

Simulation and validation of charge carrier drift in pixelated
microstructured semiconductor neutron detectors

by

Diego Laramore

B.S., Kansas State University, 2015

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the
requirements for the degree

DOCTOR OF PHILOSOPHY

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KANSAS STATE UNIVERSITY
Manhattan, Kansas

2020

Abstract

A semiconductor neutron imaging device is proposed (X-MSND) based on high efficiency, Micro-structured Semiconductor Neutron Detector (MSNDs) bump bonded onto a Timepix pixelated readout chip. The device serves as a combined neutron and photon imager with a 256 x 256 pixel array, using per-pixel time-over-threshold (ToT) energy deposition. The X-MSND design has produced thermal neutron detection efficiency of 14%, significantly greater than the theoretical maximum of less than 5% for planar devices. Simulated pixel clusters showed similar qualitative characteristics as planar neutron sensitive Timepix hybrid detectors.

A workflow for simulating the semiconductor physics, ionization by radiation, and charge carrier transport for micro-structured sensors in general has been devised and described in this work. The simulation workflow began by steady state initial conditions of the X-MSND PIN diode sensor at full bias using COMSOL Multiphysics. This simulation step served the combined purpose of providing the necessary electric field solutions used in charge transport, and provided necessary design and operating parameters for device fabrication. Radiation transport code Geant4 was used to simulate the radiation detection characteristics of the sensor: thermal neutron detection efficiency, energy deposition per detection event, and the location of the ionized charge cloud per interaction are all calculated at this step. Dassault SolidWorks was used to generate Computer-Assisted Drafting (CAD) models of the full micro-structured device geometry, which was then converted and imported into a format that can be interpreted by Geant4 for the radiation transport. Geant4 can then interface directly with a modified version of Allpix² to perform charge carrier drift over the entire X-MSND geometry.

Fabricated X-MSND devices were tested and evaluated at Kansas State University (KSU), and were found capable of producing high quality radiographs with both X-rays and neutrons. The fabrication of functioning X-MSND/Timepix assemblies was a collaborative effort among several research groups at KSU, domestic and international industrial partners, and international research groups. Fabrication of the X-MSND sensors was performed largely by Radiation Detection Technologies, Inc., with parametric design support from the Radiological System Integration Laboratory (RSIL) and Radiological Engineering Analysis Laboratory (REAL). The processes used in the production of X-MSND sensors are conventional micro-electro-mechanical system (MEMS) photolithography techniques; spin-on deposition and ultraviolet development of photoresist, metal lift-off, and wet etching of silicon are all used over the course of fabrication, and are described in detail. The Electronics Design Laboratory (EDL) of Kansas State University assisted in the design of custom printed circuit boards to which the X-MSND/Timepix assemblies are mounted. External to facilities located at KSU, various industrial manufacturing partners who specialize in Very Large Scale Integration (VLSI) and micro-fabrication assembly processes were also contracted to perform the specialized assembly processes required in assembling the full X-MSND/Timepix systems.

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Dedication

This work is dedicated to Paul and Elena Laramore, who are my parents, my mentors, my friends, and perpetually my inspiration to succeed and strive for greatness.

Chapter 1

Introduction

Neutron transmission radiography is a mature concept that has found applications in non-destructive analysis, special nuclear materials (SNM) detection, and diagnostic imaging of plastics and low- Z materials embedded in high- Z casings^{9;10}. Unlike x-rays which interact in the electron cloud of atoms, neutrons interact with atomic nuclei. The result is that radiographic images generated with x-rays contrast with high atomic mass materials, whereas neutrons interact in low atomic mass (and especially hydrogenous) materials. As both radiography techniques can provide information about the subject being imaged, particularly in mixed medium or dynamic subjects, techniques have been developed which simultaneously collect and process radiographic data from both neutrons and x-rays, so called “bimodal” radiation imaging¹¹.

Currently available state-of-the-art bimodal radiation imaging systems implement scintillation screens which are both thermal neutron and x-ray sensitive (commonly, Gadolinium Oxysulphide screens) coupled to integrated Charge Coupled Device (CCD) arrays to produce digital radiographs from both radiation types nearly instantly¹²⁻¹⁵. Although these systems are capable of producing large format, high resolution radiographs, they suffer from a fundamental limit in detection efficiency. The scintillation screens that convert neutrons to light must be thin enough to mitigate quantum efficiency losses and pixel sharing of the isotropically emitted scintillation light; still, quantum efficiency losses of 50% are common.

Optical fiber coupled and lens coupled scintillation systems have been developed to improve the spatial resolution of conventional scintillation imagers, but sacrifice portability of the system¹⁶.

Neutron converter coated pixelated silicon photodiodes have been developed to provide bimodal imaging capabilities and improve the portability of neutron imaging systems. Pixelated sensor manufacturer Advacam Oy, for example, has developed thin film coated pixelated PIN diodes for bimodal imaging in a number of semi-portable form factors¹⁷. However, these planar coated sensors suffer from very limited theoretical neutron detection efficiency¹⁸. For example, planar diodes coated with enriched ^6LiF of the kind fabricated by Advacam have been proven to have a theoretical maximum thermal neutron detection efficiency of less than 5%¹⁹.

The desire to produce a semi-portable, combined high efficiency thermal neutron and x-ray radiography system naturally arises from this gap in available technology. To this end, a research effort was solicited by Honeywell Federal Manufacturing and Technology, LLC. with the purpose of developing a low-profile, high detection efficiency bimodal sensor. A new device was proposed by a KSU research collaboration to satisfy this need, consisting of the Radiological Engineering Analysis Laboratory (REAL), the Radiological Systems Integration Laboratory (RSIL), and Radiation Detection Technologies, Inc (RDT). The device, called the X-MSND, is a small form factor bimodal radiation imager made by combining two well established and characterized basis technologies: the micro-structured semiconductor neutron detector (MSND), and the Timepix variant of the Medipix pixelated readout chip.

1.1 Basis Technology Background

1.1.1 Medipix and Timepix Readout Chips

The Medipix family of CERN developed Application Specific Integrated Circuits (ASICs) were developed as a pixelated readout solution for radiation tracking and imaging during Large Hadron Collider experiments, but has since expanded into a series of international col-

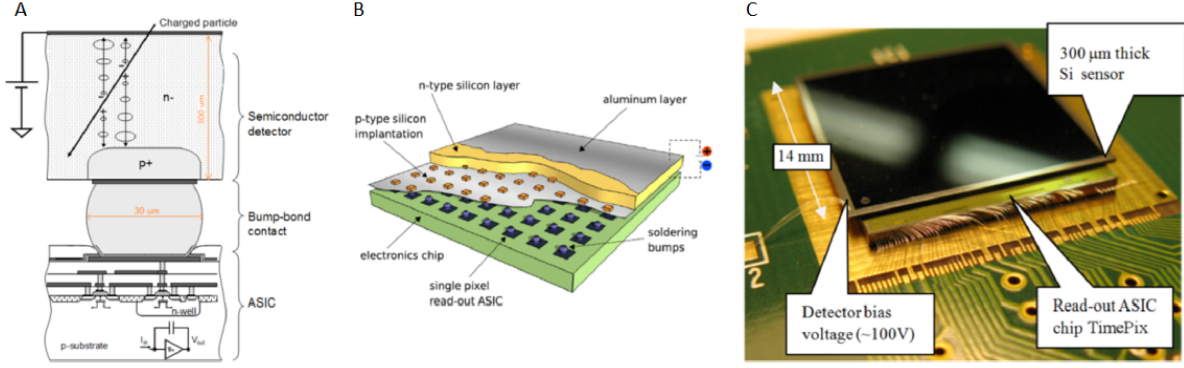


Figure 1.1: *Diagrams of hybrid Timepix sensor showing A) a single pixel of the assembly, B) a cutaway illustration, and C) a photo of a hybrid Timepix with components annotated¹.*

laborations, including the ongoing Medipix4 collaboration^{7;20;21}. The readout ASIC consists of an array of analog micro-scale inputs, each of which is coupled to a simple charge sensitive amplifier circuit leading into a threshold discriminator. Medipix based readout chips have been adapted for use in various types of compact detection systems, with the most common variant being the “hybrid” Medipix sensor^{21–23}. These devices consist of a planar silicon PIN photodiode serving as the radiation sensor, usually in the range of 300 - 500 μm thick and having pixelated contacts on one side. The sensor is bump-bonded to the Medipix chip via micro-scale solder dots, and high voltage is applied through the assembly to bias the diode and AC couple the sensor pixels to the readout electronics, effectively converting the silicon diode into a radiation imager.

The Timepix variant of the Medipix readout chip is a 256 x 256 pixel array with a pixel pitch of 55 μm , giving it chip dimensions of 14 x 14 mm. The Timepix ASIC was unique during its initial development in that each pixel can provide an estimate of the magnitude of the energy deposited above each pixel. This is done by reporting the length of time the pixel current remained over some threshold value (Time over Threshold, or ToT), which can then be converted to energy by a pre-calculated calibration profile²⁴. Illustrations and pictures of hybrid Timepix imager functionality can be seen in Figure 1.1.

Commercial hybrid Timepix based systems have been developed by the previously mentioned company Advacam Oy of Finland. Advacam provides commercial off-the-shelf sensors as well as custom order devices for a number of imaging applications, including x-ray ra-

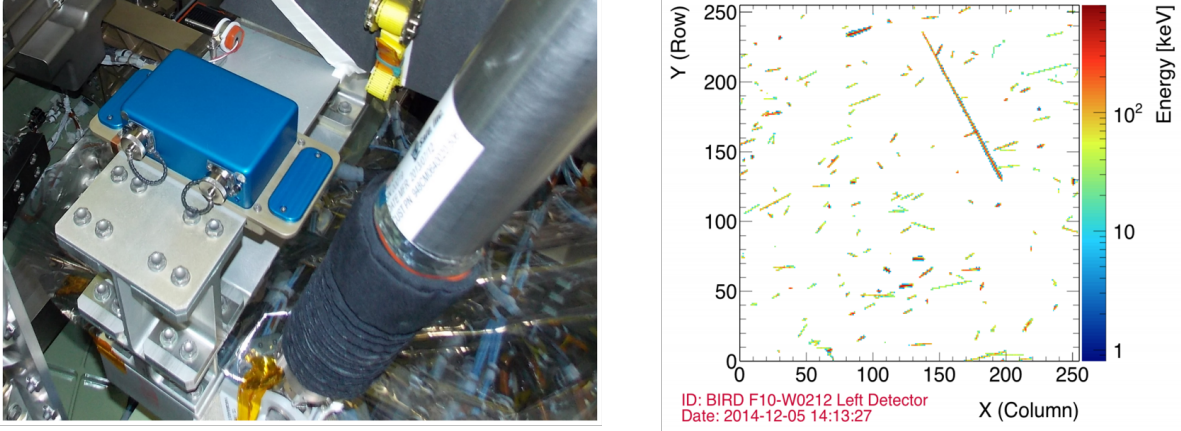


Figure 1.2: *Left: The BIRD system in place in the Orion MPCV capsule during the EFT-1 flight. Right: Example frame collected from the BIRD showing energetic charged particles ionizing the silicon sensor²*

diography, non destructive testing, and x-ray diffraction experiments¹⁷. Advacam has also developed large area radiation imagers (WidePIX series) by arraying hybrid Timepix sensors, and arrays as large as 10 x 10 sensors have been fabricated for large subject, low-framerate imaging.

Hybrid Timepix readout chips with silicon PIN diode sensors have found significant use in space radiation monitoring, particularly in detection systems developed by the National Aeronautics and Space Administration (NASA)²⁵. The Timepix based ISS-Radiation Environment Monitor (ISS-REM) has been the active radiation environment sensor system in place at the International Space Station since 2012²⁶. The hybrid Timepix based Battery-operated Independent Radiation Detector (BIRD) detector (shown in Figure 1.2) was recently taken to low Earth orbit during the Exploration Flight Test 1 (EFT-1) mission, which provided dosimetric and particle tracking data of the interior of the the Orion Multi-Purpose Crew Vehicle (MPCV) designed for crewed deep-space exploration². Advanced variants of the Timepix derived system are being continuously developed for the purpose of space radiation dosimetry and spectroscopy, such as the next generation Hybrid Electronic Radiation Assessor (HERA) to be flown on future crewed space exploration missions²⁷.

1.1.2 MSND Sensors and Variants

The MSND was developed by the Semiconductor Materials and Radiological Technologies (S.M.A.R.T.) Laboratory at Kansas State University as a high detection efficiency alternative to thin-film coated PIN diode detectors for thermal neutron counting^{4;28–30}. An evolution of neutron converter filled perforated diode detectors, MSNDs function by having high aspect ratio trenches etched on the surface of the silicon chip, effectively increasing the surface area of the sensor¹⁸. The trenches are then backfilled with a neutron converter material as shown in Figure 1.3, providing significantly higher neutron detection efficiencies than equivalently sized film coated planar diodes. Common ^6LiF backfilled MSNDs have been shown to have intrinsic thermal neutron detection efficiencies of over 30%³¹, and millimeter thick dual-sided variants (DS-MSNDs) have been developed with thermal neutron detection efficiencies of over 60%.

RDT Inc., currently fabricates commercial variants of MSND sensors in Manhattan, Kansas³, and frequently collaborates with KSU research groups to produce purpose-built variations of MSND sensors for special applications. The versatility of the MSND chip has contributed greatly to implementation in various sensor systems. For example, the Helium Replacement (HeRep) series of thermal neutron detectors are based on MSND sensors, and are designed to be cost-effective drop in replacements for ^3He based proportional gas detectors³². Current HeRep Mk III detectors based on DS-MSNDs have been developed with neutron detection performance over 50% that of equivalently sized high pressure (10 atm) ^3He tubes at a significantly reduced unit cost.

MSND technology has been developed for many low-profile neutron detection applications. The commercially available RDT Domino[®] is a modular, universal serial bus (USB) operated neutron counting system³³. The complete Domino system consists of a single USB driver board and one or several MSND sensor boards having an active area of 4 cm^2 each, with all boards have dimensions within $28\text{ mm} \times 30\text{ mm} \times 6\text{ mm}$. Fully portable examples of MSND based detection systems include the MSND Wearable Detector Device (WDD), which was designed specifically to aid in the search and localization of special nuclear ma-

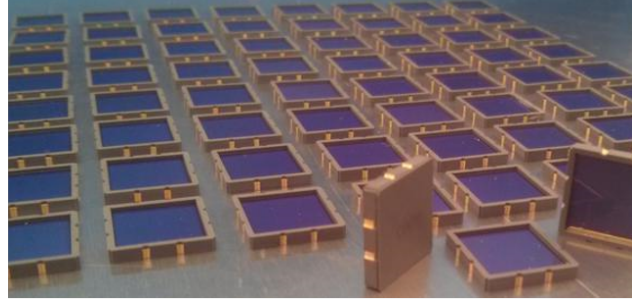
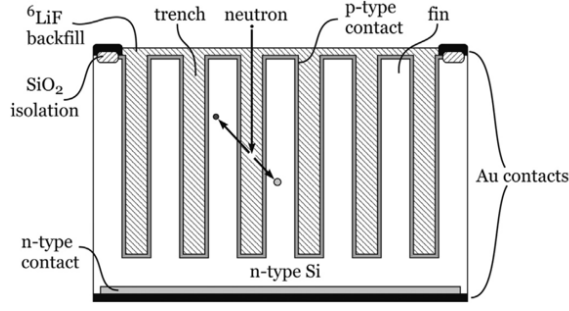


Figure 1.3: *Left: Crossection diagram showing the typical configuration of an MSND sensor. Right: Several commercial 1 cm MSND chips as fabricated by RDT, Inc.^{3;4}*

terials (SNMs)³⁴. The WDD is a vest shaped wearable detection system consisting of 16 Modular Neutron Detectors (MNDs), with each having 4x6 arrays of MSND chips, and was specifically designed with the portable identification of SNMs and illicit materials in mind.

1.2 X-MSND Design Concept

The X-MSND design concept is simply a variation of a hybrid Timepix semiconductor detector where the typically planar silicon sensor is replaced with a purpose designed MSND chip. Such an imager would provide x-ray sensitivity via photon interactions in the silicon substrate of the sensor and neutron sensitivity via the neutron converting enriched ^6LiF nanopowder backfill in the MSND trenches. The micro-structured sensor as designed has 200 μm deep trenches backfilled with a packing fraction of 50%, giving it a theoretical thermal neutron detection efficiency of close to 15%, while still preserving a large bulk silicon thickness for x-ray interactions. Figure 1.4 provides an illustration of the assembly concept and its functional mechanisms. The trench/fin pitch of the sensor is chosen to match the pixel pitch of the Timepix readout chip, with the silicon fin centered on the pixels.

To distinguish x-ray and neutron events separately, the fine pixel structure imaging capability of the Timepix readout will be leveraged to image the ionization clouds formed in the MSND. The shapes of these “clusters”, as well as their ionization magnitude and density, allow discrimination between energetic electrons (from x-ray interactions) and energetic heavy charged particles (from neutron interactions).

