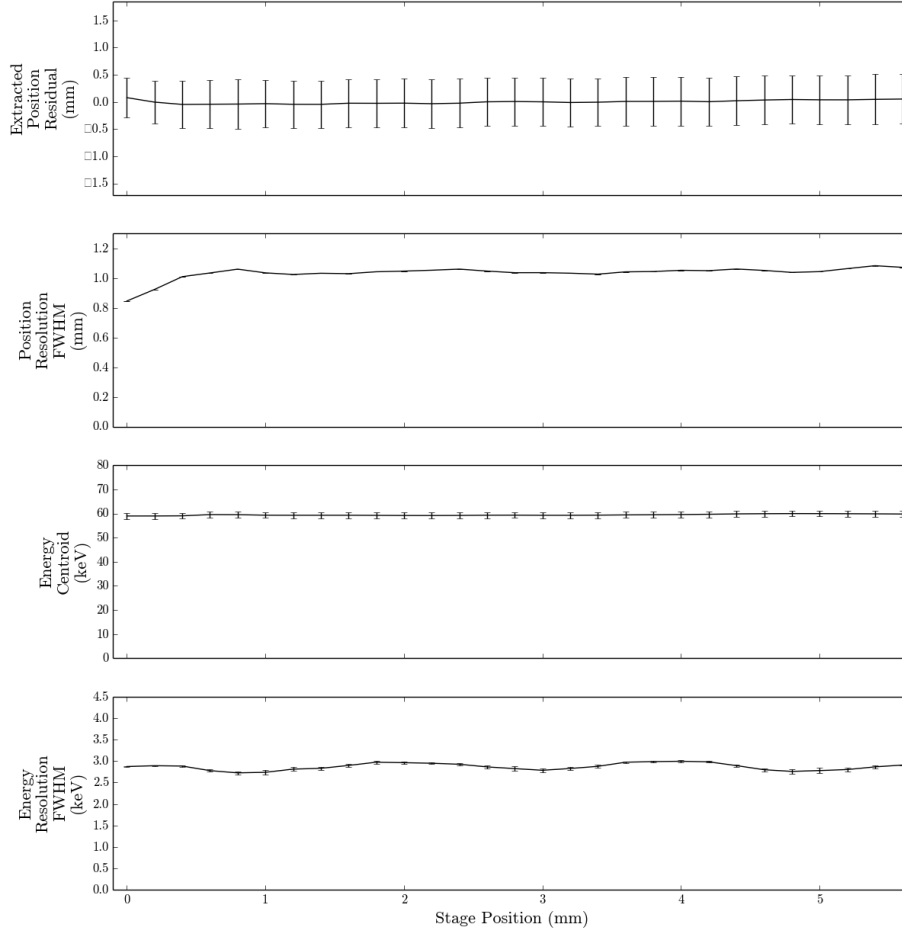


Figure 6.7: Full scan analysis for the proof of principle detector scan. From top to bottom: (1) Linear residual showing the linearity of the extracted source position. (2) Extracted source distribution FWHM as a function of position, which is generally representative of the source beam shape. (3) Extracted energy centroid as a function of position in the detector. This shows that the extracted energy does not vary throughout the detector. (4) Energy resolution as a function of position in the detector. The energy resolution is approximately constant for all positions, with a slight decrease directly below the strips (located at 1 mm, 3 mm, and 5 mm) due to larger signals.

The results of this scanning measurement show that the extracted source position resolution is much finer than the pitch of the strips. The position distribution width is approximately constant across the detector, which indicates that it is representative of the source width as opposed to the detector resolution. We can make this conclusion because we expect the position resolution to vary as a function of position, as shown in Chapter 4. Also, we expect the source distribution to have a width of approximately 1 mm, close to that of the distribution shown in Figure 6.6, based on the coarse collimator setup.

The energy centroid is also invariant with position, which is an indication that the extracted weighting potentials are accurate. Inaccurate weighting potentials would lead to variations in the energy centroid. The energy resolution varies slightly with position, with better energy resolution beneath the strips whose centers are positioned at 1 mm, 3 mm, and 5 mm in Figure 6.7. The average energy resolution of the system is 2.9 keV, and the average position histogram FWHM is 0.98 mm. The width of the position histogram at each position is dominated by the source width, and does not represent the best resolution possible with this proximity electrode geometry.

6.2 Optimized Detector Scanning Measurements

6.2.1 Coarse One Dimensional Scan

We performed three scanning measurements on the optimized detector. The optimized detector has eight strips at 5 mm pitch. Each strip is 1 mm wide. The collimator setup for the first scan was very similar to the scan performed on the proof of principle detector. The collimator was set up to produce a ~ 1 mm beam spot, and we scanned the beam across all eight strips. We stepped the source in 0.5 mm steps. We assumed that the sum of all scan data was equal to flood field illumination, and we extracted the pseudo-weighting potential ratios and pseudo-weighting potentials. With this collimation setup, we did not expect that we would be probing the position resolution limits of the system, but would show that sub-strip position resolution is possible, and much finer than the pitch of the strips.

During this scan, the detector was highly prone to microphonic noise sources (as described in Section 5.2.2) which caused a significant amount of error in some of the extracted position and energy distributions. The noise varied from strip to strip, making some regions noisier than others. The distributions that were uncharacteristically bad have been dropped from the analysis plots to better show the accurate results.

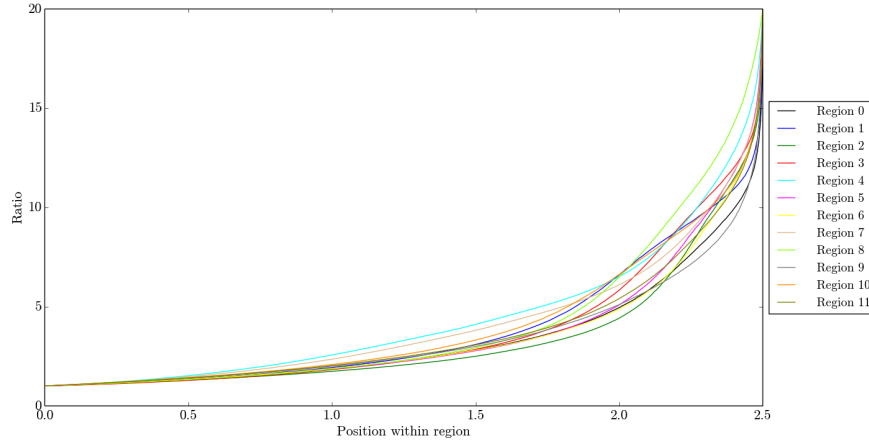


Figure 6.8: Mapping showing the relationship between pulse height ratio, p_j/p_k , and position for the first iteration of the optimized detector. All regions are plotted here. The disagreement between the curves is partially indicative of a noisy system.

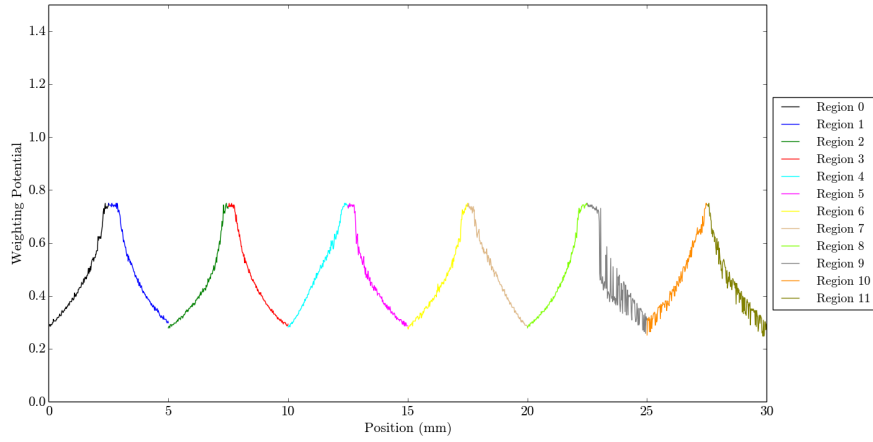


Figure 6.9: Weighting potentials extracted from flood field data for the first iteration of the optimized detector. The effects of noise on the weighting potential reconstruction can be seen in Regions 9, 10 and 11. This leads to increased event energy uncertainty.

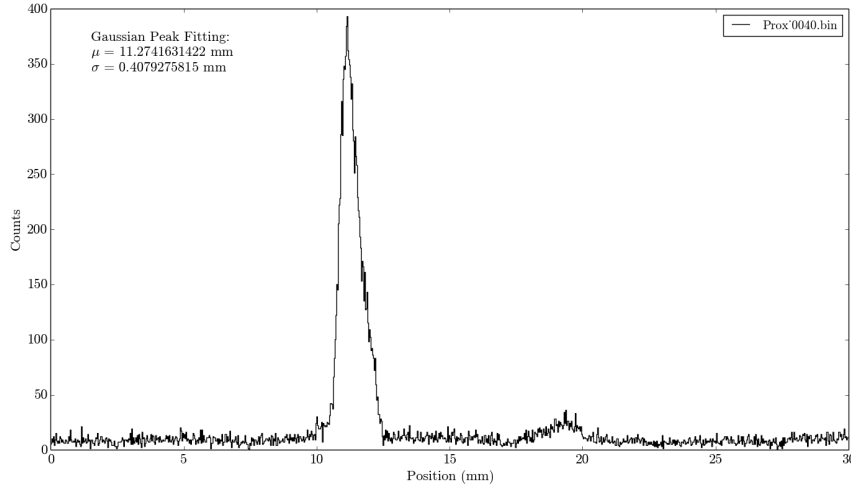


Figure 6.10: Extracted position histogram example from one scan position for the first iteration of the optimized detector. Gaussian fit results are printed in the upper left hand corner. The data file name is shown in the upper right hand corner.

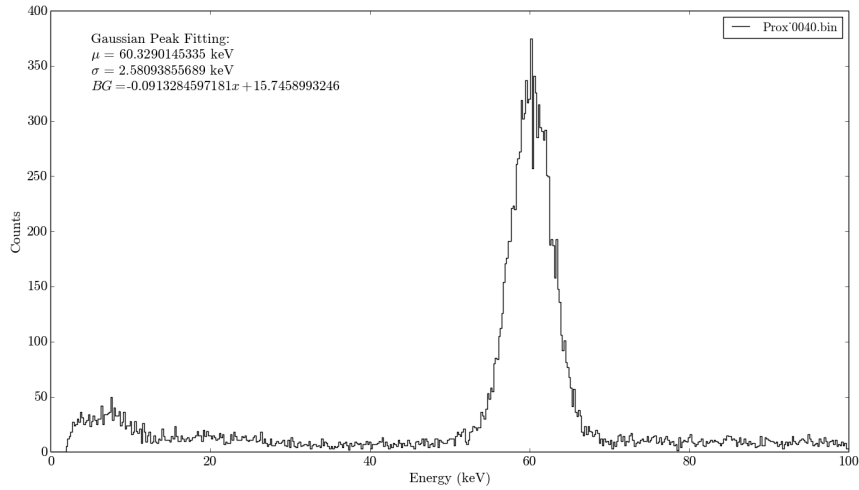


Figure 6.11: Extracted energy histogram example from one scan position for the first iteration of the optimized detector. Gaussian fit with linear background results are printed in the upper left hand corner. The data file name is shown in the upper right hand corner. The file number does not indicate the collimator position.

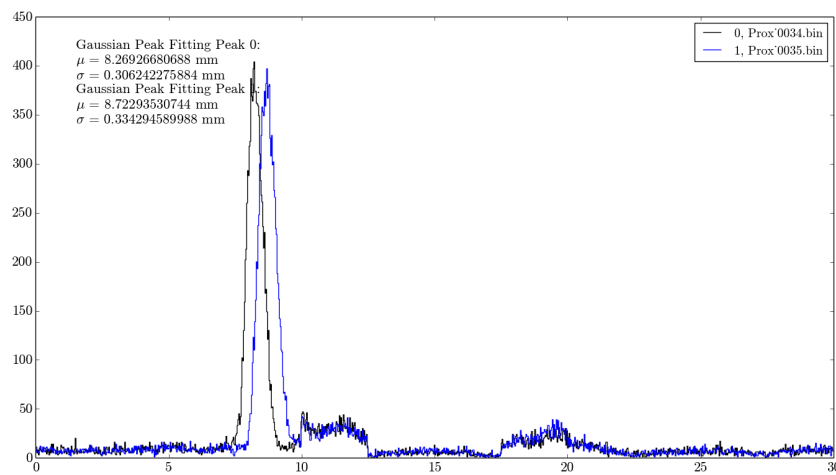


Figure 6.12: Extracted position histogram examples from adjacent scan positions for proof of principle detector. Gaussian fit results are printed in the upper left hand corner. The data file names are printed in the upper right hand corner, showing that these were adjacent scan positions, and should be separated by 0.5 mm, but are in error by ~ 0.05 mm.

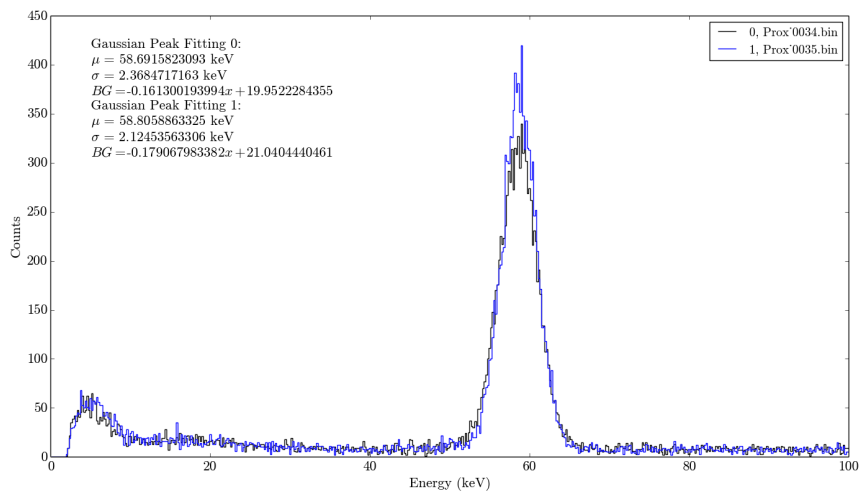


Figure 6.13: Extracted energy histogram examples from adjacent scan positions for the first iteration of the optimized detector. Gaussian fit results are printed in the upper left hand corner. The data file names are printed in the upper right hand corner. The fit results show that the energy resolution is not optimal at 5.5 keV and 5.0 keV, FWHM. The centroids are also not at 59.5 keV, indicating that the weighting potentials at these positions are not accurate.

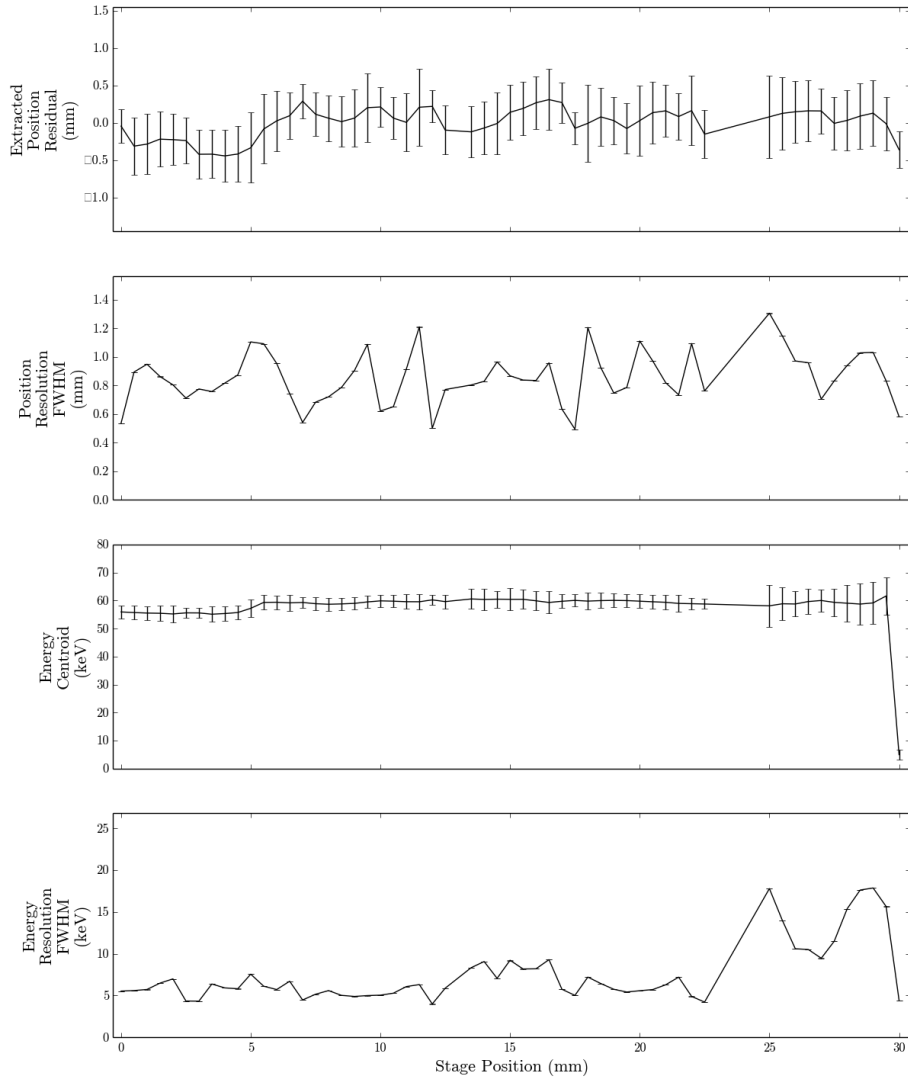


Figure 6.14: Full scan analysis for the coarse collimation scan of the first iteration of the optimized detector. From top to bottom: (1) Linear residual showing the linearity of the extracted source position. (2) Extracted source distribution FWHM as a function of position, which is generally representative of the source beam shape. (3) Extracted energy centroid as a function of position in the detector. (4) Energy resolution as a function of position in the detector.

Shown in Figures 6.8 through 6.14 are the results of this scan. Figures 6.8 and 6.9 show the weighting potential ratio and the weighting potentials reconstructed from flood field data, respectively. Figure 6.12 shows extracted position histograms for two scan positions, showing that sub-strip pitch position resolution is possible, with peak widths of 0.7 mm and 0.8 mm, despite a strip pitch of 5 mm. Figure 6.13 shows the corresponding energy histograms for the same two scan positions. This demonstrates that the extracted energy is fairly consistent with position. These same conclusions can be made looking at Figure 6.14, where the fit of each scan position is plotted as a function of the scan position.

From these data, it is clear that the noise performance of the detector in this configuration is inadequate. The average extracted position distribution full width at half maximum (FWHM) is 0.8 mm and is again mostly representative of the source distribution rather than the resolution of the detector. The average energy resolution was over 10 keV but dominated by the poor energy resolution beneath strips five and six, which were particularly susceptible to microphonic noise. This is not representative of the ability of the method, but rather is the result of the microphonic noise present. The results of this scan necessitated investigation of this noise source, which required us to change the design of the proximity electrode readout board as well as the connection between the board and the preamplifiers, which we changed to a flex circuit design.

6.2.2 Finely Collimated Scans

The second and third scans were performed after the readout board was modified such that the strips did not hang over the wings of the detector. We determined that the increased capacitance was a significant source of noise, and we made modifications intended to reduce that noise source. For these scans, we used the fine collimator setup.