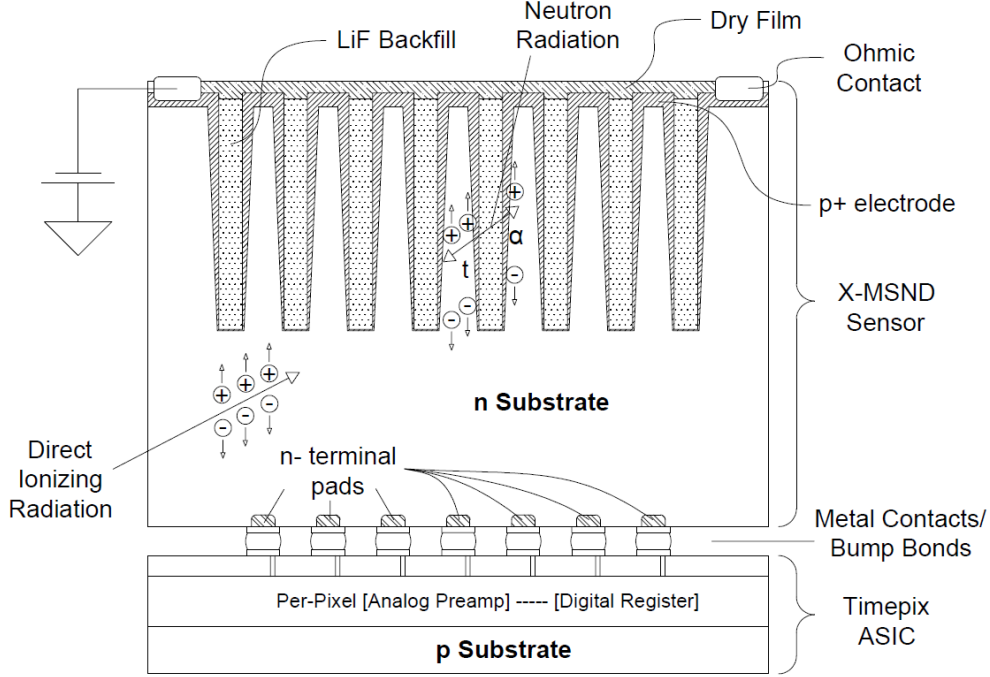


Figure 1.4: *Illustration of the X-MSND sensor bump bonded to the Timepix readout chip*

1.3 Research Goals

The efforts outlined in this dissertation are focused primarily on the simulation of the radiation imaging aspects of X-MSND devices. In particular, this work describes a physics based approach to simulating the expected response of a micro-structured imagers that relies minimally on empirical assumptions. However, the scope of this research encompasses both simulation and fabrication of semiconductor devices, the collection and processing of large data sets for comparison between simulated and measured sensor responses, analysis of the cluster characteristics of the real device hardware, and the processing of collected data to produce radioimages. The following three research fields were identified as key aspects necessary for the success of this investigation, each with several goals:

1. **Generate accurate physics based simulations of charge drift in sensors.** Simulating the response of the imagers provides important insight into the charge collection characteristics and cluster morphology. The complex, three-dimensional boundary conditions of the micro-structured devices necessitates that a physics driven charge

transport method be implemented^{35;36}. This method should allow characterization of the steady state conditions of the semiconductor device based on the doping and biasing profile of the sensor. Radiation transport should be incorporated in this method to produce physically accurate ionization tracks in the sensitive regions of the sensor. The method should also capture the drift and diffusion properties of this charge cloud as it transits the sensor; drift time, charge recombination and trapping, cluster properties, and analog to digital conversion (ADC) characteristics should all be modeled.

2. **Develop a fabrication and assembly process for X-MSND and Timepix chips that results in high functionality yields.** The commercially manufactured MSND must undergo significant design and processing changes in order to be compatible with the Timepix readout ASIC. The assembly process for bonding the two chips will also need to be characterized and iterated to ensure successful, consistent bonding and high pixel yields. Additionally, custom circuit boards and test vehicles will need to be developed to allow the assemblies to be safely biased, transported, and interfaced to.
3. **Produce x-ray and neutron images with operating sensor assemblies.** Following the evaluation of X-MSND assemblies for functionality, the most successful of these will be used to generate bimodal radiographs of various phantoms and objects. This will require significant testing infrastructure that must be prepared beforehand, including neutron and x-ray testing facilities, beam quality assessment, and data processing tools. Generating radiographs from raw frame data also requires significant post processing to account for the unique neutron cluster morphology of the X-MSND sensors, and to allow for the intelligent interpolation of masked pixels.

Chapter 2

Modeling X-MSND in COMSOL

Multiphysics

The steady state semiconductor simulations of the X-MSND device provide two critical solutions necessary for charge carrier transport. Firstly, they establish the distribution of charge carriers in the silicon substrate under bias, and secondly, they provide the potential and electric field distribution inside the sensor, which causes charged carriers to drift. These solutions are calculated to determine the electromotive force necessary for charge drift.

In addition to providing the information necessary for charge carrier transport, this simulation step can provide important hardware design and operations parameters. Key parameters informed by the simulations include the minimum resistivity of the substrate silicon, estimates of the required biasing voltage, and estimates of charge carrier lifetime.

2.1 PIN Junction Formation, Depletion, and Biasing

The X-MSND sensor operates as a negatively biased positive-intrinsic-negative (PIN) photodiode detector, where the acceptor-doped upper micro-structured surface forms the abrupt junction with the *n*-type high resistivity silicon (illustrated in Figure 1.4). Under reverse bias, the holes in the substrate are pulled away from the junction to the *p*-type contact,

and electrons are likewise pulled to the n -type contact. At the full depletion voltage, the depletion layer widens to the thickness of the substrate, producing a high resistivity region supporting a strong electric field^{37;38}. This forms a radiation sensitive region between the upper monolithic and lower pixelated electrodes, where charges generated from ionizing radiation do not readily recombine and can move freely under the influence of the electric field.

The X-MSND sensor is unique among PIN diode sensors due to its very deeply etched trenches being conformally doped^{4;29}. During the fabrication process, the acceptor junction is formed by thermally diffusing boron into the micro-structured side of the silicon wafer. This produces a heavily p -type doped surface that extends conformally around the silicon fins to the bottom of the trenches. To explore the effects of this conformal junction, both a conformal and non-conformal doped X-MSND sensor were simulated.

2.1.1 Estimating Depletion Voltage

Prior to simulating the bias-dependent depletion of the micro-structured silicon, the depletion voltage was estimated based on analytical approximations. The depletion width W of a two-sided abrupt junction can be calculated as

$$W = \sqrt{\frac{2\varepsilon_s}{q} \left(\frac{N_A + N_D}{N_A N_D} \right) V_b} \quad , \quad (2.1)$$

where ε_s is the permittivity of the material, q is the elementary charge, V_b is the bias voltage across the junction width, and N_D and N_A are the donor and acceptor concentrations, respectively^{38;39}. If the majority carrier concentration is much greater than the minority carrier concentration, then the one sided abrupt junction formula can be used:

$$W = \sqrt{\frac{2\varepsilon_s V_b}{q N_B}} \quad , \quad (2.2)$$

where N_B is now the majority carrier concentration. The value of N_B can be inferred from the resistivity ρ of the silicon substrate:

$$N_B = \frac{1}{\rho \mu_B q} \quad , \quad (2.3)$$

where μ_B is the mobility of the majority charge carriers. Solving for an n -type silicon wafer having a resistivity of $8 \text{ k}\Omega \text{ cm}$ gives an estimated donor concentration of $5.6 \times 10^{11} \text{ cm}^{-3}$. The X-MSND is designed for a wafer thickness of $525 \text{ }\mu\text{m}$. Substituting into Equation 2.2 and solving for V_b gives an estimation of the reverse bias voltage required to deplete a planar sensor:

$$V_b = \frac{q N_B W^2}{2\epsilon} = \frac{(1.60 \times 10^{-19} \text{ C})(5.6 \times 10^{17} \text{ m}^{-3})(525 \times 10^{-6} \text{ m}^2)}{2(11.7)(8.85 \times 10^{-12} \text{ C V}^{-1} \text{ m})} = 119.5 \text{ V} \quad (2.4)$$

This estimate is in line with other sensors photodiode devices, but ignores lateral depletion required to isolate the small diffused contacts on the cathode side of the sensor for the bump bond contacts. Conformal depletion around the bump bonds is critical to reducing charge sharing between pixels. The $500 \text{ }\mu\text{m}$ Timepix sensors manufactured by Advacam typically have a resistivity of over $10 \text{ k}\Omega \text{ cm}$ and are biased and calibrated at 200 V to ensure tight pixel depletion, which is more than twice the depletion voltage calculated with Equation 2.4. This implies that X-MSND sensors would need to be biased at a voltage near or over 240 V .

Charge Carrier Transport Equations

The physics of charge carrier motion in semiconductors relies heavily on the Poisson-Boltzmann model of charge carrier drift and diffusion. The nodal current density solution begins with Poisson's equation which relates the electric field $\mathbf{E}$ to the semiconductor charge carrier concentrations as

$$\nabla \cdot \mathbf{E} = \nabla \cdot (-\epsilon_r \nabla V) = q(p - n + N_d^+ - N_a^-) \quad , \quad (2.5)$$

where ε_r is the permittivity of silicon, q is the elementary charge, p and n are the electron/hole concentrations, and N_d^+ and N_a^- are the donor and acceptor concentrations respectively^{40;41}. Solutions describe the carrier concentrations throughout the geometry and the resulting depleted regions and electric field distributions. The current density at a node $J_{n,i}$ can be evaluated as the combination of carrier drift and diffusion by

$$\mathbf{J}_{n,i} = qn_i\mu_n\nabla E_i + qk_BT\mu_n\nabla n \quad , \quad (2.6)$$

where μ_n is the electron mobility. Note that the effects of electric field drift and thermal diffusion are independent of each other, and can be calculated independently at each transport step. This characteristic is key in the simulation of transient charge carrier diffusion as discussed in Chapter 4 of this thesis. The Maxwell current continuity equation relates transient nodal conditions to the current density, and completes the set of current relation equations

$$\frac{\partial n}{\partial t} = \frac{1}{q}(\nabla \cdot \mathbf{J}_n) - \Sigma R_{n,i} + \Sigma G_{n,i} \quad , \quad (2.7)$$

where $\Sigma R_{n,i}$ and $\Sigma G_{n,i}$ are the electron recombination and generation rates at node i , respectively. At steady state equilibrium, Equation 2.7 converges to zero. The same equations can be applied equally to holes as electrons, and will be needed to complement Equation 2.5 to form a complete set of equations to describe charge carrier distribution and under bias.

2.1.2 Doped Boundary Conditions

The dopant concentration profile as a function of depth in the substrate is highly dependent on the impurity diffusion process, with the two most common methods being thermal diffusion and ion implantation. In the case of MSNDs, the donor and acceptor atoms are driven into the silicon via thermal diffusion from solid sources, where wafers of boron nitrate and phosphorus oxide are held in close proximity to the silicon (masked or unmasked) and taken to high temperatures in a diffusion furnace³⁰.

This doping method can be best be approximated by Constant-Surface-Concentration

diffusion, which is found as a solution to Fick's diffusion with specific boundary conditions³⁹. Beginning with Fick's Diffusion equation, the charge carrier concentration C can be expressed as:

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} \quad , \quad (2.8)$$

where D is the diffusion coefficient of the substrate, and x and t are the diffusion depth and time, respectively. The constant surface concentration model assumes that the dopant flux at $x=0$ is constant with time ($C(0, t) = C_s$), and that the concentration is zero at infinite depth ($C(\infty, t) = 0$). Solving Equation 2.8 for these boundary conditions gives

$$C(x, t) = C_s \operatorname{erfc}\left(\frac{x}{2\sqrt{Dt}}\right) \quad , \quad (2.9)$$

where $\operatorname{erfc}(x)$ is the complimentary error function (see Appendix A).

The diffusion coefficient is experimentally measured for materials, and is a predictable function of temperature. The logarithm of the diffusion coefficient is linearly proportional to the inverse logarithm of the substrate temperature. The diffusion constant can therefore be calculated for any temperature T as follows

$$D = D_0 \exp\left(\frac{-E_a}{kT}\right) \quad , \quad (2.10)$$

where D_0 is the tabulated diffusion constant extrapolated to infinite temperature, and E_a is the activation energy required to move dopant atoms from one interstitial site to the next. This relation assumes that the diffusion coefficient is constant for all areas of the substrate, which is true from low charge carrier concentrations. At higher concentrations, the diffusion coefficient changes depending on the carrier type and substrate. An empirical equation can be used to relate the buried diffusion coefficient to the surface diffusion coefficient D_s and the surface charge carrier concentration C_s as

$$D = D_s \left(\frac{C}{C_s}\right)^\gamma \quad , \quad (2.11)$$

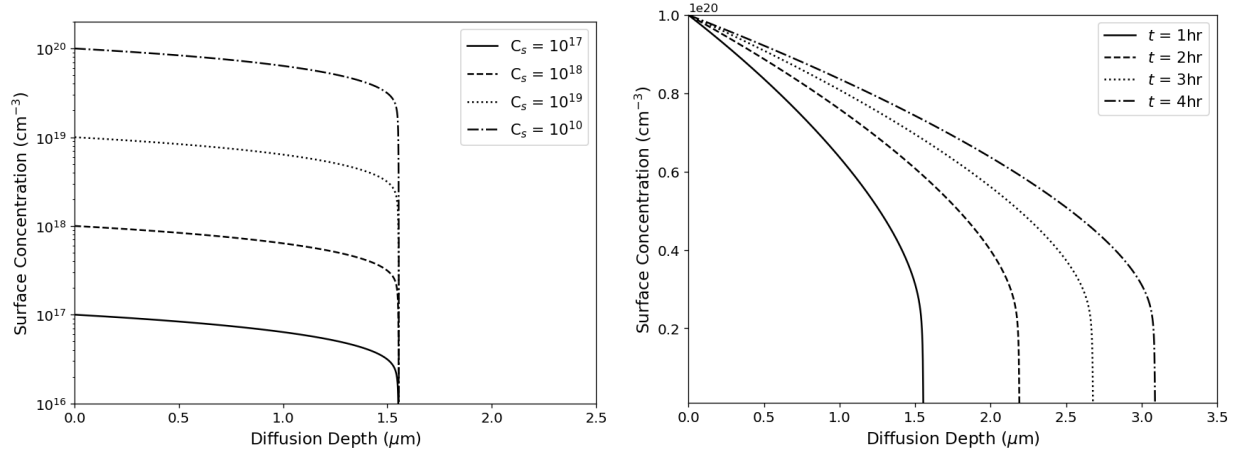


Figure 2.1: *Diffused boron concentration with respect to diffusion depth. Left: Diffusion with variation in surface concentration at a fixed diffusion time of 1 hour. Right: Diffusion with variation in time at a fixed surface concentration.*

where γ is an empirically determined quantity. For boron diffused in silicon, for example, γ is approximately equal to one.

Using the above three equations, it is possible to empirically estimate the dopant concentration profile of the X-MSND junctions. Figure 2.1 shows plots of boron doped in silicon for variations in surface dopant concentration and diffusion time. Note that the diffusion depth is independent of the surface concentration, and depends solely on the diffusion time. This is a critical factor in defining the simulation initial conditions for the conformally doped trenches of the X-MSND, as the surface concentration in the trench sidewalls varies with depth in the trench. For X-MSNDs, the doped regions are deeply diffused to a depth of approximately $3\text{ }\mu\text{m}$, corresponding to a diffusion time of just under 4 hours.

Conformal Dopant Diffusion Profile

As previously noted, both the n -type and p -type doping of the X-MSND are accomplished via thermal diffusion of a solid wafer diffusion source. However, the microstructures on the acceptor doped side of the MSND substrate result in a partially conformal doping in the interior of the trenches. The acceptor source is made from hexagonal boron-nitride (hBN) powder which has been pressed and sliced into wafers⁴². This material is very stable at high temperatures, which allows for the slow and controlled diffusion of sublimated boron to dose

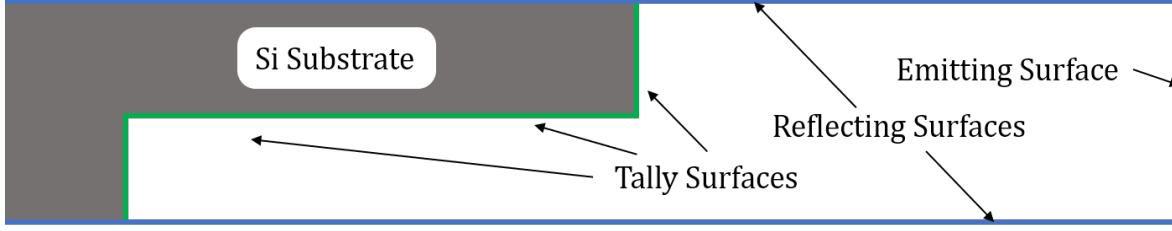


Figure 2.2: *Illustration of particle tracking simulation used to predict the acceptor dopant surface dose conformally in the X-MSND Trench. Figure dimensions are not to scale.*

the adjacent silicon.

The variation in dopant surface concentration has been difficult to measure for real devices because of the relatively poor ability to measure or image acceptor dopant concentration in high resistivity n -type silicon. This is because most chemical stains used to provide scanning electron microscope imaging contrast to doped regions are cationic (for example, solutions of copper sulfate pentahydrate and hydrofluoric acid) and bond only to donor sites, which exist at low concentrations in highly intrinsic silicon^{43;44}.

An estimate of the acceptor concentration was generated by taking the known surface concentration of the top of the anode terminal and comparing to the estimated normalized fluence of diffuse particles incident on a 2D surface with the same geometric properties as the X-MSND. This was accomplished using a simple particle tracking module implemented by COMSOL: a particle emitting plane and the 2D half pixel geometry of an X-MSND were created as in Figure 2.2. The sides of the simulation space were made to reflect the particles, simulating an infinite X-MSND chip. Particles were emitted from the emitting surface with a cosine distribution and allowed to propagate toward the X-MSND tallying surfaces, where they were frozen and tallied. The tallying surfaces were subdivided into 5 μm sections, and these are normalized by the fluence received at the uppermost tally surface, facing the emitting surface. The results of the simulation are shown in Figure 2.3.