For the first of the two finely collimated scans, our goal was to look for non-uniformities that may exist in the strip geometries. To achieve this, we oriented the collimator such that the fan beam illuminated all strips simultaneously, then to step the source along the strip length. By measuring the maximum pulse height at each position, we mapped the relative variation in maximum weighting potential as a function of position. This quantity would represent any variation in strip geometry along the strip length that could cause erroneous position or energy extraction. The results of this scan can be found in Figure 6.15. From these results, we can see that most strips are close to uniform over the entire length of the strip. The exception is Strip 0, which has a fairly significant deviation from unity.

This deviation can cause significant errors in position and energy extraction as there is no way of knowing where along the strip length an event occurred. A larger weighting potential at one end of the strip leads to a larger event ratio, which would erroneously push the extracted position closer to the strip center. Inaccurate position extraction combined with a larger pulse height will lead to incorrect energy extraction as well. This holds true for a relative decrease in maximum weighting potential from the center of the strip. The position and energy resolution is degraded as a result of this non-uniformity.

Table 6.1: Maximum percent variation in peak pulse height along the length of each strip.

Strip Number	Max Variation (%)
0	11.6 ± 0.34
1	5.1 ± 0.35
2	3.6 ± 0.35
3	4.3 ± 0.38
4	4.2 ± 0.27
5	3.9 ± 0.23
6	3.0 ± 0.23
7	4.2 ± 0.27

From these results, we can conclude that a factor affecting the peak weighting potential magnitude is varying along the strip length. The possible factors are geometry variations and inconsistent dielectric constant of the Kapton layer. The latter is unlikely, so we assume that geometry is the cause. The most likely variation in geometry along the length of the strip is the distance between the strip and the detector surface. On strip 0, the weighting potential varies by as much as 11%. This corresponds to a change in stand off distance of $\sim 50 \mu\text{m}$, which is feasible considering the implementation. We expect that these results represent a variation in geometry and not an outside influence such as gain drift because we can see the mean offset from unity from one strip to the next is consistent with a tilt in the board. If gain drift were a factor, we should see a significant deviation in the trend between one strip and its neighbor.

In the future, steps should be taken to reduce this lack of uniformity. More rigid clamping systems could be implemented, but because it is difficult to measure the actual standoff distance, this problem may persist.

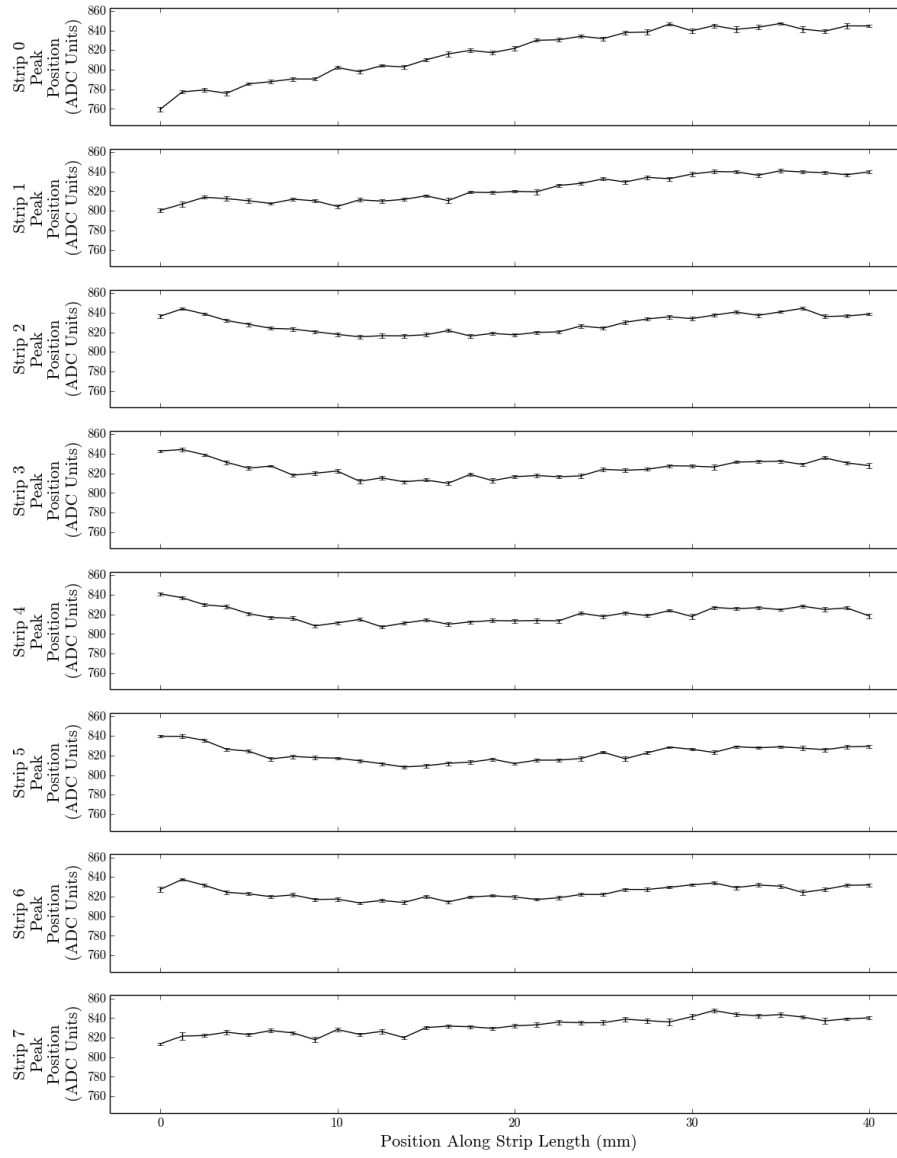


Figure 6.15: Variation in the peak pulse height along the length of each strip. Variations may be the result of readout board warping, which will affect the ability to accurately extract the position and energy of an event.

We performed a second finely collimated scan with the length of the pseudo-fan beam aligned with the length of the strip. We aimed to map the position and energy resolution as a function of position with this setup. The summed data from all scan positions was used to simulate a flood field measurement. We used these data to produce a map between pulse height ratio to position, and this map, plotted for each region, is shown in Figure 6.16. It is clear that most of the histograms follow the same trend except for regions 4 and 7. This is due to noise mimicking real events in those regions. This noise can be seen in Figure 6.22, but the source of this noise is unknown. The discrepancy in region 5 cannot be explained by this same noise source, and it is unclear why it deviates from the other regions.

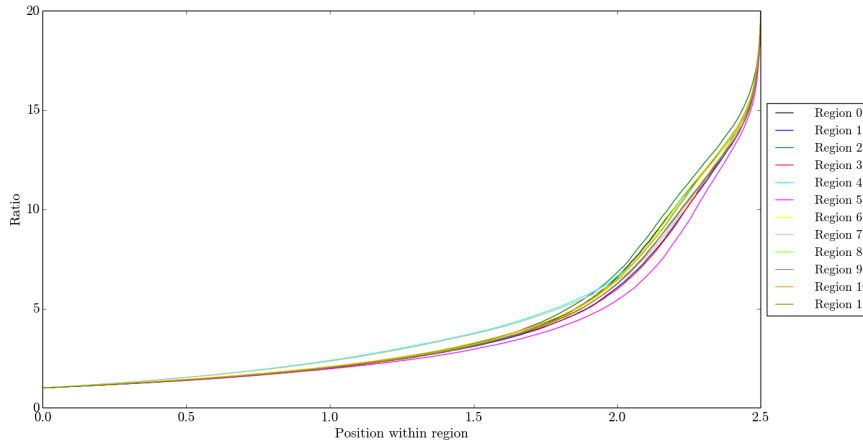


Figure 6.16: Mapping showing the relationship between pulse height ratio, p_j/p_k , and position for the second iteration of the optimized detector. All regions are plotted here.

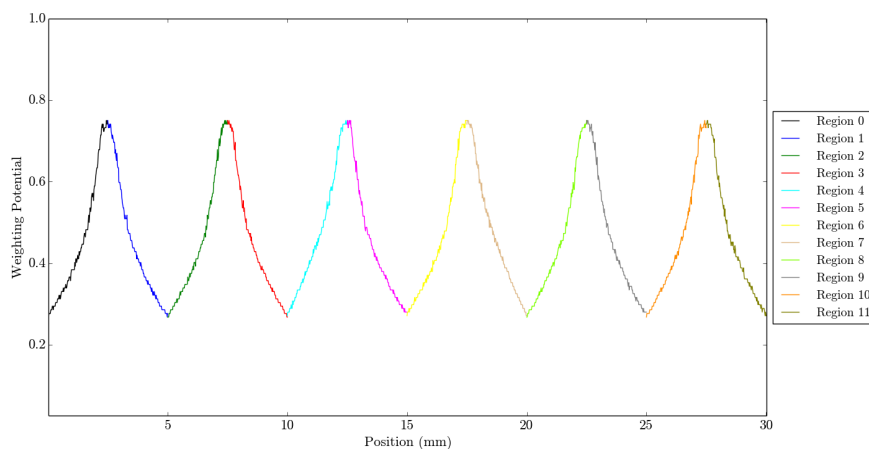


Figure 6.17: Weighting potentials extracted from flood field data for the second iteration of the optimized detector.

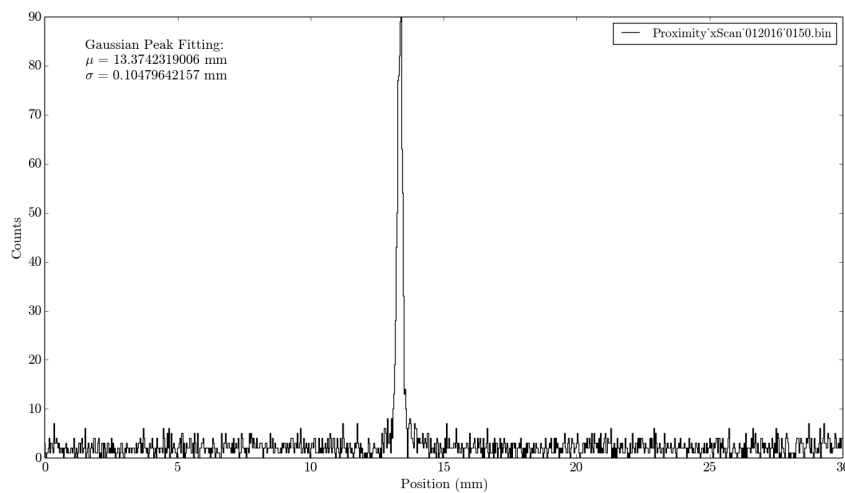


Figure 6.18: Extracted position histogram example from one scan position for the second iteration of the optimized detector. Gaussian fit results are printed in the upper left hand corner.