Although this model does not perfectly simulate the kinetic effects of the sublimated dopant, it provides a reasonable estimate of the surface flux within the doped trench. Most importantly, this simulation indicates that the resistivity of the doped silicon within the trench is well under $1\,\Omega\text{cm}$ for p -doped room temperature silicon, even at the bottom of

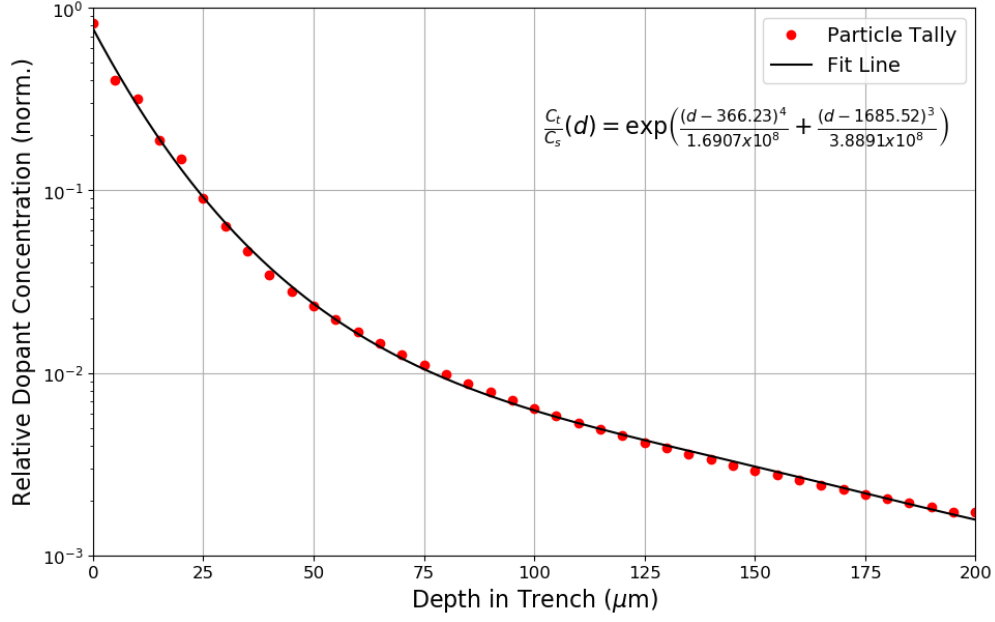


Figure 2.3: *Dopant concentration on the trench sidewalls relative to the dopant concentration at the top of the fins as a function of trench depth.*

the trench and assuming surface concentration of $5 \times 10^{19} \text{ cm}^{-3}$ at the uppermost doped surface⁴⁵.

2.1.3 Oxide Boundary Conditions

The effects of thermally grown oxides on semiconductor devices is well studied in the advent of metal-oxide-silicon transistor (MOSFET) technology^{38;46}. For this study, the modeling of oxide interfaces is particularly important for non-conformally doped X-MSND sensors with thermally grown oxides in the trench sidewalls. The primary effect of this oxide is the formation of trapped charges at the interface, shown in Figure 2.4. The interface trapped charge Q_{it} results from charges that exist in the forbidden band of the silicon substrate and has a population density that increases exponentially with proximity to the conduction and valence band energies^{39;47;48}. These can behave as both donor and acceptor impurity sites. Untreated grown oxides can have interface trapped charges as high as 10^{15} cm^{-2} , and properly hydrogen annealed sensors can have trapped charge concentrations as low as 10^{10} cm^{-2} ⁴⁹.

The fixed oxide charge Q_f and oxide trapped charge Q_{ox} are caused by stoichiometric

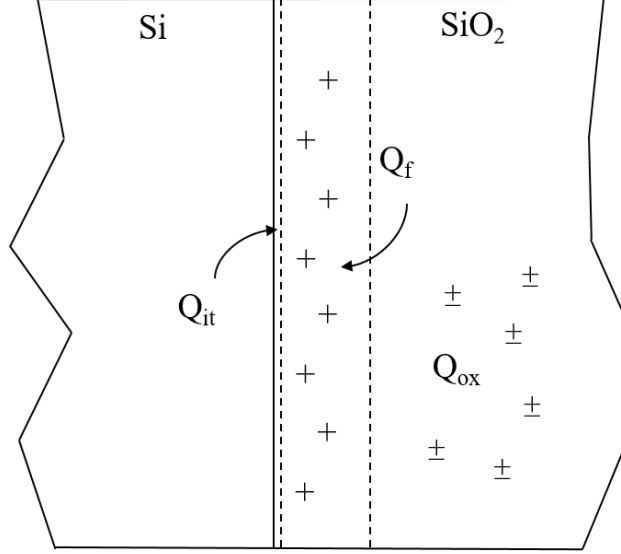


Figure 2.4: *Illustration of charges found in thermally grown oxides on silicon substrate.*

imbalances (SiO_x) charge carrier dislocations in the silicon dioxide, respectively. The effects of the fixed charges are especially problematic as they are generally positive charges that cannot be discharged, producing a fixed sheet charge at the oxide surface. The result is that the balance of positive and negative charges at the terminal sites is disturbed, and electric field lines passing through the oxide region are allowed to terminate at the fixed charges.

In the fabrication of MSND sensors, this type of thin oxide is typically grown in the trenches as a dopant barrier that prevents unintended diffusion of donor ions on the acceptor side of the wafer^{50;51}. After donor diffusion, this layer is removed with buffered hydrofluoric acid (BOE) in preparation of acceptor doping, but it is still of interest to model this dopant configuration as a possible alternative for X-MSND-specific fabrication processes. A Scanning Electron Microscope (SEM) image of the oxide grown along the MSND trench sidewalls is shown in Figure 2.5.

2.2 Finite Element Modeling of X-MSND

With the above modeling conditions established, the simulation and boundary conditions can be implemented in finite difference modeling code. The 3D structure of the X-MSND

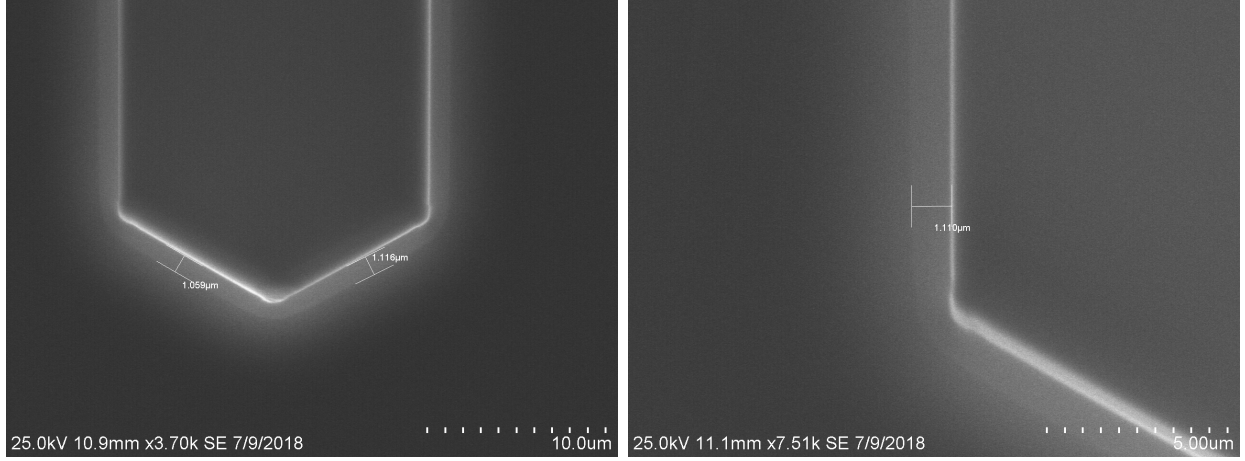


Figure 2.5: SEM images of thermally grown oxides in X-MSND trench sidewalls prior to removal with hydrofluoric acid.

devices and the circular pixel contact necessitates that solutions also be calculated for a 3D unstructured nodal mesh with volume and surface defined boundary conditions.

2.2.1 COMSOL Multiphysics

COMSOL Multiphysics was chosen as the semiconductor physics modeling code to determine the steady state conditions of the sensor under reverse bias⁴⁰. The primary advantages of COMSOL over other modeling code packages is in its relatively shallow learning curve, excellent validation of various physics packages, and built-in support for coupling various physics packages that are available for COMSOL. The final point is of particular interest as COMSOL allows solutions from the semiconductor module to communicate with the circuitry design module to construct simulations of Timepix charge sensitive amplifier circuits.

The semiconductor physics solutions are exported as a nodal mesh solution, where each node has values for the x , y , and z components of electric field, electron concentration, hole concentration, and dopant concentration. The weighting potential is similarly exported. MATLAB is used to prepare the solution for import where the unstructured solution is barycentrically interpolated to produce a voxel matrix with uniform cubic dimensions.

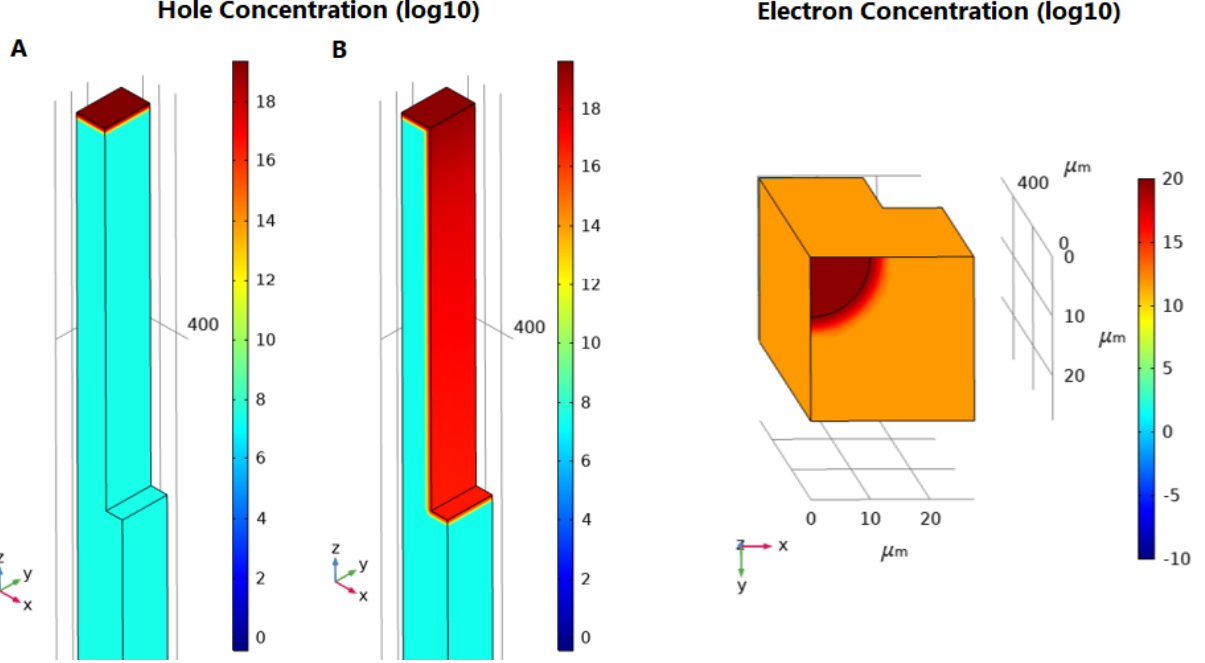


Figure 2.6: *Dopant concentrations of the conformal (left-A) and non-conformal (left-B) p-type contact, and of the pixel shaped n-type contact (right). Only one quarter of the pixel column geometry is modeled.*

2.2.2 Symmetries and Boundary Conditions

To reduce the computational resources required to model the steady state conditions of the PIN diode sensor, the size of the model geometry was minimized as much as possible. It was assumed that the steady state conditions of each pixel column are identical for all pixels. This is generally true for real sensors, assuming that the dopant flux and terminal metallization are uniform across the sensor. Pixels at the periphery of the sensor will often experience slightly different electrical properties due to surface leakage currents originating from the sensor edges. These effects are mitigated in part by a metallized guard ring around the pixel array and were ignored in this analysis.

For each $55\,\mu\text{m} \times 55\,\mu\text{m} \times 525\,\mu\text{m}$ pixel column, the dopant and charge carrier concentration is symmetric along the x and y axis. Similarly, the x -component of the electric field solution will be symmetric across the y -axis and anti-symmetric across the x -axis, and the inverse is true for the y -component of electric field. Therefore, only one quarter of the pixel column was simulated.

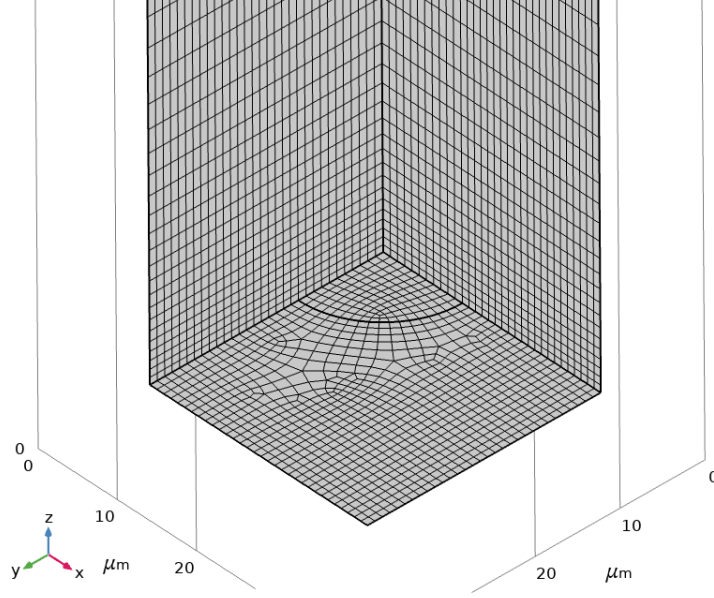


Figure 2.7: Image of the mesh generated for the quarter pixel model in COMSOL. The quad dominated mesh at the cathode side can be seen, as well as the geometrically increasing swept mesh size.

The n -type silicon substrate in the simulation was modeled with a resistivity of $8 \text{ k}\Omega \text{ cm}$, which equates to a majority background charge carrier concentration of $5.6 \times 10^{11} \text{ cm}^{-3}$. The dopant configuration was modeled according to manufacturer provided specifications as follows: The pixel terminal was simulated with a donor dopant concentration of $1 \times 10^{20} \text{ cm}^{-3}$, and the upper pixel electrode at the top of the fin was doped to an acceptor concentration of $5 \times 10^{19} \text{ cm}^{-3}$. For the conformally doped case, the sidewalls were doped with acceptors according to the profile shown in Figure 2.3. Negative voltage was applied to the fin tips, and the pixel was treated as the ground terminal, both simulated as ohmic metal contacts. The initial conditions of the simulated pixel column can be seen in Figure 2.6.

Geometry Meshing

COMSOL includes a meshing toolkit, which supports unstructured meshing, swept, and mapped meshes. For this geometry, a swept mesh provides the best results by minimizing the number of unstructured internal nodes in the 3D solution while still allowing control of mesh spacing. The abrupt junction formed by the terminal doping requires that the mesh be

very fine in doped regions. However, dimensionally the junction depth of $3\text{ }\mu\text{m}$ is significantly smaller than the full geometry thickness of $525\text{ }\mu\text{m}$.

To accommodate this wide variation in length scales, the spacing of the swept mesh is determined via a geometric series such that the maximum node spacing is exactly 10 times the size of the minimum node spacing, and the spacing increases with distance from either terminal. The resulting mesh can be seen in Figure 2.7 for the region near the pixel terminal. This method ensures that total node count is lower, with a much higher node density located near regions where electric field and charge carrier concentration gradients are expected to be high.

2.2.3 Steady State Results

Steady state solutions were found for two possible X-MSND doping conditions: a simplified case where the acceptor dopant is not conformally present in the trench sidewalls, and the realistic case where a semi-conformal acceptor dopant is present in the trench. To obtain a steady state solution, the nodal forms of the equations found in Section 2.1.1 are applied to the meshed geometry for the described boundary conditions, and with a potential bias applied at the terminals. The pixel terminal is held at ground potential, and a negative voltage at the anode is applied. To ensure that solutions to the equations converge successfully, several successive simulations are run where the voltage is ramped slowly from no bias to 300 V negative bias, with each simulation at an increased bias taking the previous solution as an initial condition.

As an illustration of the charge carrier and electric field distribution at the bump bonds, Figure 2.8 shows the voxelized solution of the electron concentration and electric fields near the circular pixel bump bonds. The electron concentration features a sharp gradient at the boundary of the dopant site. From Equation 2.5, the gradient of charge carriers is proportional to electric field strength. This results in a very strong electric field at the abrupt junction, both in the z -direction (along the thickness of the silicon) directly above the bump bond, and laterally (in the xy plane) directed inwards toward the bump bond near

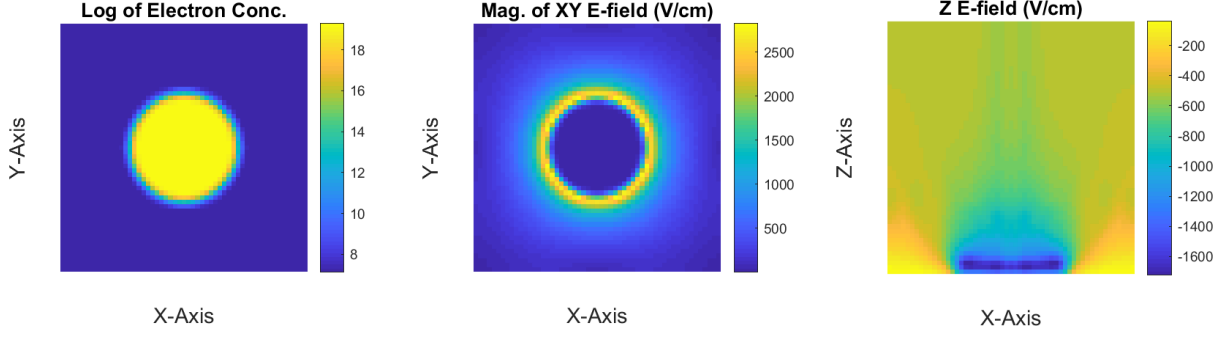


Figure 2.8: *Voxelized results from COMSOL steady state solution that have been interpolated and have had symmetries applied to show the full pixel column.*

the edges of the dopant boundary.

A strong localized electric field can be detrimental to the operation of diode sensors if it exceeds the breakdown field of silicon at $3 \times 10^5 \text{ V cm}^{-1}$ ⁵². At breakdown field strengths, charge carriers obtain enough velocity to produce additional electron-hole pairs, resulting in significant leakage currents through the diode even under reverse bias. The maximum electric field strength in an X-MSND is encountered at the edge of the doped pixel at the diffusion depth of $3 \mu\text{m}$, where the gradient of electron concentration is highest. From COMSOL, the calculated maximum electric field was found to be approximately 3300 V cm^{-1} for the conformally doped case, well below the breakdown field strength.

Nonconformally Doped Model

In the case of the nonconformally doped sensors, the electric field and dopant concentrations behaved as expected for a planar diode, shown in Figure 2.9. The device was very well depleted before the 300 V bias was reached, and plots of electron concentration from COMSOL suggest that depletion across the width of the sensor was reached between 150 and 200 V (Figure 2.10). The silicon substrate depleted uniformly throughout the sensor to a charge carrier concentration of near zero. The electric field was shown to be higher in the X-MSND fins than in the bulk silicon region. This can be explained by the continuity of electric field lines, where a larger effective cross section (the bulk versus trenched region) results in a lower electric field.

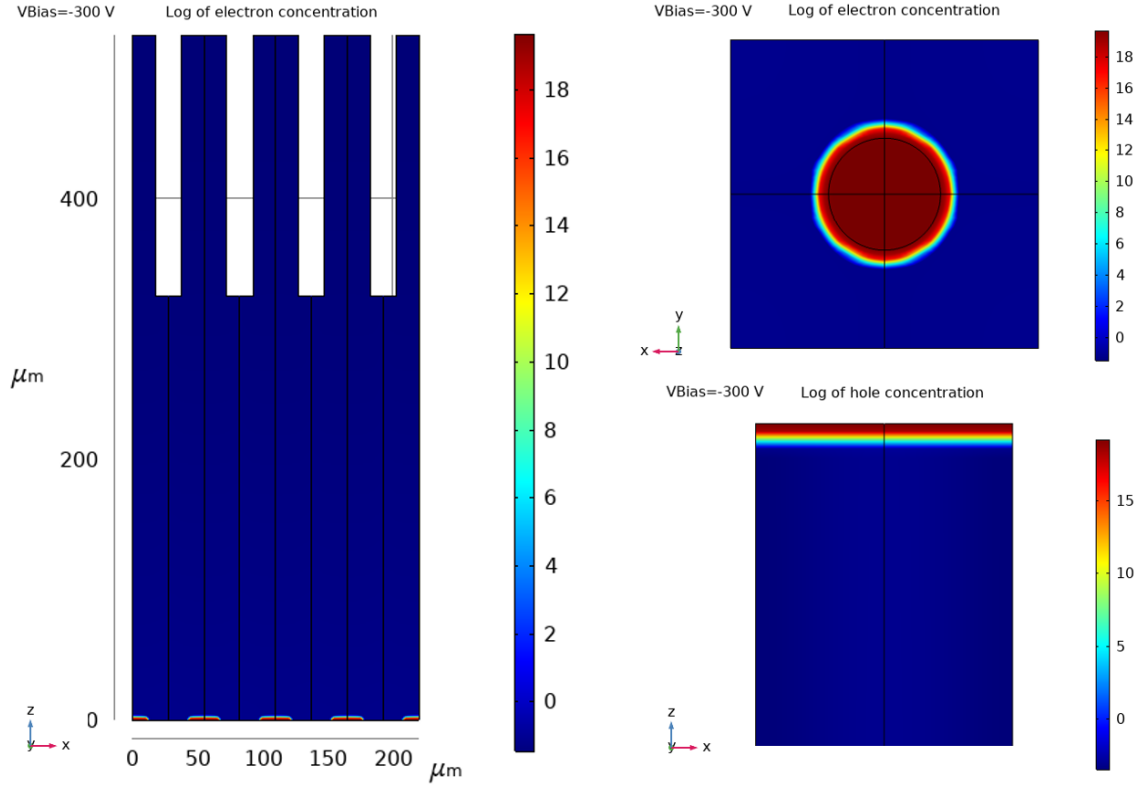


Figure 2.9: Left: Electron concentration in the non-conformally doped X-MSND sensor at a bias voltage of 300 V. Top-Right: Electron concentration at the n-type pixel. Bottom-Right: Hole concentration at the p-type contact.

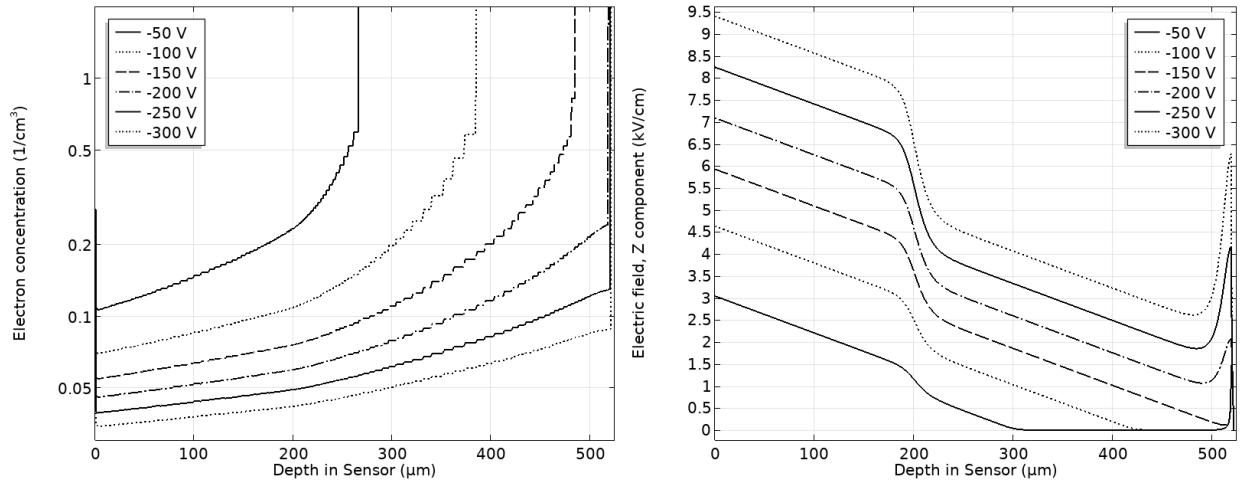


Figure 2.10: Left: Electron concentration as a function of depth over the center of the pixel contact in non-conformally doped X-MSND sensors. Right: Electric field in the z-direction as a function of depth.

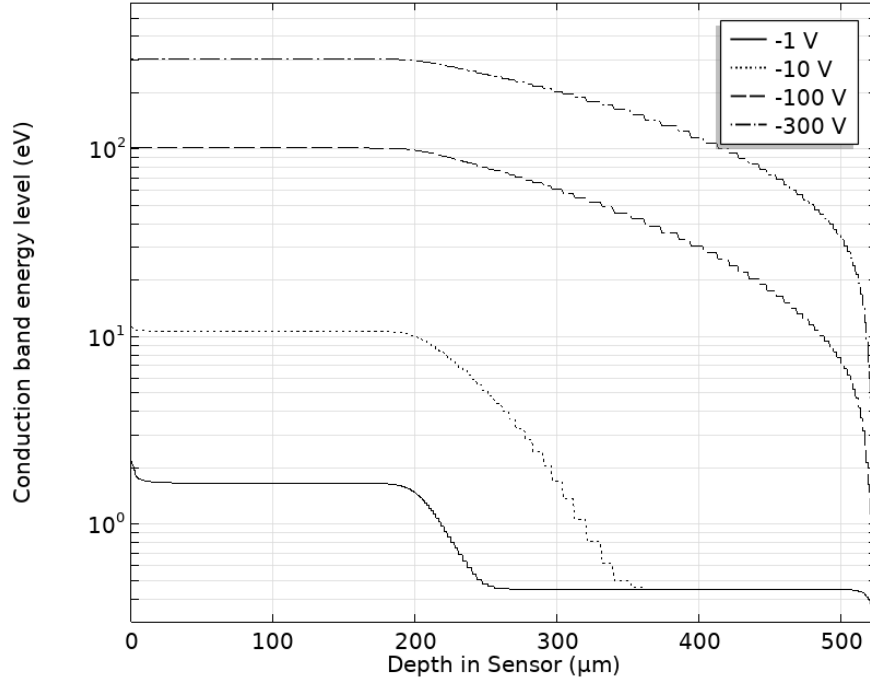


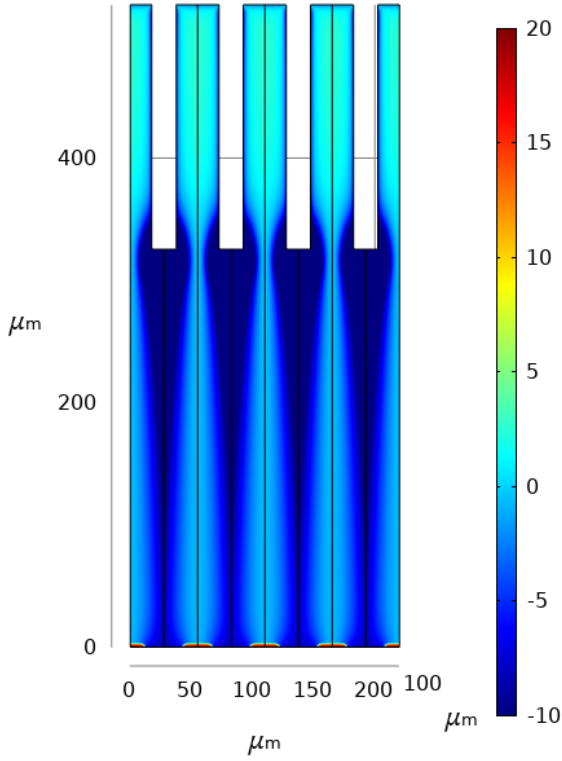
Figure 2.11: *Conduction band energy level as a function of sensor position and voltage for conformally doped X-MSND sensors.*

Conformally Doped Model

The conformally doped model experiences an entirely different depletion profile. The presence of acceptors at the trench surface results in a highly conductive shell forming around the silicon fins. From Gauss’s law, the electric field in a volume is proportional to the divergence of electric flux lines, meaning that a relatively stationary electric flux gives a low electric field; the electric field in the fin region is therefore nearly zero. This is well illustrated by observing the variation of the conduction band energy level with respect to bias voltage, as shown in Figure 2.11. The gradient of the conduction band energy level is zero in the trench region for any voltage, implying that the region is not fully depleted.

This can also be observed in the simulated electron and hole concentration in the X-MSND fins plotted in Figure 2.12. The hole concentration in the fins is much greater in this case than in the non-conformal case, but is still near the intrinsic level. This indicates that minority charge carrier lifetimes in the fins are still on the order of milliseconds for electrons^{53;54}. Nearer to the doped fin sidewalls, however, the hole concentration increases

VBias=-300 V Log of electron concentration



VBias=-300 V Log of Hole Concentration

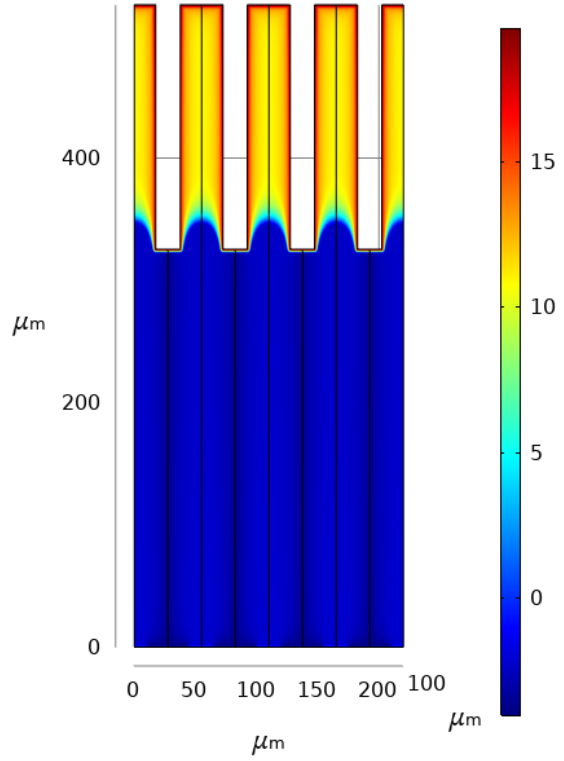


Figure 2.12: *Electron (Left) and hole (Right) concentration in the conformally doped X-MSND sensor at a bias voltage of 300 V. Sensor is not depleted in the fin region.*

to nearly 10^{20} cm^{-3} . This implies that the mean electron lifetime at the fin boundary is only a 1-2 nanoseconds^{54;55}, and would likely recombine if they diffuse into this region.

By differentiating the potential field in the sensor, it is also observed that the electric field in the depleted region is greater in conformally doped sensors than in the nonconformally doped case. This can be rationalized from equation 2.2, where the effective width of the diode is reduced by the conformal electrode, resulting in a greater electric field strength.

2.3 Weighting Potential

The weighting potential in a charge drifting system is an important concept that is used to determine the charge and current induced at any electrode as a function of the charge carriers position and velocity⁵⁶. In its simplest form, Shockley-Ramo current induction theorem can

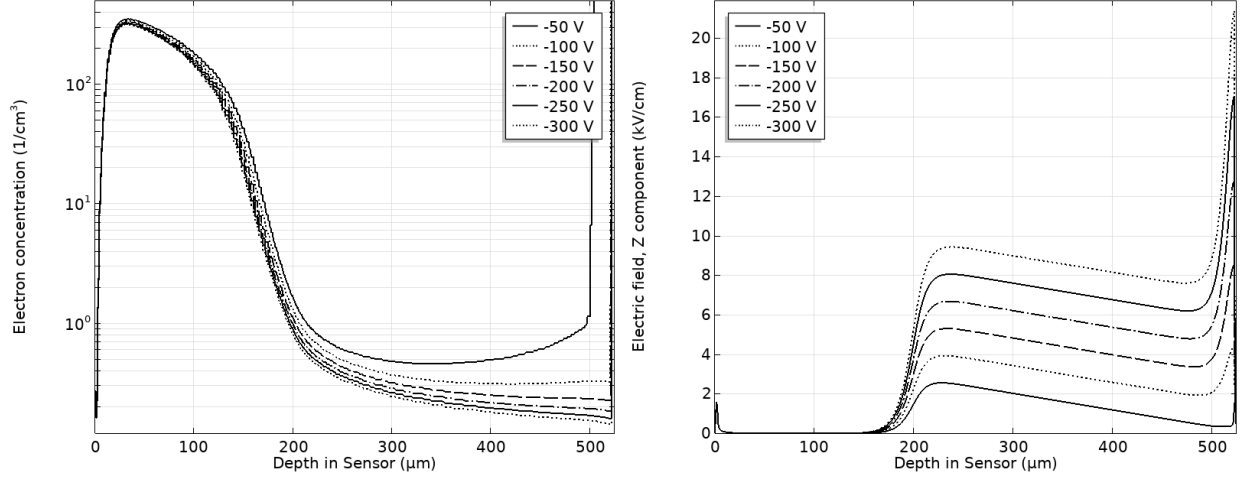


Figure 2.13: *Left: Electron concentration as a function of depth over the center of the pixel contact in conformally doped X-MSND sensors. Right: Electric field in the z-direction as a function of depth.*

be expressed as

$$i_L = q\mathbf{v} \cdot \mathbf{E}_L \quad , \quad (2.12)$$

where i_L is the induced current at an electrode L , q is the charge of the carrier, $\mathbf{v}$ is the charge carrier velocity, and $\mathbf{E}_L$ is the weighting field calculated for electrode L . Note that $\mathbf{v}$ and $\mathbf{E}_L$ are vector fields, and are a function of the location P in the sensor volume. Equation 2.12 can be integrated to give the net charge induced at the electrode as the charge carrier travels from P_i to P_f

$$\Delta Q_L = \int_{P_i}^{P_f} q\mathbf{E}_L \cdot dP = -q[\varphi_L(P_f) - \varphi_L(P_i)] \quad , \quad (2.13)$$

where φ_L is the scalar weighting potential. This concept is explored more in future sections when the weighting potential is applied to charge carrier drift, but the weighting potential is calculated within COMSOL as a node-wise solution.