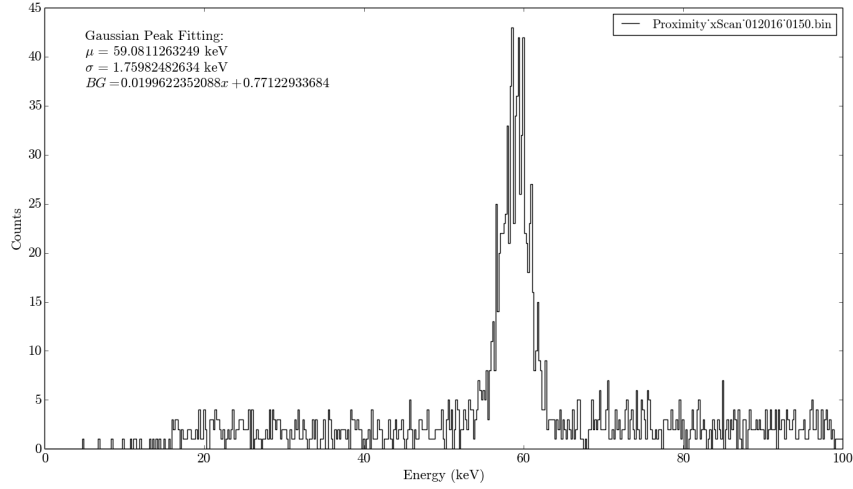


Figure 6.19: Extracted energy histogram example from one scan position for second iteration of the optimized detector. Gaussian fit with linear background results are printed in the upper left hand corner.

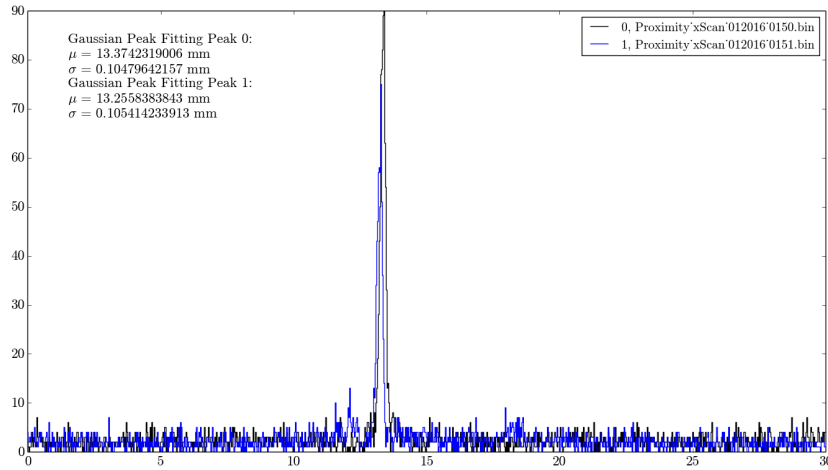


Figure 6.20: Extracted position histogram examples from adjacent scan positions for second iteration of the optimized detector. Gaussian fit results are printed in the upper left hand corner.

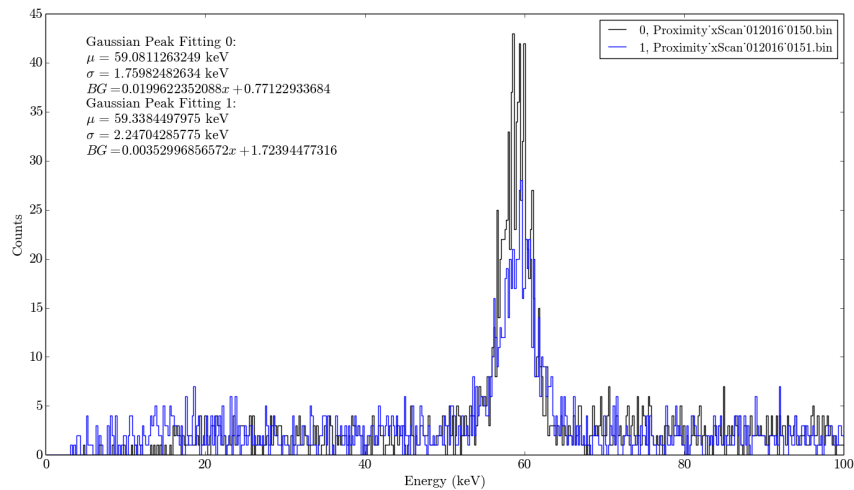


Figure 6.21: Extracted energy histogram examples from adjacent scan positions for second iteration of the optimized detector. Gaussian fit results are printed in the upper left hand corner.

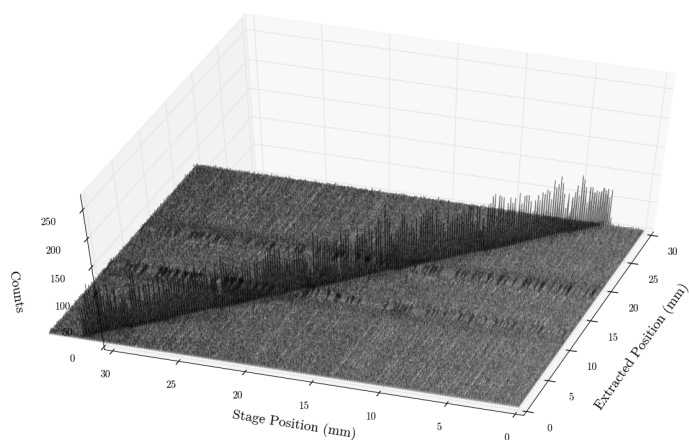


Figure 6.22: Extracted position histograms for all scan positions that fell within the reconstruction region. One histogram is plotted for each scan file with the x-axis for position and z-axis for counts, which is associated with a stage position (y-axis). A noise source is present that results in the events presenting between 10 and 12.5 mm as well as 17.5 and 20 mm.

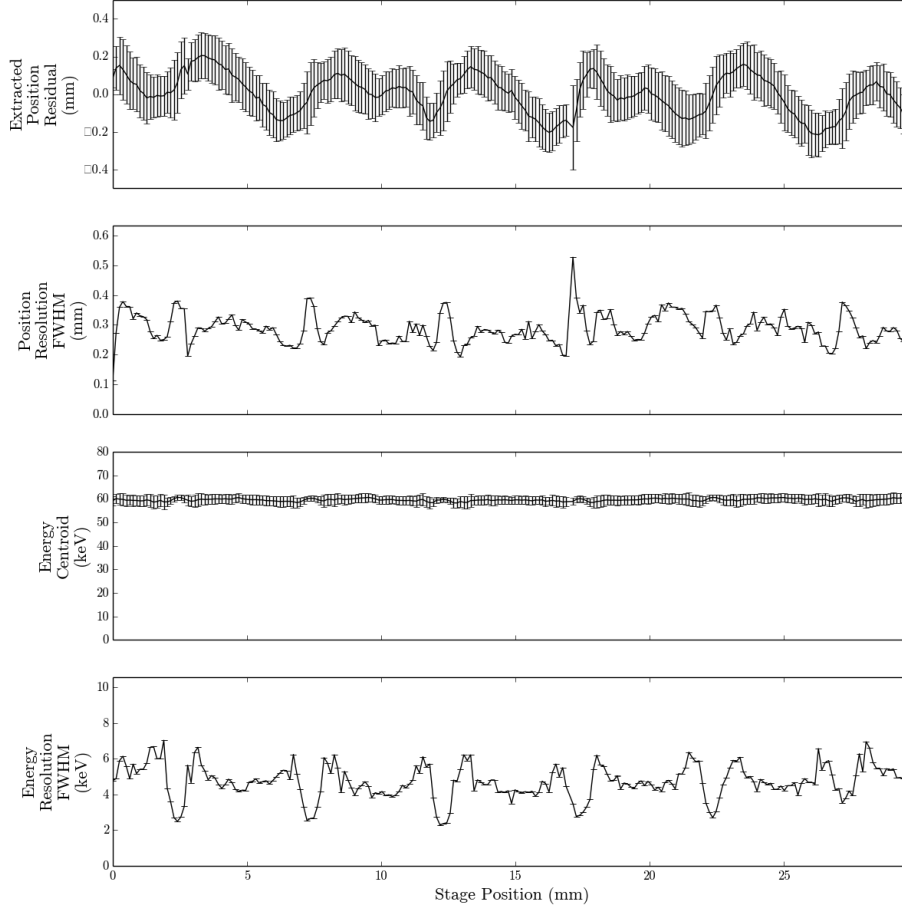


Figure 6.23: Full scan analysis for the second iteration of the optimized detector scan. From top to bottom: (1) Linear residual showing the linearity of the extracted source position. (2) Extracted source distribution FWHM as a function of position, which is generally representative of the source beam shape. (3) Extracted energy centroid as a function of position in the detector. This shows that the extracted energy does not vary throughout the detector. (4) Energy resolution as a function of position in the detector. The energy resolution is approximately constant for all positions, with a slight decrease directly below the strips (located at 1 mm, 3 mm, and 5 mm) due to larger signals.

The results from this scan show much better position extraction performance due to the finely collimated source. As shown in 6.23, the position resolution varies as a function of position, indicating that we are probing the limits of position resolution for this system. As predicted in Figure 4.21, the position resolution between strips is approximately constant and appears to be better than directly beneath the strip. The average position resolution measured from this scan is $288\ \mu\text{m}$. This is very slightly worse than anticipated from modeling, where the Monte Carlo method predicts an average FWHM of $260\ \mu\text{m}$, but is of the right order and shows the expected variation as a function of position. The same can be said of the energy resolution. The energy resolution is approximately constant as a function of position between strips, and the resolution improves directly below the strip. This was predicted by the analytic method, but the Monte Carlo method incorrectly predicted that the energy resolution would be poor directly below the strip. The error in the Monte Carlo model was only applying the method to one region. Inevitably, noise will push the signal ratio to a magnitude outside of the region's ratio mapping. To address these events, we added a linear extension to the ratio mapping, which is an erroneous method for mapping these types of events. In the physical detector, these events will also exist, but will be mapped using the region that they would be pushed into, rather than attempting to extract the position with the mapping of the correct region. The resulting energy resolution on average is $4.7\ \text{keV}$, which is worse than, but qualitatively has the shape predicted by the analytical modeling (Figure 4.7). The analytic model predicted an average energy FWHM of $3.8\ \text{keV}$. The Monte Carlo model predicted an energy FWHM of $5.5\ \text{keV}$.

The energy centroid varies slightly as a function of position below the strips, indicating that the extracted weighting potentials are not perfectly accurate. This is likely due to poor position resolution directly beneath the strip, leading to a larger spread in pulse heights from a given position range, which are used to reconstruct the weighting potential. With a wider spread, the binning of the peak counts may not be adequate, leading to errors in the extracted weighting potential height for these positions.

The extracted position residual also shows variation as a function of position that is periodic in nature. While the period of the oscillations match the pitch of the strips, the offset from the strip positions ($2.5\ \text{mm}$, $7.5\ \text{mm}$, $12.5\ \text{mm}$, $17.5\ \text{mm}$, $22.5\ \text{mm}$ and $27.5\ \text{mm}$) and the asymmetric shape of the curve leads me to believe that the residual is not caused by errors in extracted position, but rather by non-linear movement of the translation stage. Because of the weight of the collimator, we used a mill table as the translational stage. To scan perpendicular to the strips, we moved the stage vertically. The crank dial had $0.001\ \text{in}$ ($0.025\ \text{mm}$) markings, and with each full turn, moved $0.200\ \text{in}$ ($5.08\ \text{mm}$). This also matches the period of the oscillations

measured in the residual plot. The asymmetry can be explained by the effects of the pulling the crank up for half of the revolution and down for the other half, leading to non-linear motion.

Chapter 7

Conclusions and Future Work

7.1 Position Sensitive Proximity Charge Sensing Summary

The objective of our work was to investigate the advantages and limitations of a novel position sensitive charge readout scheme applied to HPGe detectors, named proximity charge sensing. Position sensitive HPGe detectors are in use in the fields of nuclear physics, homeland security, medical imaging, environmental remediation, and astrophysics. The technology we investigated aimed to address some of the complications encountered when working with position sensitive HPGe detectors, specifically the number of readout electrodes needed to achieve fine position resolution on large area detectors as well as the complications present in making connections to those electrodes. Proximity charge sensing also simplifies detector fabrication because electrode geometries can be easily exchanged without the need for re-fabricating the detector.

We fabricated two detectors at LBNL to test the methods developed, and we probed the limitations of this technology through scanning measurements of these detectors. The purposes of the first fabricated detector were to test the fabrication methods, the position and energy extraction methods, and to show that sub-strip pitch position resolution was possible using the proximity charge sensing method. We were able to show that much better than 1 mm position resolution is possible with 2 mm pitch strips. The distribution width achieved was 0.98 mm, on average, and was dominated by the spatial distribution of the source. The energy resolution of this system was also acceptable for HPGe, where, on average, we measured 2.9 keV at 59.5 keV. We learned that the calculated weighting potential position and energy extraction method presented in Section 3.1 is difficult to apply. Position

extraction using this method is inaccurate due to the incomplete knowledge of the geometry of the proximity electrodes. We were able to overcome this challenge with the development of a data based method, where the pseudo weighting potential ratio ($\tilde{\phi}_j/\tilde{\phi}_k$) and pseudo weighting potentials ($\tilde{\phi}_j$) were extracted from flood field data. Using this method, we were able to more accurately extract the position and energy of each event, and we achieved sub-strip pitch position resolution with the proof of principle detector.

We investigated the dependence of position and energy resolution on the proximity electrode geometry using two error propagation methods, an analytic error propagation calculation and a Monte Carlo approach. By holding the strip pitch constant at 5 mm and varying the strip width and the distance between the detector surface and the strips, we mapped out the variable space and found that the position resolution improved when the strips were thinner and closer to the detector surface. Conversely, wider strips provide better energy resolution.

To optimize for position resolution, we chose 1 mm strip width positioned approximately 0.1 mm from the detector surface. We implemented the design on a large volume HPGe detector, and we were able to achieve 288 μm resolution, averaged over the full active area, with 5 mm pitch strips. This is a drastic improvement over double sided strip (DSSD) technology, which would need 300 μm strip pitch to match this position resolution without transient signal analysis. With this granularity, 100 readout channels would be needed to instrument the 3 cm active area covered by the proximity electrode readout. The proximity electrode method only required eight channels to instrument this area, significantly reducing the associated electronics needed to digitize and process the data. Predictably, the gains in position resolution were at the cost of energy resolution. The energy resolution of this electrode geometry was 4.7 keV at 59.5 keV, a significant degradation from standard HPGe resolution. We also showed that readout electrode modifications could be made easily, without the need to re-fabricate the detector. Simply removing and replacing the readout board allows for different readout electrode geometries that can be optimized for position resolution or energy resolution.

In this dissertation I have presented a novel, position sensitive charge readout method for HPGe detectors that can achieve very fine position resolution with large strip pitches, minimizing the number of electrodes needed to instrument large area crystals. I have shown that the fabrication techniques are simple when compared to existing technologies, and the methods for fabrication are well documented.

7.2 Future Work

It is clear that there is a trade-off between position and energy resolution for varying strip widths. The choice of electrode design would need to be chosen based on the application for which it will be employed. Further work can be done to investigate how strip pitch and Kapton (or similar) dielectric constant would change the performance.

To compete with double sided strip technology, the proximity charge sensing method must be able to provide two dimensional readout capability. Two dimensional readout techniques such as the one presented in Section 5.2.3 need to be developed and tested. Undoubtedly, challenges will arise when implementing the 2D readout, and will need to be overcome.

This technology currently has no methods for dealing with multi-site events such as a Compton scattering event followed by photoelectric absorption. If this technology is applied to γ -ray measurements, this challenge will need to be addressed. Compton imaging is a common application for which HPGe DSSDs are employed, and the ability to handle multi-site events within the same detector is an important feature. To compete, this technology must reckon with this challenge.

The proximity readout method is not limited to HPGe detectors. Any ionization type detector material could use proximity readout to measure charge from radiation events. The application of this technology to Si detectors would be an interesting endeavor. Si is lower Z and detectors are thin, making the material more applicable to lower energy photons, < 100 keV. Photoelectric absorption dominates at these energies and single-site, low-energy events are desirable in the current state of this technology.

Position sensitive proximity charge readout requires further investigation to be comparable to current position sensitive HPGe technologies. This dissertation provides the foundation for continuing research to develop this technology to maturity, where it can be used for the betterment of the physics community as a whole.

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Appendix A

HPGe Fabrication

End product overview:

- Amorphous Ge (a-Ge) on top and sides sputtered in Ar with 7% H₂
- a-Ge on bottom sputtered in pure Ar
- Full surface electrode on top
- Two, edge, strip electrodes on bottom

Many crystals present in our lab have been fabricated into detectors before, and are often left with the amorphous surface layers and electrodes intact. Figures A.1 and A.2 show a Ge crystal that had been fabricated into a detector with guard ring, center and HV Al electrodes. This configuration is common for testing crystal material and a-Ge contacts and their associated processing techniques.

To prepare for deposition of new contacts and electrodes, the existing features must be removed to expose the bare Ge crystal. The first step in achieving this is a hydrofluoric (HF) acid dip to remove the Al electrodes. The solution used is a 1% HF acid in water (100:1 H₂O:HF dip).

Rinse the crystal with deionized water and blow dry with dry nitrogen gas. Place the crystal in the HF dip, and make sure no bubbles persist on the surface. Allow to etch for one hour, checking occasionally for bubbles. Remove the crystal from the HF dip and quench the etch in deionized water. Rinse thoroughly with deionized water and blow dry with dry nitrogen gas.

After removing the Al electrodes, the former amorphous layers must be removed from the crystal surface. This can be achieved with a solution of hydrofluoric acid (HF) and HNO₃ (Nitric) acid. The proportions commonly used in the field for this etch are 4:1 HNO₃:HF.

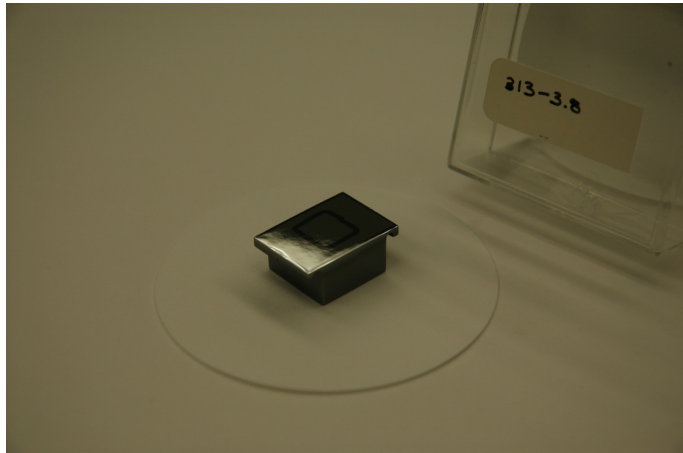


Figure A.1: Detector with former contacts (bottom).