The weighting potential is derived from Poisson's equation

$$\nabla^2 \varphi = \rho / \epsilon_s \quad , \quad (2.14)$$

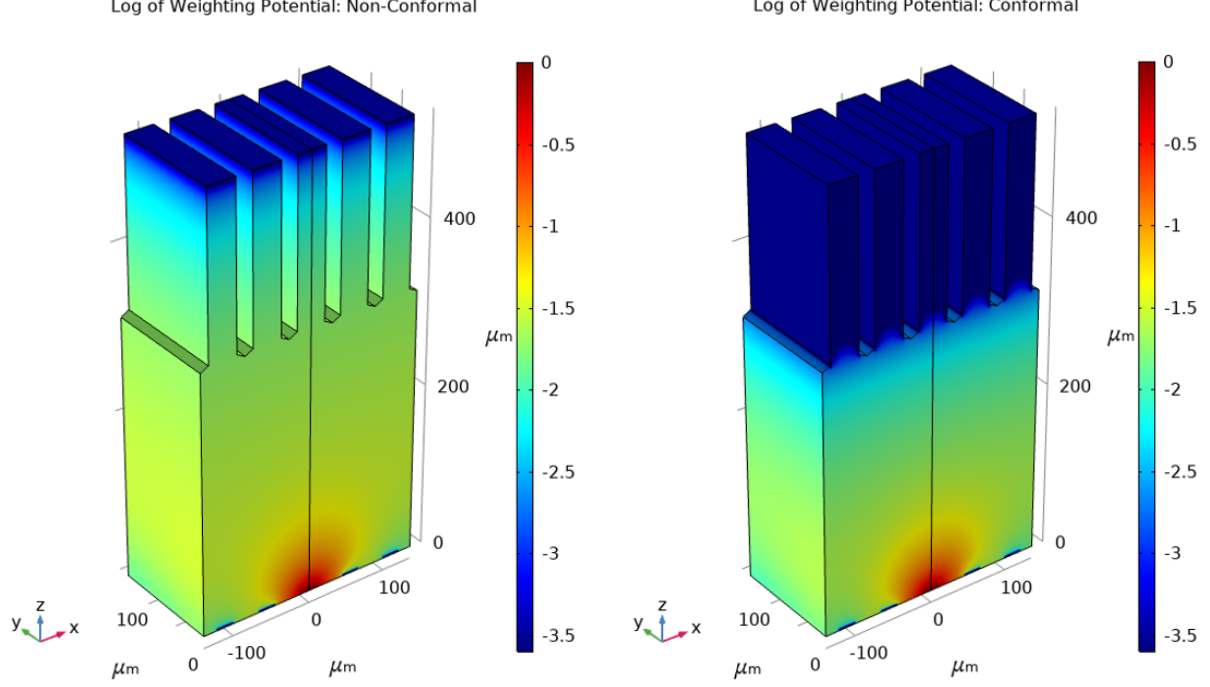


Figure 2.14: *Left: Weighting potential field for non-conformally doped X-MSND sensor about one pixel. Right: Weighting potential for conformally doped sensor with identical geometry.*

where φ is the electric potential, ρ is the charge density, and ε_s is the permittivity of the material. In most cases, a semiconductor device at steady state is fully depleted, and therefore the internal charge density in the device volume is very near zero. This allows the right-hand side of the equation to reduce to zero, giving the Laplace equation. In the case of X-MSNDs, the charge carrier density in conformally doped fins is still relatively high compared to the depleted region in the sensor, but is still 10 orders of magnitude lower than the surface concentration for doped regions. Therefore, the Laplace equation still well approximates the conditions expected in the X-MSND.

The Laplace operator ∇^2 in the case of three dimensional orthogonal components is given as

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \quad (2.15)$$

and can be solved analytically for a given geometry and set of boundary conditions. Weighting field solutions are solved per electrode in the system, and therefore the solution cannot

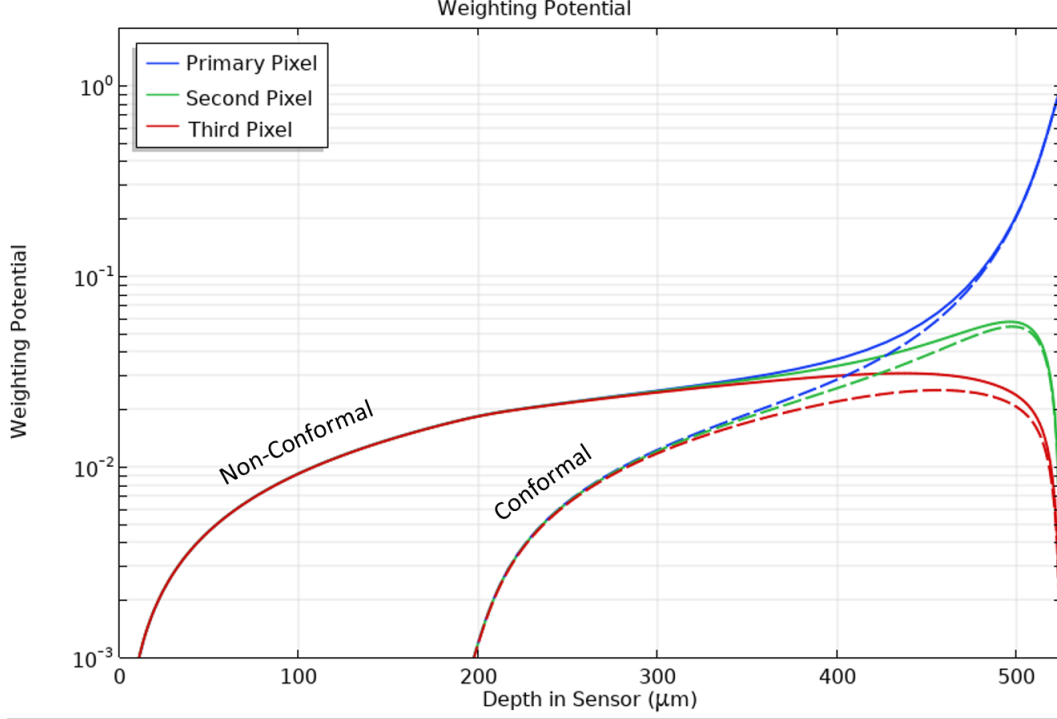


Figure 2.15: *Weighting potential field for both X-MSND doping configurations as a function of depth over the center of the primary pixel terminal.*

be arrayed. Symmetric boundary conditions can however be applied. Solving for a single pixel requires that the desired pixel have an exact solution of one, and all other electrodes have an exact solution of zero. The conformal and non-conformal cases will have slightly different upper electrode definitions, as the sidewalls and bottom of the conformally doped sensor behave as electrodes.

The weighting field solution calculated for the 5 x 5 pixel case is shown for both non-conformal and conformal cases, shown volumetrically in Figure 2.14 and with respect to depth in the sensor in Figure 2.15 (note that the solutions are shown as the base ten logarithm of the weighting potential). This solution was found by simulating a 2.5 x 2.5 electrode column centered on the pixel of interest, and the solution was mirrored across the x - and y -planes. The two solutions behave similarly, with the weighting potential decreasing exponentially with increasing distance from the bump bond, and in both cases decreases asymptotically at the doped junction transition. From these plots, it is observed that **roughly 90% of the induced charge is generated in the final 50 μm of the charges drifting into the**

terminals, which are electrons for the case of X-MSNDs.

The weighting potential calculated in the fins of the conformally doped case was calculated to be near zero through the entire volume of the fin. It can be assumed that most charge carriers will be generated in this region of the X-MSND, as only this area is in direct contact with the neutron converting material. This implies that the **holes which diffuse to the p -type electrode from within the fins will induce virtually no charge**, even for large numbers of holes being produced. This has significant implications for the charge transport simulations described in Chapter 4, as holes do not need to be tracked for simulations involving thermal neutron interactions to produce accurate results.

2.3.1 Chapter Summary

The physics based simulations implemented in this chapter have revealed several important characteristics of X-MSNDs at steady state that will impact the operation and imaging characteristics of the sensor. The bias voltage of the X-MSND sensor at full depletion was estimated to be 250-300 V at the designed resistivity and sensor thickness. The electric field at this voltage and dopant configuration did not exceed the breakdown voltage of silicon at any point in the sensor. The conformal doping of the sensor trench caused the fin region to remain largely undepleted at the intrinsic charge carrier concentration. This results in distinct charge transport characteristics in the fin, where the charge motion is dominated by thermal diffusion.

Chapter 3

Radiation Interactions in X-MSNDs

3.1 Ionization of Silicon by Radiation

The ionization energy of mono-crystalline silicon is related, but not equal, to the band gap energy. Indirect bandgap semiconductors like silicon require additional energy to be transferred to the tightly bound crystal structure of the substrate to fully ionize an atom and produce an electron-hole pair^{57;58}. This additional energy is lost as crystal lattice momentum, which can be discretely quantified as phonons, and band energy levels vary independently with crystal momentum. The ionization energy is therefore the difference between the highest valence band energy and the lowest conduction band energy, plus the energy lost to crystal vibrations. For crystalline silicon, this value is 3.6 eV per charge carrier pair, compared to 1.1 eV for the bandgap energy.

3.1.1 Photon Interactions

In general, only photons in the x-ray energy range (10-100 keV) are useful for X-MSND radiography; lower energy photons are incapable of penetrating the imaging subject, and higher energy photons preferentially interact in matter via scattering and pair-production in the atomic nucleus^{59;60}. These interactions can be seen in Figure 3.1, where the attenuation coefficients of photons in silicon are plotted against photon energy. However, all photons with

enough energy to penetrate the insensitive doped regions of the silicon are capable of ionizing the depleted region and producing an imagable charge. High energy electron scatters (i.e., Compton scatters) generally present themselves as long, curled clusters, and their point of origin is very difficult to localize with typically charge centroiding techniques^{61;62}. Because of this, it is preferred that photon interactions produce photoelectric electrons with ranges below one or two pixel widths.

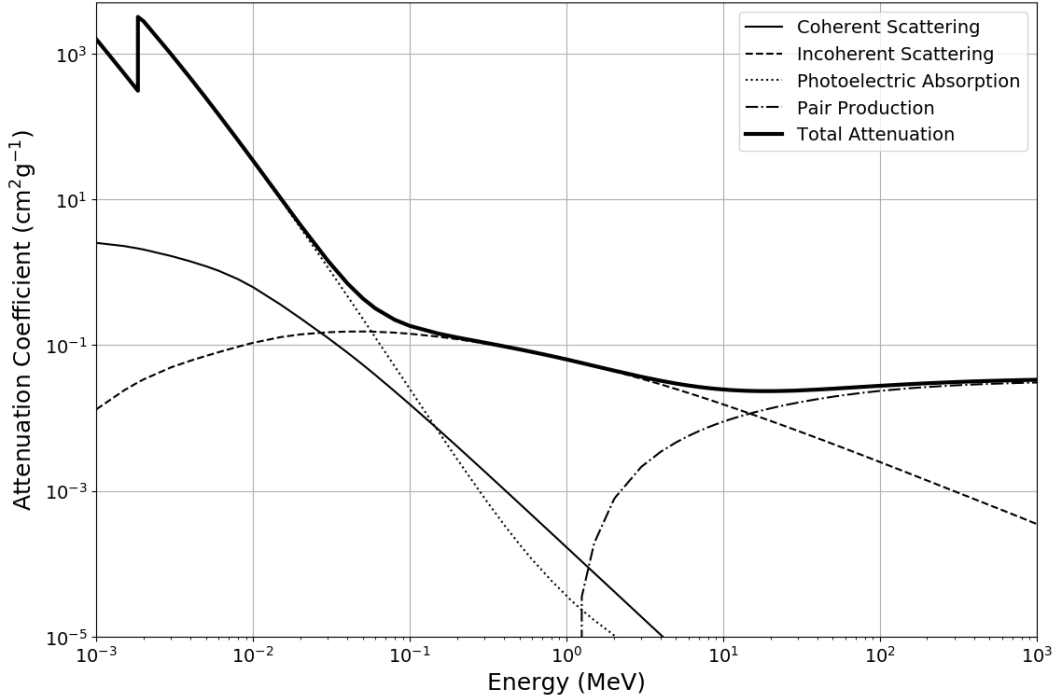


Figure 3.1: *Photon interactions in silicon. NIST data compiled by XCOM⁵*

As with any photodiode, the X-MSND is also sensitive to photoelectric currents generated by ambient light. Bare crystalline silicon has a work function of between 4.60 and 4.85 eV, corresponding to light with wavelength of 270-256 nm depending on the crystal plane exposed to light. This additional induced current can raise the baseline leakage current of sensor per pixel, and direct exposure to light should be minimized as much as possible.

Estimating X-Ray Interactions from RS1800

To predict the x-ray interaction characteristics of the X-MSND sensor in an actual x-ray field, a simulation of the RadSource RS1800 x-ray generator used to generate radiographs

Table 3.1: *Cumulative RS1800 x-ray filter characteristics and effects*

Position	Material	Density	Thickness	$\overline{E}_t$ @ 60kV
1	Zn	7.14 g/cm ³	10 mils	41.0 keV
2	Al	2.70 g/cm ³	50 mils	42.3 keV
3	310SS	8.00 g/cm ³	24 mils	47.6 keV

from X-MSND assemblies will be carried out. The expected baseline x-ray spectrum from the RS1800 was first calculated using SpekCalc, a semi-empirical code for determining x-ray emission spectra from tungsten anode x-ray generators^{63;64}. The predicted x-ray emission spectrum from the RS1800 is shown in Figure 3.2 as calculated by SpekCalc for a tungsten anode tube at a voltage of 60 kV and anode angle of 30 degrees.

In practice, zinc, aluminum, and 310 stainless steel (310SS) filters are used to reduce the low energy x-ray flux density of the raw generator output, called spectral “hardening”. This hardening reduces the flux density of low energy x-rays which does not contribute greatly to image quality due to its inability to penetrate deeply into the subject being imaged, but can still impart surface dose to and damage the sensor assembly. The filters are added cumulatively in the order listed in Table 3.1, which also contains the properties and thicknesses of the filters.

To calculate the attenuation of this spectrum by the filters, a Monte Carlo simulation was run in MCNP6.2 wherein a beam of x-rays was transported through the three filter configurations, and spectral flux density is tallied at the other side of the filters. The $\overline{E}_t$ value is the mean energy of the x-rays transmitted through the cumulative filter configuration at a tube voltage of 60 kV. The resultant spectra are also shown in Figure 3.2, with the fully filtered x-ray spectrum having a mean energy of 48 keV. By comparing this value to Figure 3.1, the total attenuation coefficient for this energy is 0.44 cm² g⁻¹. Assuming a silicon density of 2.33 g cm⁻³ and a sensitive silicon thickness of 325 μ m, this corresponds to a detection efficiency of 97%.

Of particular interest is the predicted length of the tracks produced by electrons emitted from photoelectric absorption. Several models exist for predicting the range of electrons, with many of them using the Bethe-Bloch charged particle range model⁶⁵. A model presented by

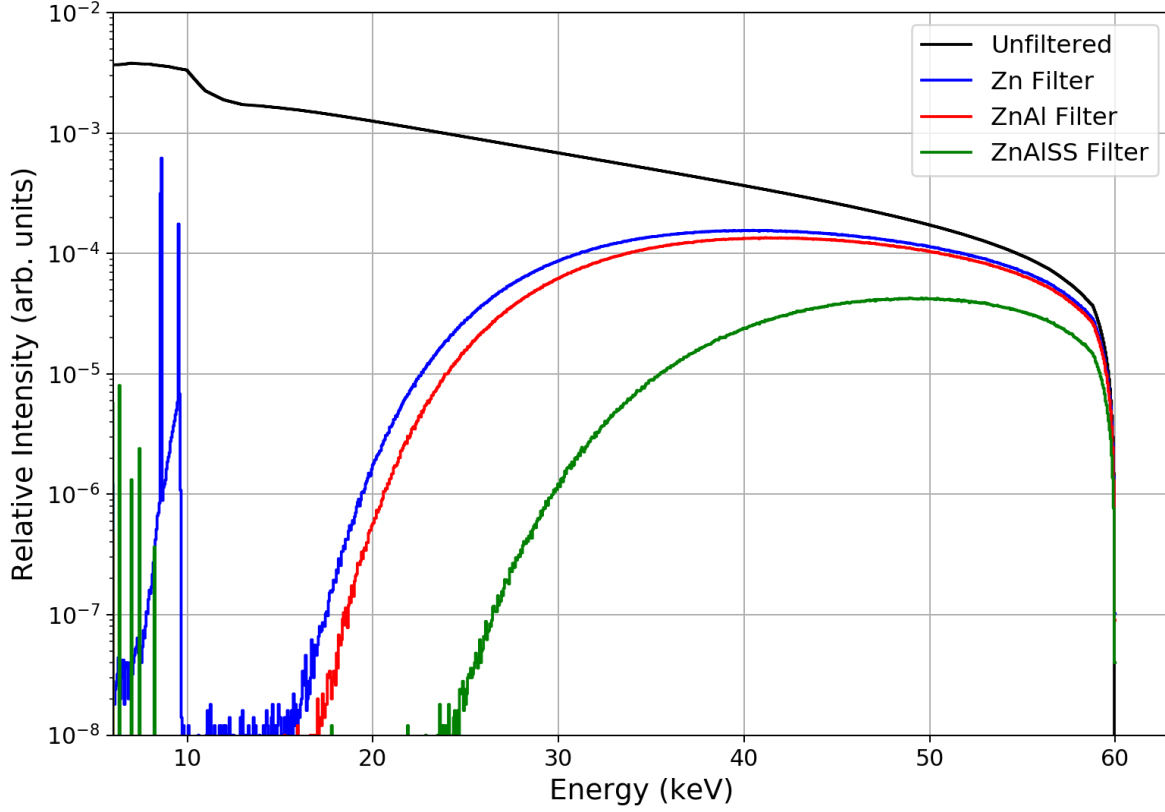


Figure 3.2: *X-ray spectrum from the RS1800 x-ray generator showing the attenuation and spectral shift of three filter configurations*

Gurler et al. uses a semi-empirical approach to provide tabulated ranges for electrons in silicon, and compares them with continuous slowing down approximation ranges (R_{CSDA})^{66;67}. From these electron range tables and assuming a maximum photoelectron energy of 60 keV, the emitted electron will have a range of 10.3 μm and a R_{CSDA} of 32.8 μm , well within the 55 μm pixel pitch of the Timepix.