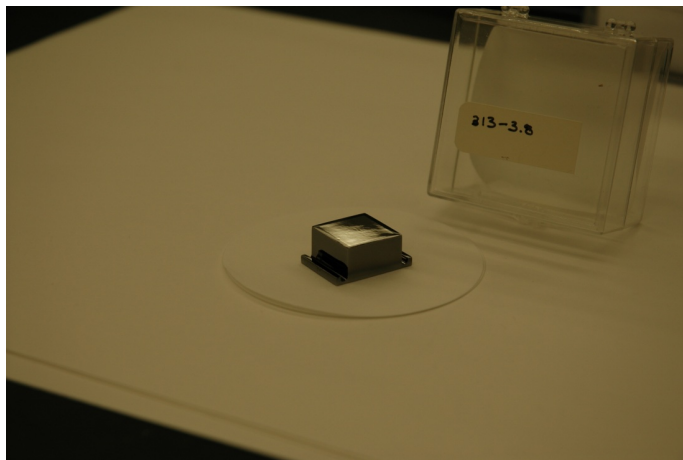


Figure A.2: Detector with former contacts (top).

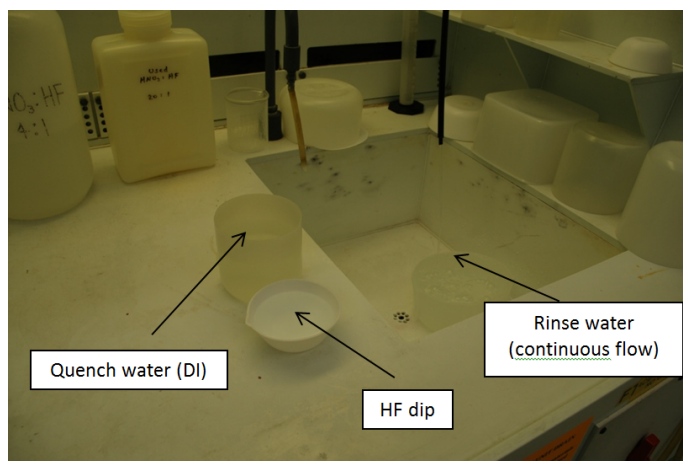


Figure A.3: Setup for HF dip to remove prior Al electrodes.

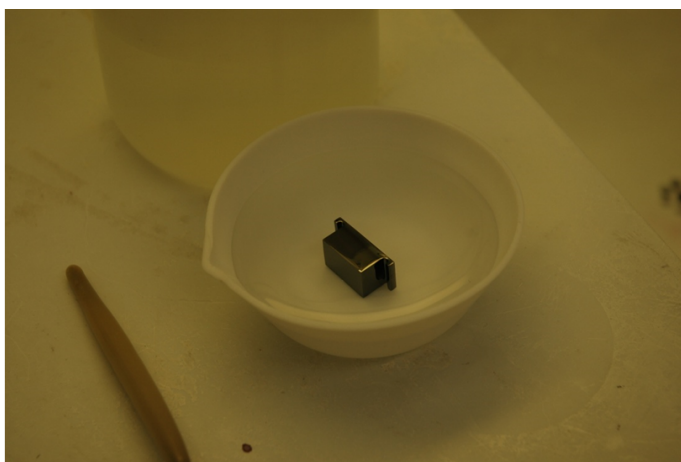


Figure A.4: Detector in HF dip. Note full surface electrode has been etched away.



Figure A.5: Detector in HF dip. Note guard ring configuration electrode has been etched away.

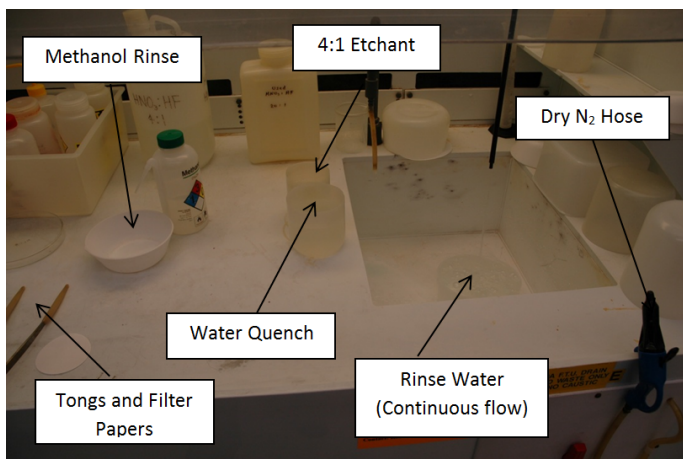


Figure A.6: Setup for 4:1 HNO₃:HF etch.

Submerge the crystal in the acid mixture and agitate by swirling to avoid the persistence of bubbles on the surface. Continue agitating for 30 seconds, then remove the crystal, quench the etch in a deionized water bath, and rinse thoroughly with deionized water. Rinse the crystal again with methanol, then blow dry with dry nitrogen gas. Inspect the surface for blemishes, rinsing again with methanol if necessary. If more substantial defects are present, repeat this process.

After etching, the crystal must be prepared for sputtered deposition of the amorphous layers. This involves loading the crystal on to a jig such that the wings are the only parts of the crystal that are contacted and particular surfaces are shielded from deposition. The order in which the amorphous depositions are performed will not affect the end product. Choosing which is done first is simply a matter of crystal handling logistics.

In Figures A.7-A.10, the crystal is being flipped so that it can be loaded on to another jig that is used for sputtered a-Ge deposition on the top and the sides. It is then loaded into the sputtering machine on the rotating stage, shown in Figure A.11. The crystal should be loaded into the sputtering machine directly after the 4:1 etch and methanol quench.

These crystals are fragile and prone to cracking, so handling of the crystal should be performed with extreme care at this point. Dropping the crystal or brushing critical surfaces against anything can cause scratching and/or residues to be deposited onto the surface, yielding opportunities for surface channels on the finished detector, causing increased leakage current.

In the process shown here, a-Ge on the top and the sides of the crystal was deposited first. The Al block the crystal was placed on to be loaded into the sputtering machine has ridges on either end, spaced out such that they support only the wings of the crystal. The gap below the crystal is small enough that no Ge will be deposited on the bottom.

The vacuum chamber used for sputtering was pumped overnight (to a pressure $\sim 5 \times 10^{-6}$ Torr), then brought to 15 mTorr by connecting a gas tank of Ar with 7% H₂ and throttling the turbo pump. The a-Ge layer was sputtered at 300 W, 1.1 kV between the target and anode, and sputtered in 2 minute intervals with 5 minutes in between for cooling. This is repeated 6 times. The crystal is also slightly offset from the target and rotated during sputtering in order to sufficiently coat the sides. This should produce an a-Ge layer that is approximately 3000 Å.

For the bottom amorphous layer, the crystal is flipped and loaded on to a different jig. The sides are then protected from deposition by an Al foil shield. The detector is again loaded into the sputtering machine, this time on a water cooled stage. The a-Ge layer is deposited with a plasma power of 300 W, with 1.1 kV on the anode, and at a pressure of 15 mTorr, this time in pure Ar. This is again performed in 2 minute intervals separated by 5 minutes for cooling. For the bottom of the crystal, this is only repeated 3 times. See Figures A.11-A.22 for pictures taken during this process.

After sputtering is finished, the crystal should be loaded on to the shadow mask alignment jig. To align the shadow mask, place the jig, along with a crystal dummy and the mask, under the alignment camera. Adjust the four lines on the screen such

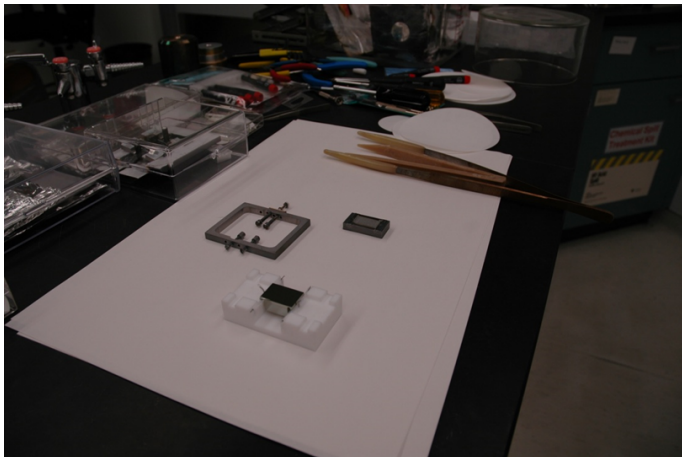


Figure A.7: Preparation for loading into sputtering machine.

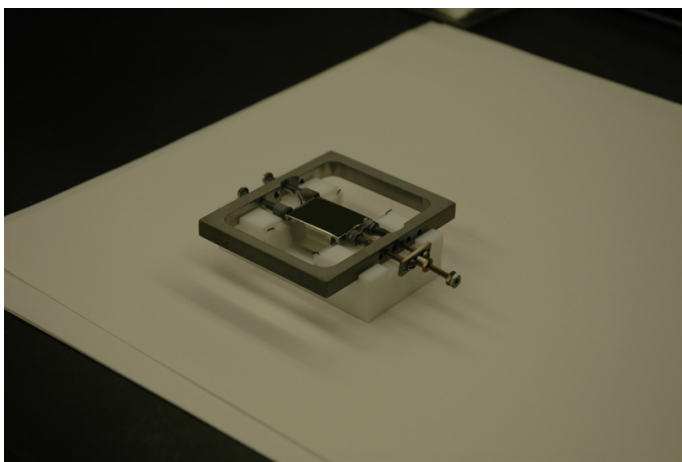


Figure A.8: Jig for flipping the crystal.

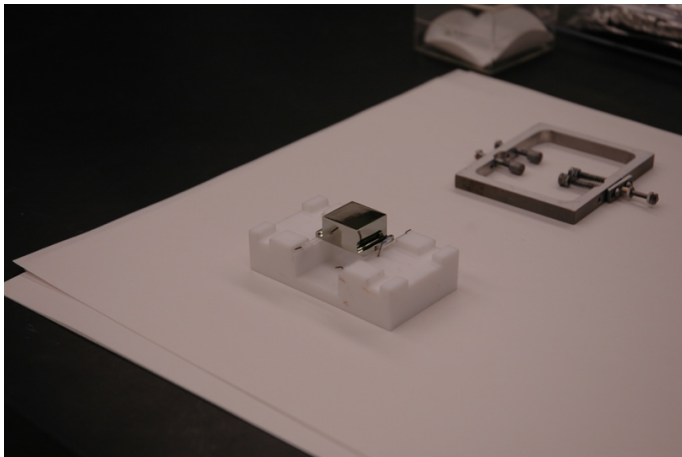


Figure A.9: Flipped crystal.

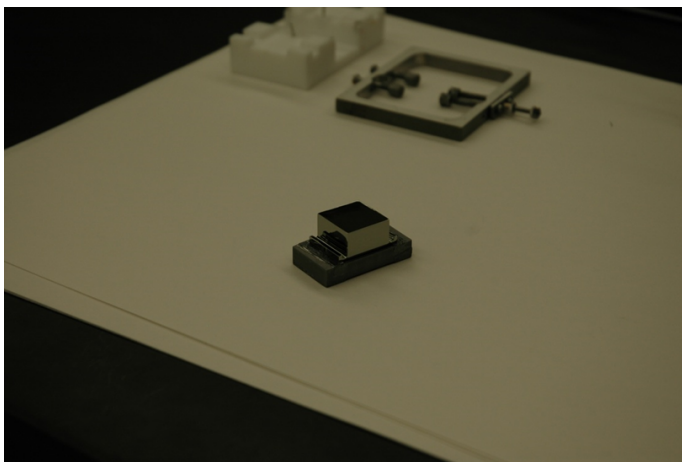


Figure A.10: Crystal on Al block ready to be loaded into sputtering machine.

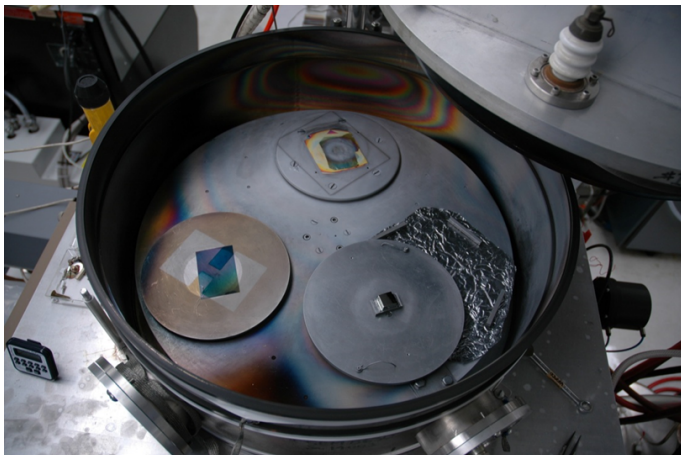


Figure A.11: Crystal on Al block loaded into sputtering machine on rotating stage.

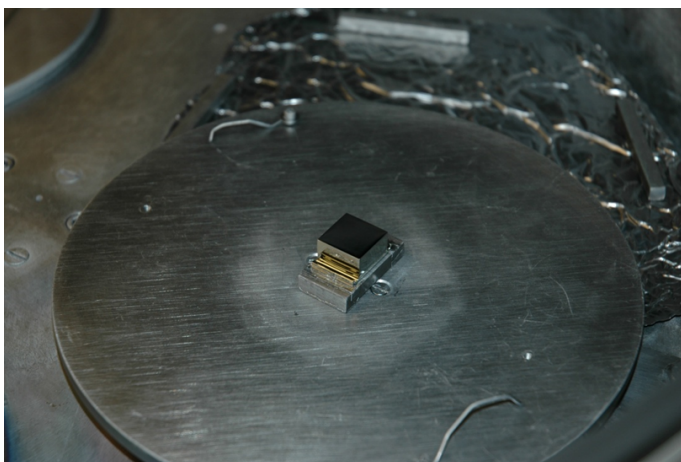


Figure A.12: Crystal on rotating stage.

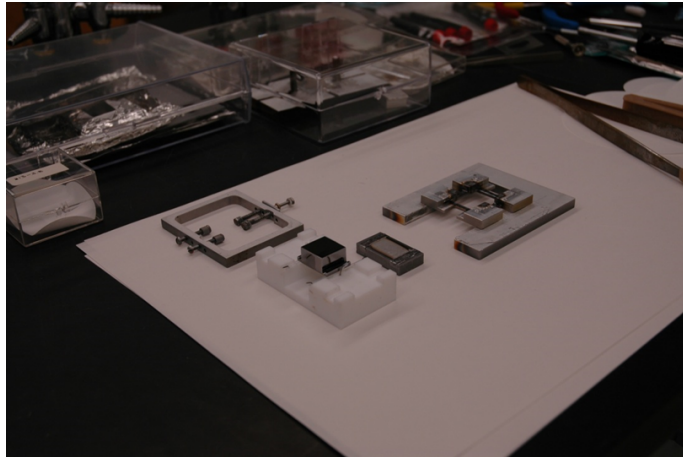


Figure A.13: Crystal after first sputtering (for top and sides) transferred for flipping.

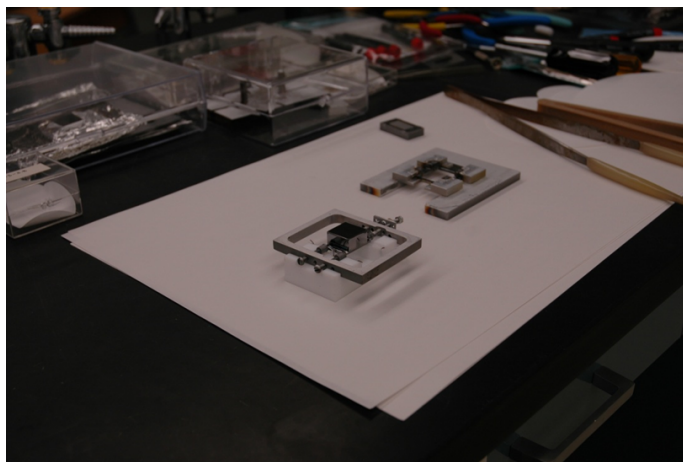


Figure A.14: Crystal flipping.

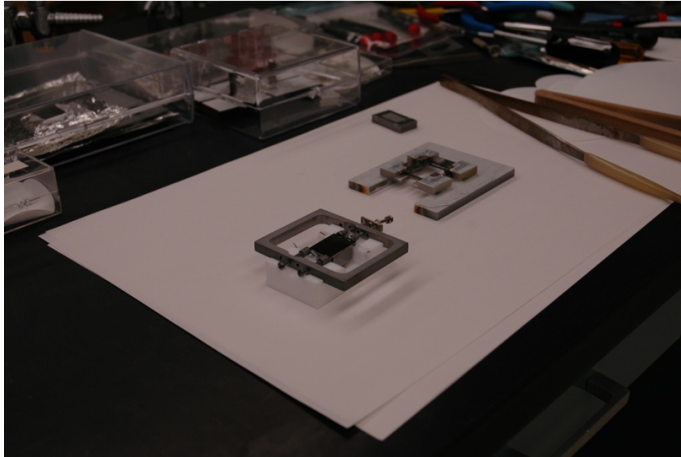


Figure A.15: Crystal flipped.

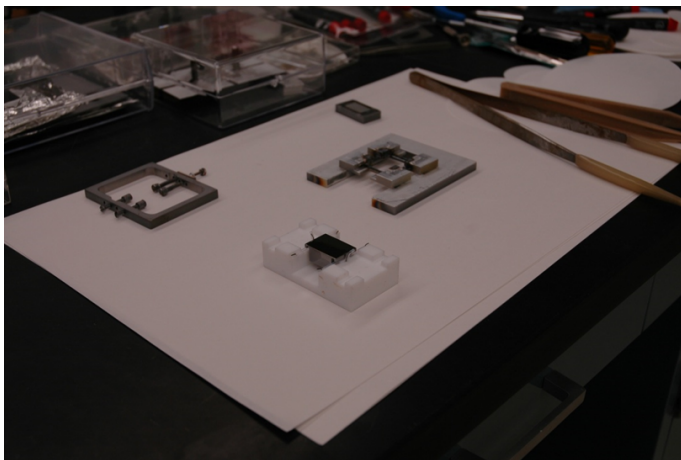


Figure A.16: Crystal ready for loading onto jig for bottom sputtering.

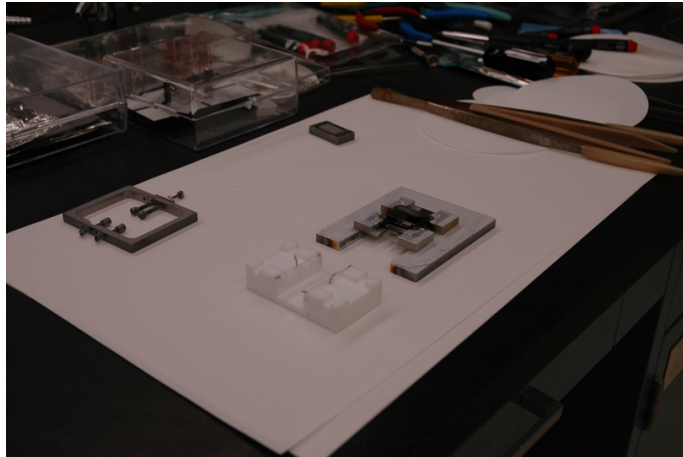


Figure A.17: Crystal loaded onto jig.