3.1.2 Neutron Detection Mechanism

The neutron detection mechanism of the X-MSND is dependent on the decay reaction that occurs when ^6Li in the X-MSND trench backfill absorbs a thermal neutron. ^6Li has a relatively high neutron absorption cross section of 940 b, as compared to 0.17 b for silicon or 0.045 b for ^7Li ¹⁹. This ^6Li takes the form of 96% enriched lithium fluoride nanopowder with a fill fraction of approximately 0.50. The enrichment of the lithium is key in increasing the

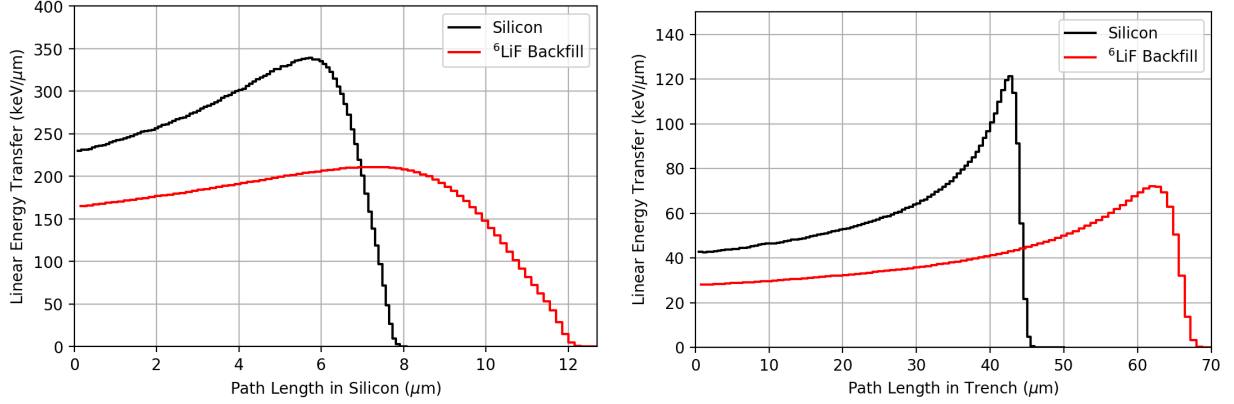


Figure 3.3: Stochastically modeled LET for alpha (left) and triton (right) daughter products produced in the ^6Li decay from neutron capture. Plots show traversal in both silicon and 96% enriched ^6LiF at 50% backfill. Data taken from SRIM simulation.

neutron absorption probability of an incident neutron, as naturally occurring lithium has a ^6Li abundance of only 7.5%. The neutron absorption reaction at rest is shown below:



where the conservation of momentum give the alpha and triton particles energies of approximately 2.055 MeV and 2.728 MeV, respectively. It can be assumed that these reaction products are emitted nearly exactly anti-parallel from each other at the reaction site as a product of conservation of momentum, as the reactant particles are very nearly at rest and contribute little initial momentum. These reaction products have the potential to ionize the sensor silicon, and Figure 3.3 shows the linear energy transfer (LET) and range of the energetic ions as they traverse both the silicon sensor and the lithium fluoride backfill as calculated with SRIM⁶⁸.

The high range of the ^6Li reaction products in the LiF backfill is a favorable feature of this neutron converter, as it ensures the reaction products transfer as little energy as possible to the backfill. By comparison, ^{10}B (another common neutron converter) has a thermal absorption cross section of 3835 barns, nearly 4 times that of ^6Li , but has a significantly lower reaction Q-value. There are two neutron absorption reactions for ^{10}B , given below

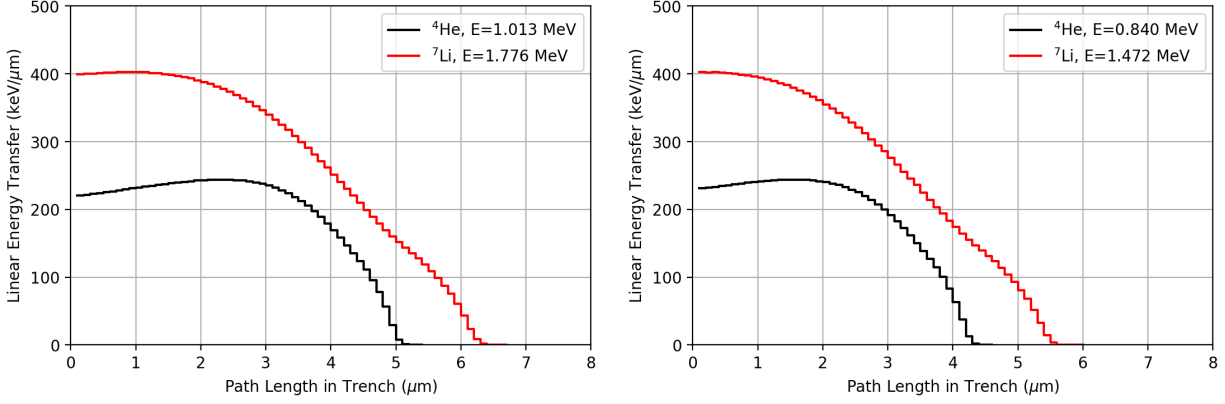
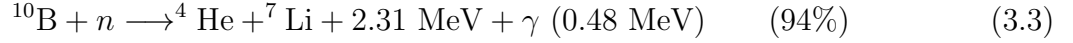


Figure 3.4: Stochastically modeled LET for reaction products of ^{10}B neutron capture from equations 3.2 (left) and 3.3 (right) transiting a backfill of ^{10}B powder at 50% packing fraction. Data taken from SRIM simulation assuming properties of commercial 3M 99% enriched ^{10}B powder⁶

with their corresponding probabilities:



The kinetic energies of the alpha and ^7Li reaction products for Equation 3.2 are 1.013 MeV and 1.776 MeV, respectively, and the corresponding reaction products for Equation 3.3 have energies of 0.840 MeV and 1.472 MeV. These energies are lower than those of the $^6\text{Li}(n,t)\alpha$ reaction, and the reaction products would have a correspondingly lower range. The LET and range of ^{10}B reaction products in a backfill of ^{10}B powder was also calculated with SRIM, and shown in Figure 3.4. The maximum ranges of these reaction products are between 4 and 6 μm, significantly smaller than the designed trench width of the X-MSND. As the trench-fin pitch in the X-MSND is fixed to the pixel pitch of the Timepix readout chip, the sensor geometry cannot be modified to optimize for the shorter range of ^{10}B reaction products.

Notably, the range of the alpha particle in the backfill material is still much smaller than the width of the X-MSND trench (12 μm compared to the trench width of 20 μm). This implies that the majority of the silicon ionization from detection events is caused by the

energetic triton, and this is supported by previous simulation work on MSND sensors^{28;69}.

3.2 Radiation Transport

The primary radiation transport code used in this study was Geant4⁷⁰. This is primarily because of direct coupling to the Allpix² code package, but Geant4 offers several advantages over other common codes. By default, Geant4 enables more flexible nuclear physics options than other transport codes via the combined physics lists. The physics list chosen for these simulation are QGSP_BERT_HP physics: the QGSP identifier denotes that the Quark Gluon String model for high energy interactions; the BERT identifier denotes that the Bertini cascade model for primary protons, neutrons, pions and Kaons below approximately 10 GeV is used; and the HP identifier denotes that the high precision physics for neutrons below 10 MeV down to thermal energies is enabled. The high precision physics package is also required to simulate the neutron capture reactions which occur in the neutron conversion materials described earlier. Further, Geant4 contains built in computer assisted drafting (CAD) import tools in the form of its unified Geometry Description Markup Language (GDML) input format, which will be described in the following subsections.

3.2.1 Constructing Model Geometry

The full X-MSND geometry was recreated in Dassault SolidWorks CAD software in preparation for import into Geant4. To facilitate this import, a custom coordinate system was applied to the CAD geometry such that the origin of the coordinate system was centered at the lower-left most pixel of the X-MSND, and halfway into its thickness. The geometry was then exported as an ASCII stereolithography (STL) file format, with the feature accuracy being limited to 5 μm . This tolerance is acceptable as the geometry features no curved surfaces that require small faceting tolerances, and the large tolerance prevents floating point round-off errors that may lead to geometry overlaps in Geant4. The backfill of the sensor was also modeled and similarly exported as a separate STL file.

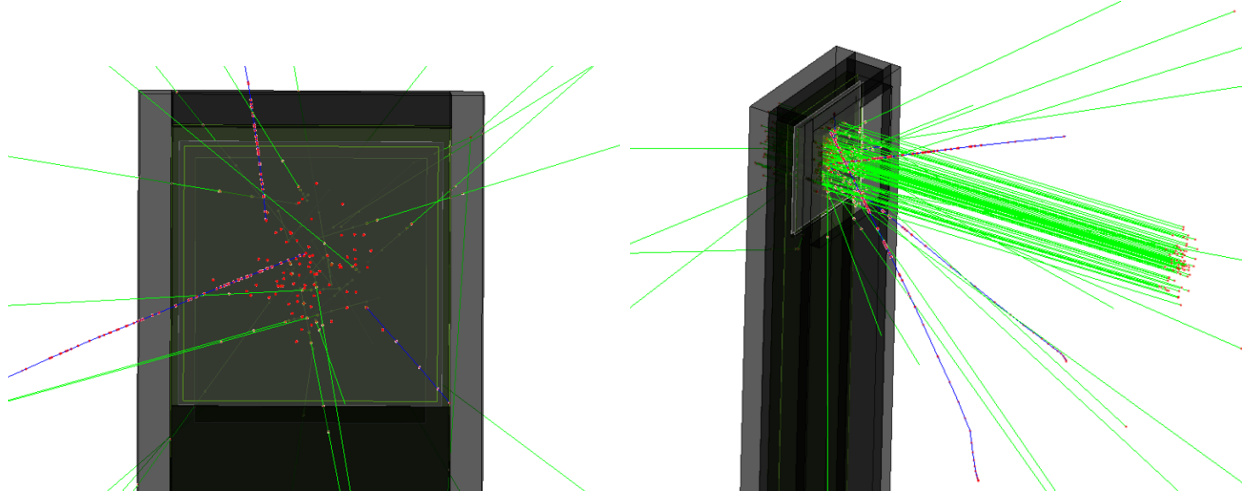


Figure 3.5: *Geant4 simulation of a thermal neutron (0.025 eV) beam incident on a LiF coated Minipix, with resultant alpha/triton ionization.*

The native CAD import file format for Geant4 is GDML, which is an XML-like language that supports primitive geometry descriptions, tessellated solids via triangular mesh definitions, material assignment, and placement of physical volumes from defined logical volumes. STL defined geometry can be easily converted to GDML format via the tessellated solid definitions, as both standards construct solids from point-triangle constructions.

Reference Minipix Model

To provide a reference simulation that can be compared to data collected by a well characterized device, a commercially available planar Timepix imager (the Advacam Minipix) was also modeled in Geant4. These devices are $500\text{ }\mu\text{m}$ thick sensors that operate in hole collecting mode (p -type silicon, acceptor doped pixels) that typically operate at 200V reverse bias. The electric field, weighting field, and charge carrier concentrations were calculated in COMSOL; results for this sensor showed the linearly tapering potential field typical of planar diodes.

The Minipix devices are available in bare sensors and enriched LiF coated variants, and both types were modeled in Geant4. Simulations were produced for common disk shaped X-ray and gamma ray check sources (^{109}Cd , ^{57}Fe , and ^{137}Cs), and for a circular thermal neutron beam. Figure 3.5 shows the simulated Minipix geometry in a thermal neutron beamline.

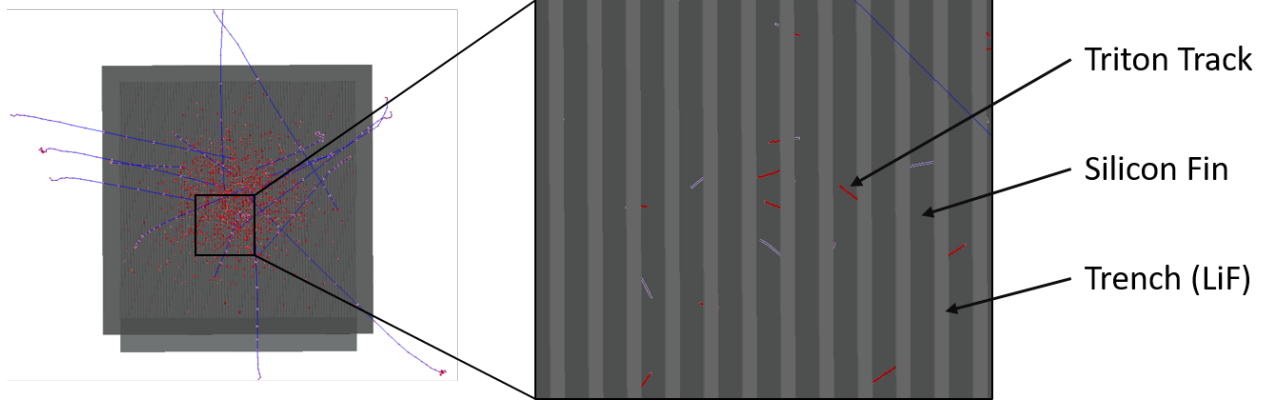


Figure 3.6: *Geant4 simulation of alpha/triton ionization in the silicon. Blue tracks are positive ions (alpha and triton particles). Red tracks are ionization events in the silicon fins occurring along the positive ion tracks.*

The thickness and density of this enriched LiF coating was not well characterized by the manufacturer, and so the thermal neutron interactions from the coated Minipix devices were only used for qualitative analysis in the following sections.

3.2.2 Neutron Transport and Reactions

To provide neutron induced charge cloud data to Allpix², a Gaussian beam of thermal neutrons (0.025 eV, $\sigma=3$ mm) normally incident to the X-MSND assembly is simulated for one million source particles. This beam was sufficiently narrow that it represented the intrinsic detection characteristics of the sensor. The model of the X-MSND included the CAD imported X-MSND sensor, the Timepix chip, the interfacing tin-lead solder balls, and the fiberglass printed circuit board (PCB). The model optionally allows for the inclusion of the epoxy dry-film on the sensor, as some sensors were manufactured without this layer. The exterior environment was modeled as dry air at sea level. The lithium fluoride backfill was simulated as a solid material with 50% the density of lithium fluoride to emulate the 50% nominal packing fraction of the powder, with a ⁶Li enrichment of 96%.

Ionizing radiation in the sensor (the alpha and triton reaction products) were tracked such that the maximum track length between tracking steps was 0.2 nm or the maximum track time step was 0.5 ns. Examples of these tracks in the silicon sensor generated from

the alpha-triton reaction products are shown in Figure 3.6. The incoming neutrons and the probe card PCB are hidden in this figure. Note also that this model does not have the dry film layer applied, which allows some tritons generated near the surface of the sensor to escape in the environment (visible as long blue tracks).

The resulting deposited energy spectrum is shown in Figure 3.7. This spectrum displays several distinct features characteristic to real pulse height spectra of MSND sensors¹⁸:

1. The mean energy deposited in the silicon averaged across the full spectrum is 2.2 MeV.
2. There is a sharp drop at 2.73 MeV, corresponding to the energy of the triton reaction product. Energies above this can only be produced when both the alpha particle and the triton ionize the silicon.
3. The spectrum tapers as it approaches the maximum possible deposited energy of 4.78 MeV. This energy is vanishingly unlikely to be observed, as some energy is usually lost in the backfill material, except for interactions at the very bottom corners of the trench.

Neutron Detection Efficiency

Simulation from the previous section resulted in X-MSNDs having a thermal neutron interaction efficiency of 15.6% and a detection efficiency of 13.8%. Interaction efficiency here is defined as the probability that a source neutron will interact with the enriched LiF material, but does not necessarily produce ionization in the silicon. This was calculated by using the command based scoring manager in Geant4. This outcome is well above the theoretical maximum for thin-film coated planar devices³¹.

Detection efficiency is defined here as the probability that a source neutron will produce any ionization in the silicon from interactions in the LiF, without a lower threshold. This is for two reasons: (1) The threshold of Timepix sensors is adjusted on a per-pixel noise level rather than a global minimum, and (2) the sensor/imager was intended by design for bimodal x-ray/neutron imaging, necessitating a very low threshold to permit x-ray cluster imaging.

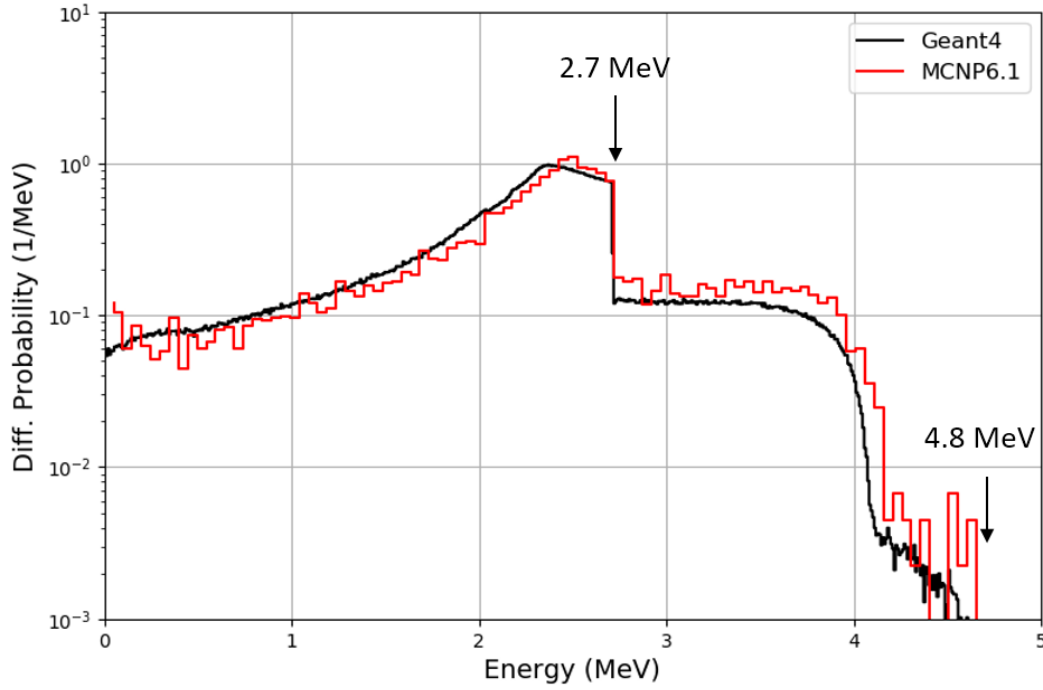


Figure 3.7: *Differential energy deposition spectrum output by Geant4 and MCNP6.1 for thermal neutrons interacting in X-MSNDs.*

Commercial Timepix devices by ADVACAM Oy. typically advertise minimum detectable x-ray energies of 3 keV, much lower than is typically used as a minimum threshold energy in prior MSND simulation work³¹. It was therefore concluded that calculations omitting a threshold energy are reasonably representative of the true practical value while avoiding excessive assumptions. However, a per-pixel threshold energy of 3.2 keV was applied during the cluster morphology analysis.