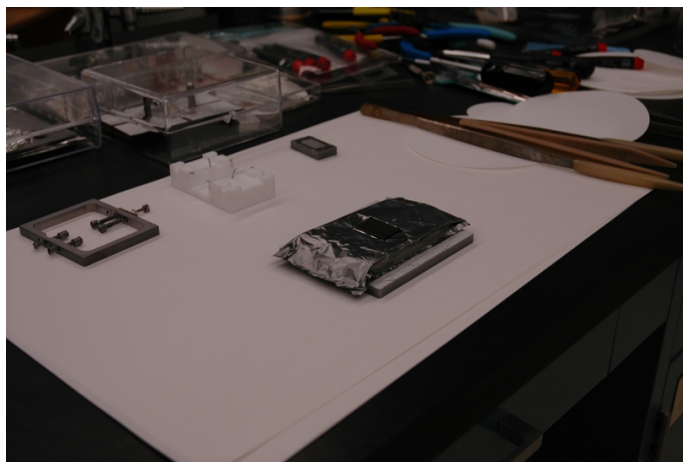


Figure A.18: Al foil side shield added.



Figure A.19: Weights added to secure Al foil shield.

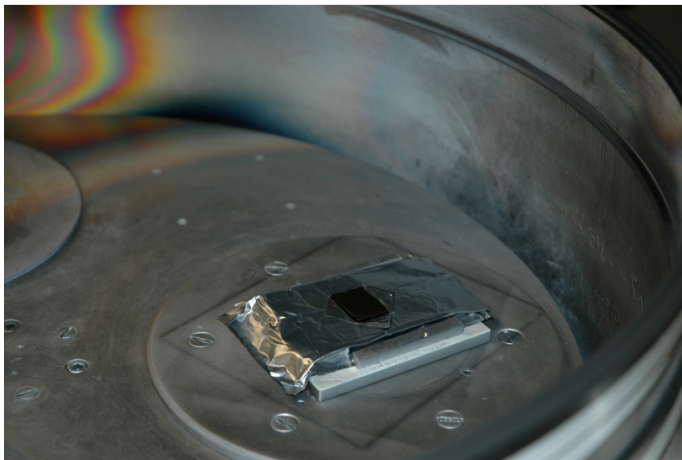


Figure A.20: Jig loaded into sputtering machine on water cooled stage.

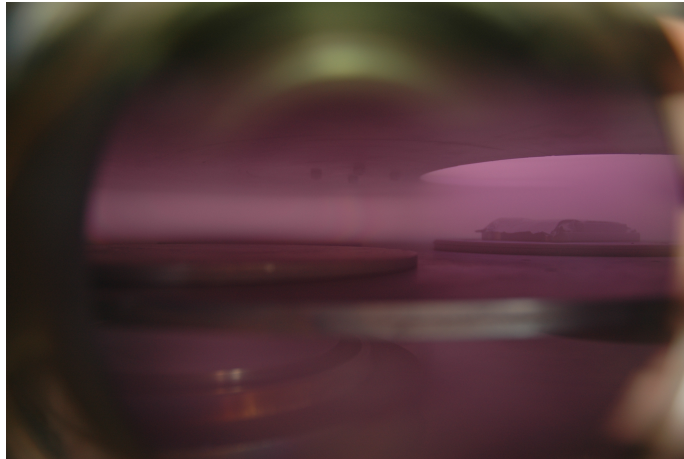


Figure A.21: During sputtering.

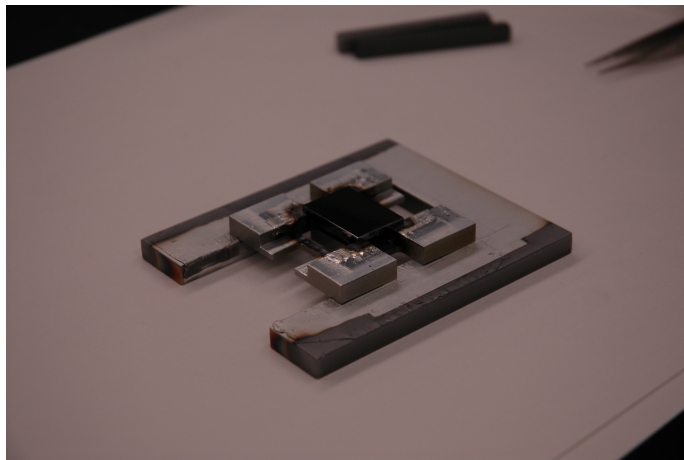


Figure A.22: Al foil side shield removed after sputtering.

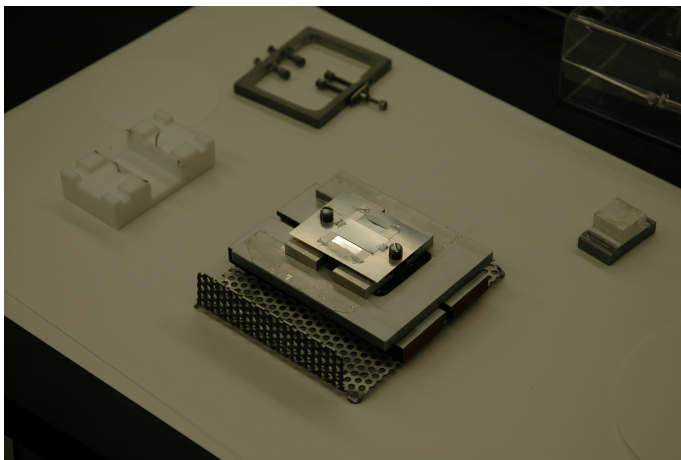


Figure A.23: Crystal loaded onto evaporation jig with shadow mask in place.

that they are collinear with the edges of the mask. Leave the jig under the camera and remove the mask and the dummy crystal. Place the real crystal on the alignment jig, adjusting it such that the shadow mask will be centered on the face on which the electrodes will be deposited (using the lines positioned where the perimeter of the mask will be). Place the mask over the detector, making sure the orientation is the same as when it was first positioned (the masks are not always symmetric). The setup is now ready to be loaded into the evaporator.

The evaporator must be prepared before loading the detector onto the stage (or the suspension jig, if evaporating up) to ensure nothing is dropped onto the crystal. This includes loading filaments that are pre-loaded with Al and positioning a screen (to help prevent spitting incidents, if necessary). After loading the crystal, make sure to replace the shield for the window and clear the vacuum sealing surface of any debris.

Allow the chamber to pump down to $\sim 10^{-6}$ Torr. For this process, $500 \text{ \AA}$ of Al is deposited for both the guard ring electrodes and the full surface, high voltage electrode. Allow the filament to heat up slowly. If heating too quickly, spitting can occur. Once deposition begins, allow about 1.5 minutes before opening the shutter for the molten Al to reach stability. Monitor the deposition rate and the filament while depositing. The deposition rate should be between 2 and 3 $\text{\AA}/\text{s}$.

After Al deposition on one side of the crystal has been finished, flip the crystal and align the appropriate mask with the alignment camera. After positioning the second mask over the (flipped) crystal, the process described in the last two paragraphs is repeated. Visuals of this process can be found in Figures A.23-A.27.

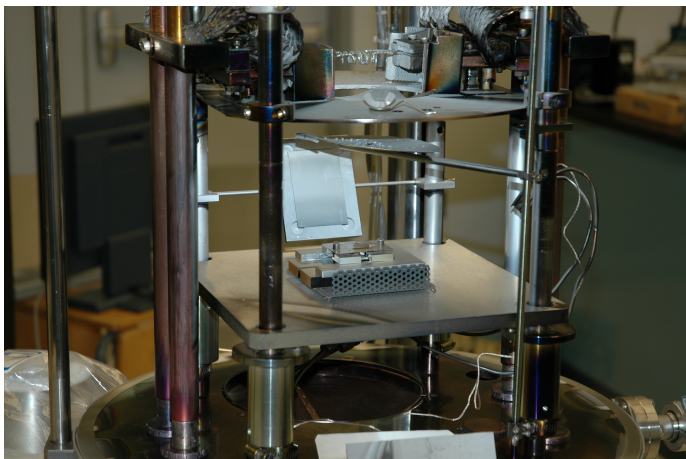


Figure A.24: Jig loaded into evaporator.

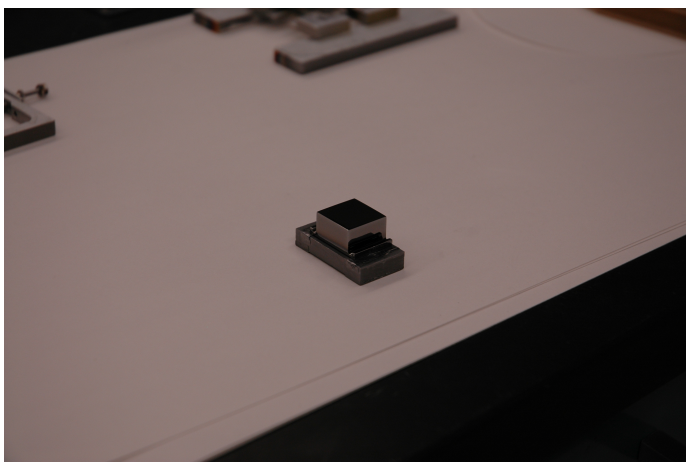


Figure A.25: Two edge strip (guard ring) electrodes on crystal bottom.



Figure A.26: Crystal loaded onto evaporation jig with shadow mask in place.

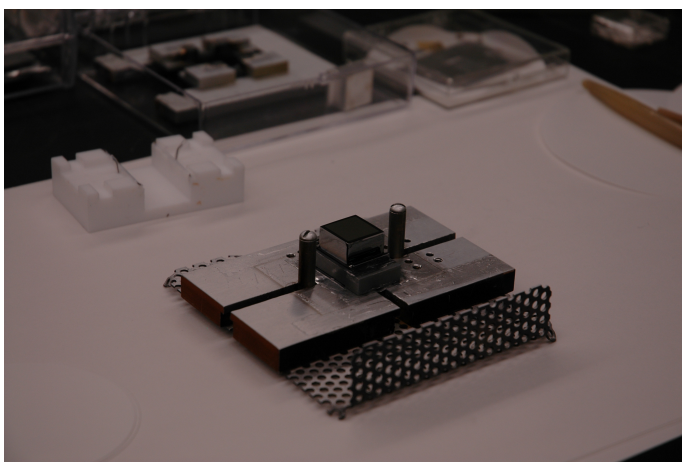


Figure A.27: Detector after top Al deposition.