These calculations were independently verified in MCNP simulations courtesy of Radiation Detection Technologies, Inc., where the X-MSNDs were found to have a interaction and detection efficiency of 15.5% and 13.3%, respectively⁷¹. The differential energy spectrum calculated in MCNP6.1 (shown in red in Figure 3.7), agrees well with the Geant4 spectrum. The mean energy deposited by a neutron interaction calculated from MCNP6.1 is 2.31 MeV, a difference of 5.2% from the Geant4 result.

Chapter 4

Mobile Charge Carrier Transport in X-MSND Sensors

The charge motion equations relevant to charge transport were previously outlined in Chapter 2 of this work, and in that context, were framed as nodal relations that are used to find analytic solutions to sparse matrices. Although COMSOL by itself is capable of time-dependent charge transport, the computational burden of 3D finite element analysis for large geometries becomes very high for nodal current density problems, particularly those with complex boundaries and where it is expected that portions of the charge cloud will be collected across several pixels. This also implies that quarter-pixel symmetry can no longer be used to reduce the simulation geometry, and this requires that the number of nodes required to solve for nodal charge transport increase by a factor of 36 compared to a quarter-pixel for a 3 x 3 pixel column geometry, increasing the sparse matrix size by $36^2=1296$ entries.

The AllPix² framework, which simulates mobile charge carrier transport as being decoupled from the steady state of the sensor, provides a good alternative to COMSOL for time-dependent charge transport⁷². If it is assumed that the electric field in the sensor is not dramatically affected by the introduction of the radiation induced charge cloud, then the steady state electric field can be treated as constant through the charge transport simulation. The methods commonly used in this form of rapid modeling of charge transport in pixelated

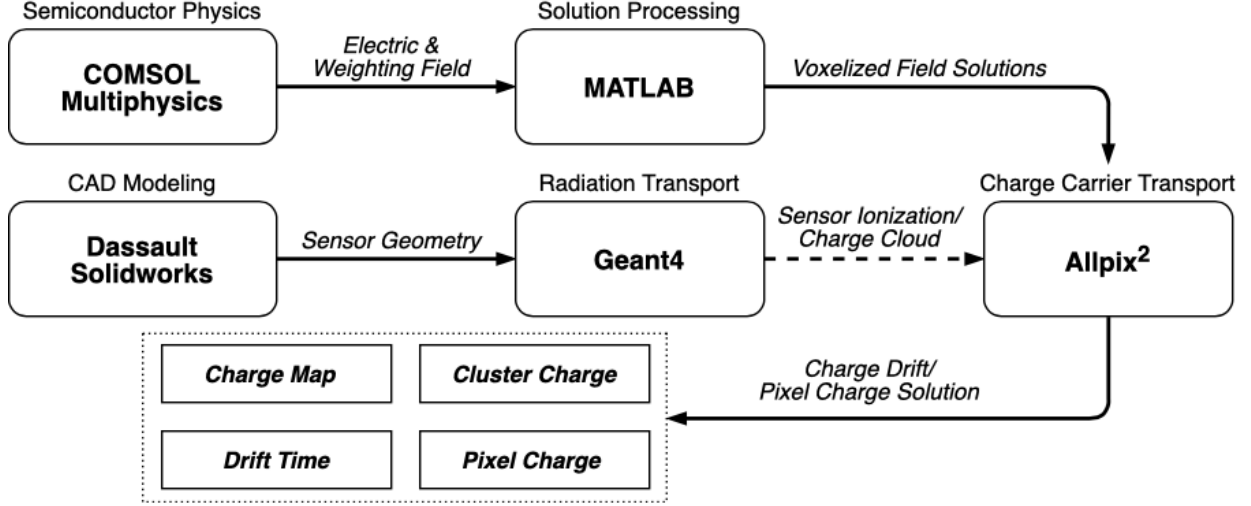


Figure 4.1: Modeling workflow for fully simulating the X-MSND sensor response.

sensors can be classified into two types, both of which are implemented in Allpix²^{72;73}: empirical charge projection methods and transport-based methods. The charge projection method does not require any information about the electric field of the biased sensor. Rather, it assumes that each charge carrier that drifts down to the pixels follows a deterministic conical path that's width is empirically defined. Although very fast to implement, this method ignores the complex interior electric fields that may be present in sensors, especially for the 3D geometry found in MSND sensors. Instead the explicit transport method was used exclusively for this work. This charge transport method is based on the Ohm's Law for discrete charge drift and Monte Carlo sampling for charge carrier diffusion. For complex electric fields, AllPix² is capable of accepting voxelized electric field values computed with specialized electric field solvers, including COMSOL. AllPix² also has the advantage of coupling directly to Geant4 to provide radiation transport and ionization capabilities. After Geant4 has logged the locations and magnitude of the charges produced by ionizing radiation in the sensor volume, this information is passed to the explicit charge carrier transport module of Allpix², where charges are transported through the volume of the sensor.

A summary of the workflow described above is illustrated in Figure 4.1. This workflow is divided into two branches, one each for the steady state conditions of the sensor and radiation transport into the sensor. In principle, this workflow is capable of simulating any

arbitrary sensor structure.

4.1 Drift and Diffusion Modeling

The drift and diffusion modeling of the X-MSND is handled by the Allpix² framework, which itself utilizes the Eigen mathematics library for rapid matrix operations⁷². The spatial distribution of charge carriers produced by Geant4 for each interaction event are first passed to Allpix² as coordinate triplets, where each charge carrier pair is given a single coordinate, and holes and electrons are transported beginning at that coordinate. The individual charges can be grouped together into transport clusters based on user specification prior to the transport steps. This grouping reduces the number of total charge transport steps that are required to transport the entire charge cloud, which can contain several hundred kiloelectrons of charge. For example, a detection event which deposits the simulated mean energy of 2.2 MeV will produce 6.11×10^5 charge carrier pairs. For this study, the maximum charge carrier group size was 50 charges for x-ray source simulations and 300 charges for neutron detection events.

4.1.1 Timestep Modeling with Allpix²

To implement the time dependent charge transport, charge transport Equation 2.6 and 2.7 must be reformulated such that the charge displacement is only a function of time. As discussed in Chapter 2, the charge drift and charge diffusion transport forces are uncoupled, and can be calculated separately then summed. If it is assumed that the space charge effects of the charge cloud are very small such that the electric field in the vicinity of the cloud is not disturbed, then the charge drift component of Equation 2.7 can be approximated as a function of the timestep t_s as

$$\mathbf{s}_{\text{drift}} = \mu_q \mathbf{E}_i t_s \quad , \quad (4.1)$$

where $\mathbf{s}_{\text{drift}}$ is the displacement in x -, y -, and z -components of the charge carrier group due to drift, μ_q is the mobility of the charge carrier being transported, and $\mathbf{E}_i$ is the electric field

in voxel i in which the charge is located. The term $\mu_q \mathbf{E}_i$ is simply the charge carrier drift velocity vector, and Equation 4.1 assumes that $\mathbf{E}_i$ is constant over the short time step.

The diffusion component of Equation 2.7 accounts for thermally induced random diffusion of charge carriers. This type of random diffusion closely resembles the Brownian motion of kinetic gas particles, and is entirely independent of electric field. The diffusion coefficient, D , relates the mobility of a charge carrier to temperature, and can be calculated from the Einstein-Smoluchowski-Sutherland relation,

$$D = \frac{k_B T}{q_t} \mu_q \quad , \quad (4.2)$$

where q_t is the total charge of the transport group, and T is the absolute temperature of the substrate, and k_B is Boltzmann's constant⁷⁴. The magnitude of the displacement due to diffusion can be approximated by sampling from a Gaussian probability distribution function with a standard deviation derived from the diffusion length $L = \sqrt{Dt_s}$, given as

$$\sigma_{diff} = \sqrt{\frac{2k_B T}{q} \mu_q t_s} \quad . \quad (4.3)$$

Sampling the normal distribution gives the magnitude of the displacement of the charge carrier for that timestep, $|s_{diff}|$ (see Appendix A for specifics on random sampling). To determine the displacement vector, the magnitude can be multiplied with a randomly sampled unit vector

$$\mathbf{s}_{diff} = |s_{diff}| \mathbf{u} \quad (4.4)$$

where $\mathbf{s}_{diff}$ is the displacement in x -, y -, and z -components of the charge carrier group due to diffusion, and $\mathbf{u}$ is a randomly sampled unit vector in $\mathbb{R}^3$. In typical depleted PIN diode sensors, the magnitude of the diffusion displacement is less than the magnitude of the displacement due to drift. However, the steady state simulations from Chapter 2 imply that this is not the case for the charge transport in the fins of the X-MSNDs, where the majority of neutron induced ionization will take place.

Allpix² requires as input two transport parameters: the maximum displacement at each transport step that a charge group can traverse and the estimated timestep that is allowed to progress at each step. This, however, presents an initial value problem, as the desired spatial resolution may not necessarily be met with the initial timestep estimate. To determine the optimal timestep t_s , a fourth-order Runge-Kutta-Fehlberg (RKF) method with fifth-order error estimation was used to integrate the particle propagation in the electric field, with the initial estimated timestep and voxelized electric field used as initial conditions^{75;76}. The diffusion component of charge carrier displacement is then randomly sampled and added to the drift displacement. The timestep of the charge propagation is then adjusted to reach the desired spatial accuracy after calculating the uncertainty from the fifth-order residual of the RKF method.

4.1.2 Code Modifications for Interior Boundaries

Allpix² by default assumes that all sensors are planar, and has no “sense” of the microstructure in the imported geometry. As such, it is possible for charge carriers to diffuse into the trench region where no silicon is present. In reality, charges that migrate into the fin sidewall would not penetrate into the trench, and would immediately recombine due to the high density of charge carrier traps and recombination sites at the sidewall. Therefore, some modifications to the charge transport code were required to account for charges being transported in these regions.

The voxelized electric field solution import into Allpix² must always be a square pillar array, in this case 55 x 55 voxels at the base representing the pixel pitch, and 525 voxels tall representing the sensor thickness, where each voxel is cubic with edge lengths of 1 μm each. Voxel coordinates that do not have silicon in them are assigned x -, y -, and z -components of electric field a value of zero. In most biased sensor applications, it is very unlikely that any point in the sensor would have an absolute electric field magnitude of zero, and so this is used as a check to determine if the charge carrier group has exited the sensor. At this point, the charge carrier transport is stopped, and the magnitude of the charge group is passed to

the charge induction module of Allpix², along with the starting and ending locations of the charge group.

The decision to cease tracking when a charge carrier reaches the etched surface of the silicon trench is well supported by silicon processing literature; etched surfaces, especially following a standard RCA cleaning process, are densely populated by interface charge traps⁷⁷. In the absence of passivation with something like a HF hydrogen-passivation process, it is very likely that an intersecting charge will be trapped at the surface, even with a thin oxide present as described in Section 2.1.3⁴⁸. This is also the case for conformally doped sensors, where high concentration of acceptors reduces the mean lifetime of mobile electrons significantly, as described in Section 2.1.2.

4.2 Transport Results for Microstructured Devices

The full charge transport simulation workflow was completed for one million source thermal neutrons in the Geant4 configuration described in Chapter 3. The charge transport was completed for the electric field voxel map calculated for both non-conformally and conformally doped X-MSND cases. Examples of simulated charge carrier group paths for both cases are shown in Figures 4.2 and 4.3, calculated for non-conformally and conformally doped sensors, respectively. In both, the positive charge carrier tracks are colored orange, and negative charge carriers are colored blue. In Figure 4.2, it can be seen that the neutron interaction in the LiF resulted in both reaction products entering and ionizing the silicon, with the alpha particle ionizing the fin over x -pixel 80, and the triton penetrating deeply into the fin over x -pixel 81. Note that no electron or hole group tracks are allowed to exist within the trench region of the silicon.

Another observable feature of the sensor is the presence of strong lateral electric fields near the bottom corners of the trenches and near the pixel bump bond. These lateral fields have the effect of “steering” charges into the pixel, and is a feature of all sensors that have pixelated electrodes.

The charge transport observed in Figure 4.3 for the conformally doped sensor produced

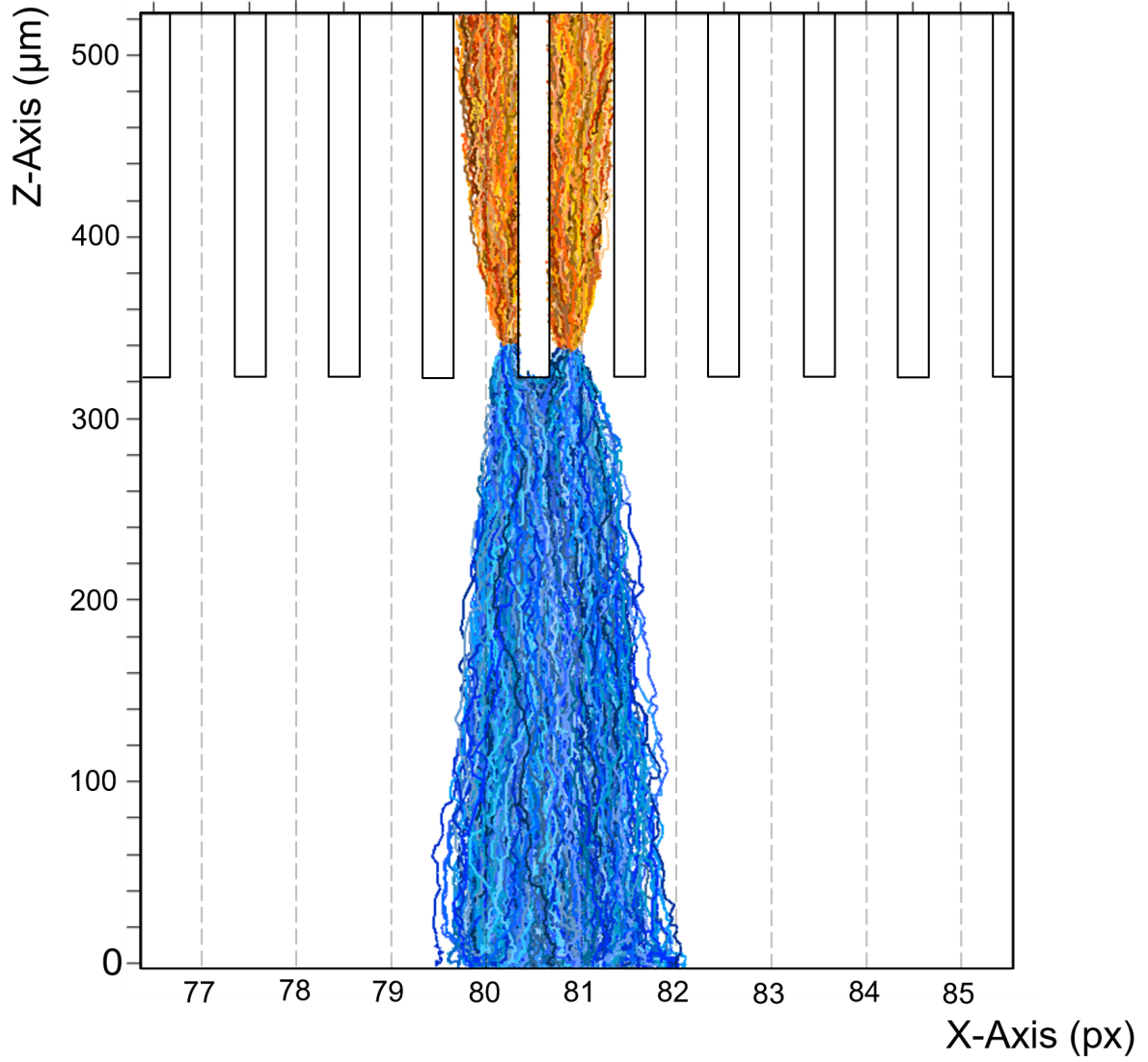


Figure 4.2: Charge carrier drift in non-conformally doped X-MSNDs for a neutron detection event. Section view is perpendicular to the fin direction. Orange tracks are hole groups, blue tracks are electron groups.

significantly different charge drift characteristics compared to the non-conformal case. The relatively weak electric field, and especially the weak z -component of electric field, results in charge carrier motion in the sensor fins being largely dominated by random thermal diffusion. The lateral electric fields in that region play a significant role in the conformally doped sensor's function. The high concentration of acceptors on the fin boundary cause it to become conductive and produce a strong negative electric field perpendicular to the sidewall. This repels electrons from the fin sidewall where recombination rates are the highest, and effectively increases mean electron lifetime as the charge cloud diffuses out of the X-MSND fin. The result is a charge cloud that may diffuse only along the fin dimension, and results in a dramatically elongated cluster.

The formation of the elongated clusters is well illustrated by the charge carrier distribution plotted with time in Figure 4.4, where the number of charge carriers is projected on the xy -plane as a function of several time increments after an initial ionization event by a triton reaction product. The dense charge cloud initially produced by the triton is shown in the first frame at a transport time of zero. The charge diffusion in the fin can then be shown to propagate symmetrically along the y -axis, such that the center of the charge cloud still corresponds to the initial interaction location.

The charge carrier drift times and total charge collection times for all neutron interactions are plotted in Figure 4.5. The slow diffusion of the electrons out of the fin results in a long, almost exponential tail to the accumulated diffusion time. The figure also indicates that the time needed to drift 95% of the electron is nearly a full microsecond. By comparison, the drift time of typical planar hybrid Timepix sensor is usually on the order of 10-25 ns, depending on bias voltage²². This is also much longer than the Timepix preamp peaking time of 110 ns, which could result in non-linearity of the pixel charge to ToT conversion for actual sensors.

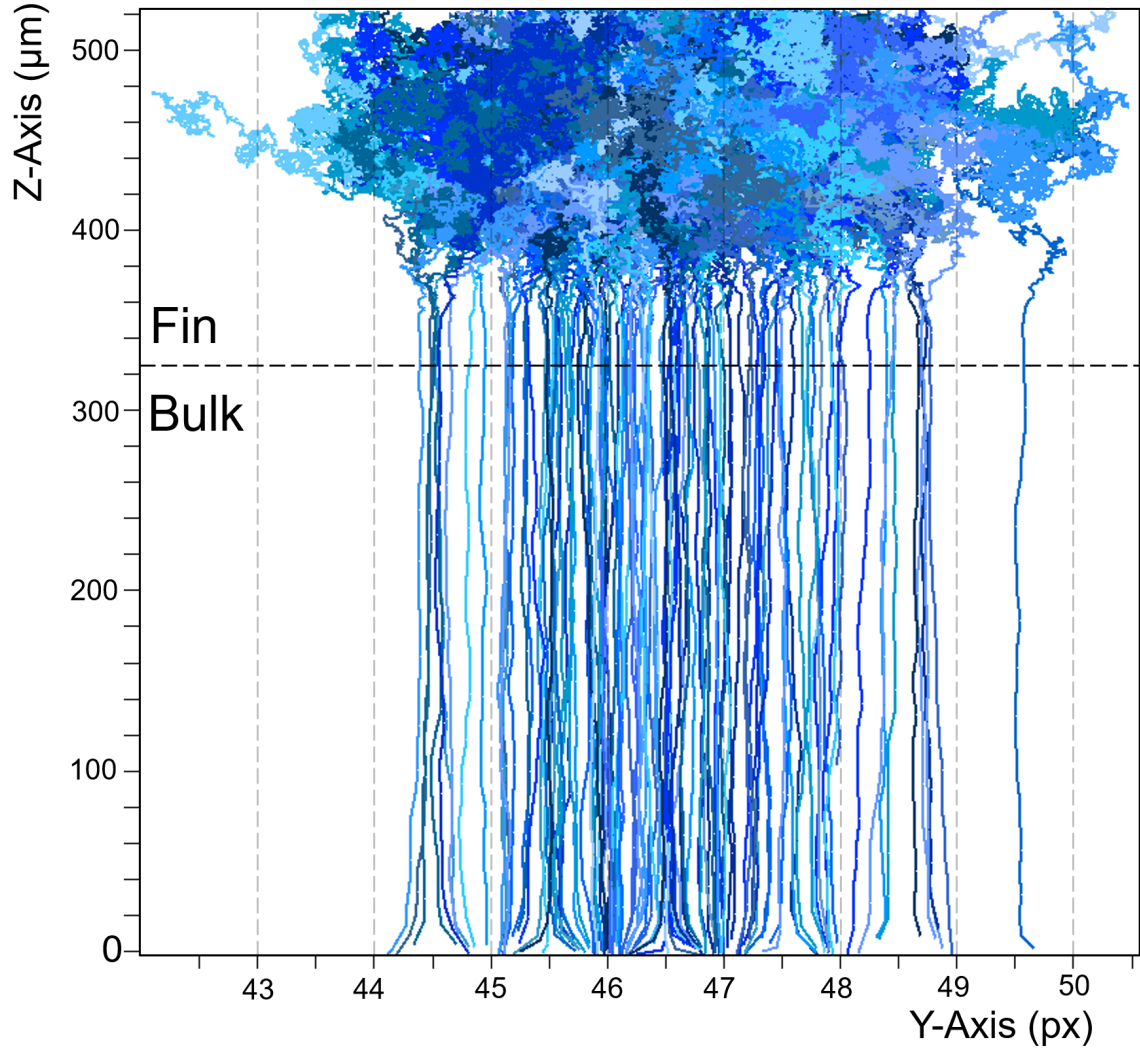


Figure 4.3: *Charge carrier drift in conformally doped X-MSNDs for a neutron detection event. Section view is parallel to the fin direction. Blue tracks are electrons (only electrons are tracked to reduce computation time).*

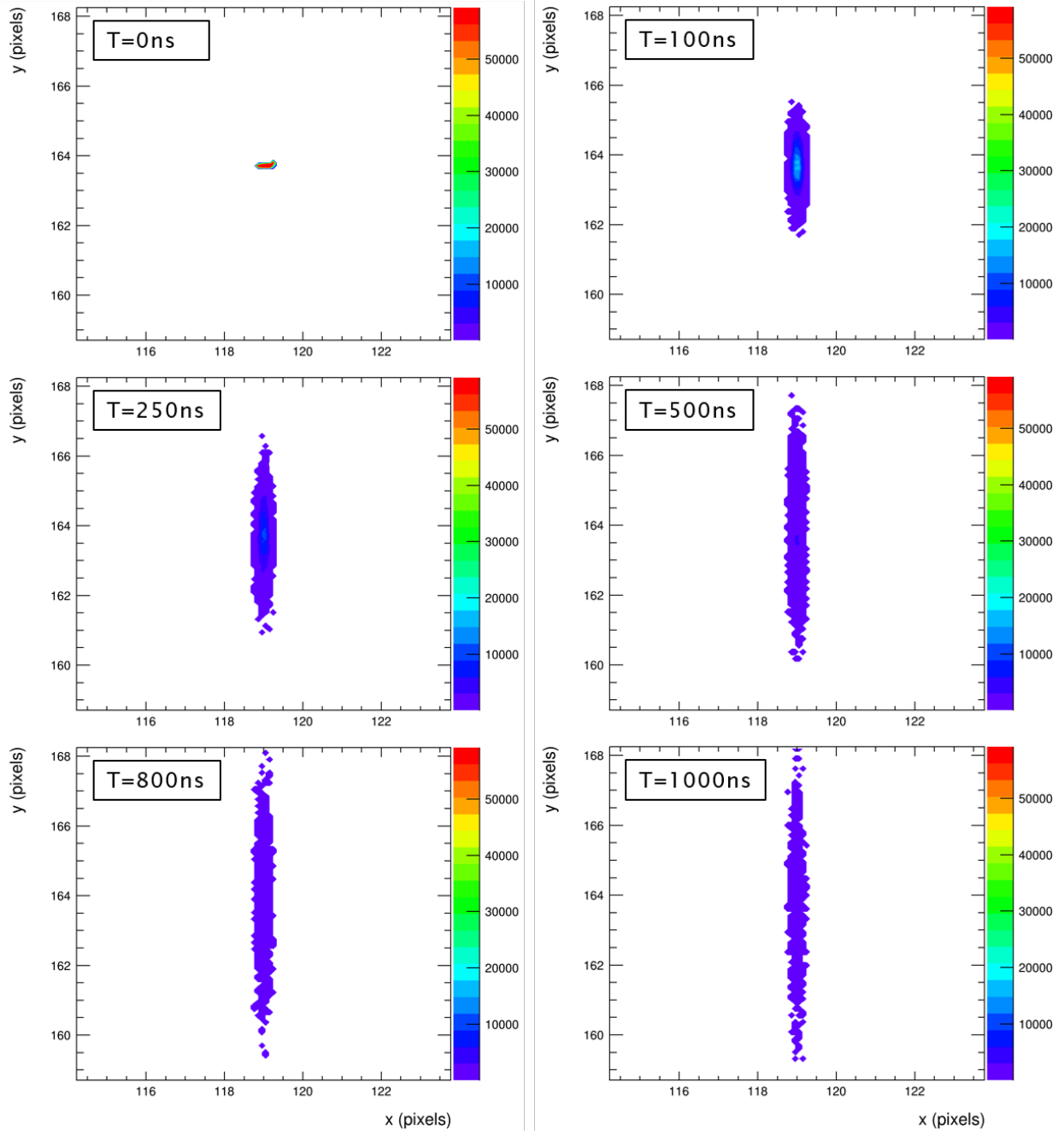


Figure 4.4: *Top view of a charge cloud diffusing through a fin after an energetic triton has ionized the silicon for several points in time. Color scale indicates the charge carrier population at that location in units of electron groups.*

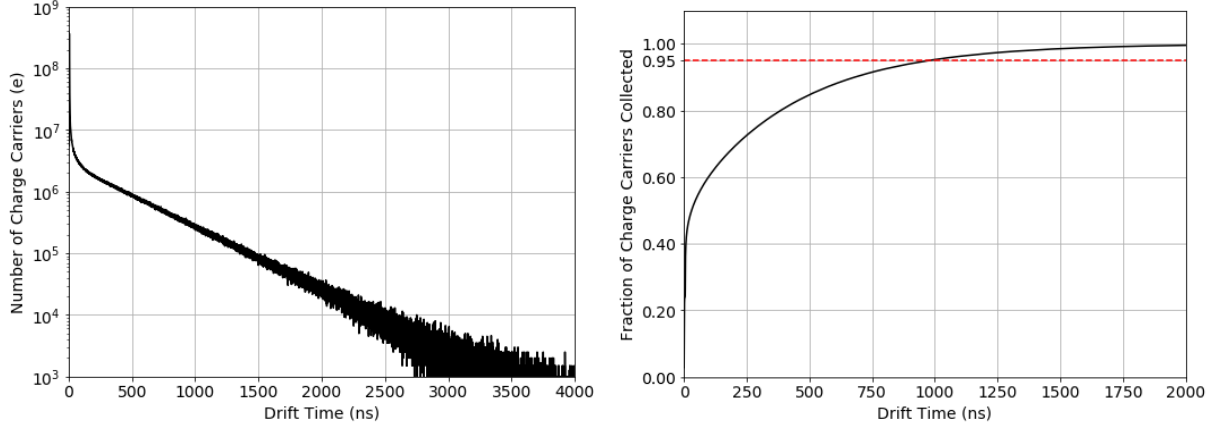


Figure 4.5: Charge collection time for neutron detection events in conformally doped X-MSNDs. Approximately 50% for charge is collected in 100 ns, and 95% of charge is collected in 1000 ns.

4.3 Charge Collection and Total Charge Induction

Charge induced on signal electrodes is calculated in Allpix² by applying spatial displacement formulation of Shockley-Ramo theorem. The total charge induced at the considered electrode by a charge carrier group being transported from 3-D point P_i to point P_f is calculated as

$$\Delta Q_L = -q[\varphi_L(P_f) - \varphi_L(P_i)] \quad , \quad (4.5)$$

where Q_L is the charge induced on electrode L , q is the charge magnitude of the charge carrier group, and $\varphi_L(P_i)$ is the weighting potential calculated for electrode L evaluated at point $P_i = (x_i, y_i, z_i)$. The weighting potential is calculated as the three-dimensional solution for the Laplace equation, producing a scalar field solved for a 5 x 5 pixel matrix. As demonstrated in the weighting field calculation of Chapter 2, the peak charge induced by a charge carrier transiting the thickness of an X-MSND displaced two pixels from the primary pixel is only 2% of the charge induced on the primary pixel itself. Restricting the size of the weighting field solution to 5 x 5 pixels was therefore deemed statistically adequate for capturing the cluster shape characteristics of neutron induced clusters, and saves computational resources.

This method of determining pixel charge via charge induction can be compared to the

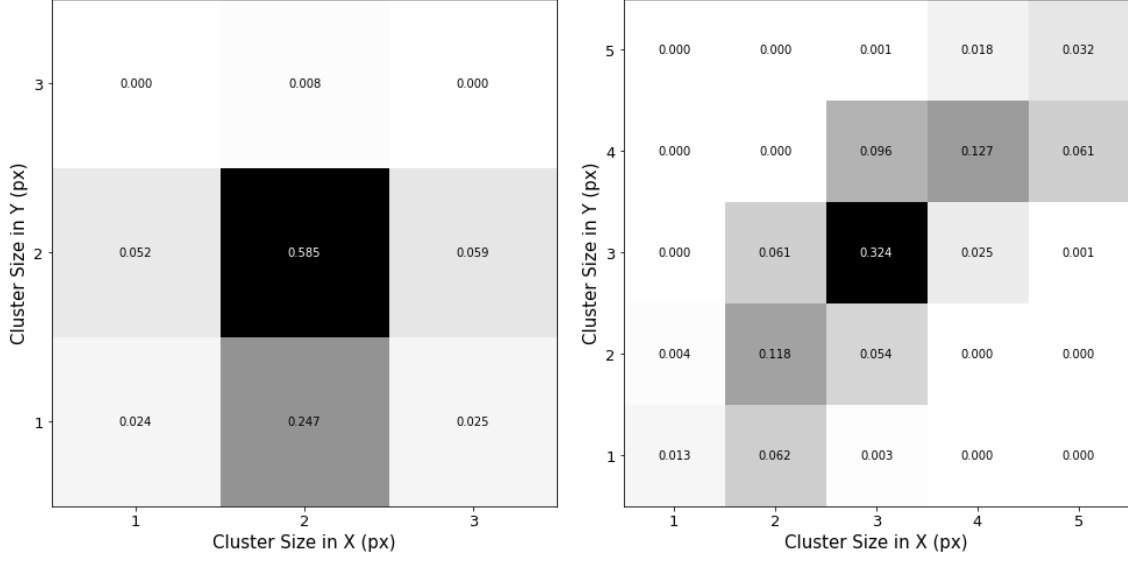


Figure 4.6: Cluster span in x and y direction for charge tallying (left) and charge induction (right) methods. Values are the normalized probability distribution.

alternative charge tallying method (also implemented in Allpix²). In charge tallying, the pixel charge is exactly equal to the sum of the magnitude of charge groups which terminate above the pixel coordinate. This method does not require a weighting field solution to calculate pixel charge, but neglects the induction of charge to pixels neighboring the primary pixel. The potential importance of including induced charge in this simulation workflow was previously demonstrated in Laramore et. al. for the case of micro-structured sensors³⁶. Cluster shape was simulated for non-conformally doped micro-structured sensors using the charge induction method described above, and contrasted with the charge tallying method. The resulting cluster span for both methods is shown in Figure 4.6, where the mean cluster span was calculated to be 2 x 2 pixels and 3 x 3 pixels for the charge tallying and charge induction methods, respectively.

4.3.1 Timepix Krummenacher Circuit and Timing Characteristics

Similar to many charge collecting sensors, the Timepix analog front-end features a charge sensitive pre-amplifier (CSA) circuit to convert the charge collected at each pixel to a voltage pulse. The energy deposited by the radiation is then inferred by relating the time that the

voltage pulse is over a threshold level to the charge deposited in the sensor. This ToT comparator counter circuit is the basis for pixel and cluster charge measurements taken with Timepix devices, typically reported in units of ADC counts. The Timepix preamplifier circuit is based on the Krummenacher feedback current pre-amplifier circuit with a feedback capacitance of 8 fF⁷. Typical RC style charge sensitive pre-amplifiers require a large feedback resistance to “tune” the timing constant of the pre-amplifier output voltage. Instead, the Krummenacher circuit implements MOSFET feedback control, as shown in Figure 4.7. The PFET in the upper left of the circuit diagram is operated in saturation, giving it a trans-conductance of

$$g_m = \frac{2I_D}{V_{fbk} - V_T} \quad , \quad (4.6)$$

where I_D is the drain current, V_{fbk} is the adjustable feedback voltage at the gate, and V_T is the threshold voltage of the PFET. The trans-conductance controls the timing characteristics of the CSA according to the relation

$$\tau_{pk} \approx \frac{C_f}{g_m} \quad . \quad (4.7)$$

The average peaking time for the Timepix CSA is approximately 110 ns for the default V_{fbk} value. This is much shorter than the predicted drifting time of the conformally doped X-MSND neutron events from Figure 4.5. As a result, the V_{fbk} value should be increased to better match the timing characteristics of the X-MSND sensor to the Timepix CSA.

Variation in the trigger time of the pulse rise and fall caused by the fixed clock time results in slight variations in the ToT per charge. To account for this, the charge value collected at a pixel can be gaussian broadened, where the collected charge is the mean and the standard deviation is an experimentally determined parameter. In Allpix², this standard deviation parameter is called “ADC Smear”, and is given in units of charge carriers.

Vgnd	1.0 V
Vfbk (Default)	1.1 V
Vcas	1.2 V
IPreamp (Default)	1 μ A
Ikrum (Default)	20 nA
Preamplifier Gain	$\sim 18 \text{ mV}/1\text{ke}^- [\text{h}^+/\text{e}^-] @ \text{Ikrum}=20\text{nA}$
Peaking time	$\sim 110 \text{ ns}$
Dynamic Range	$1\text{V} \pm 1\%$ (Vfbk from 500mV to 1.5V)
Linearity	Up to $\sim 50 \text{ ke}^- @ \text{Gain}=18\text{mV}/\text{Ke}^-$
Dead Time	$< 1\mu\text{s}$ if $Q_{\text{in}} < 20\text{Ke}^-$
Leakage current compensation	Electron collection: -10 to 0 nA/pixel (-330 to $0 \mu\text{A}/\text{cm}^2$) Holes collection: 0 to $\sim 20 \text{ nA}/\text{pixel}$ (0 to $\sim 660 \mu\text{A}/\text{mm}^2$)
Output Noise	$\sim 75 \text{ e}^- @ \text{Ileak}=0\text{nA}$
Output mismatch	$\sim 112 \text{ e}^- @ \text{Ikrum}=12\text{nA}$
<i>All values given are simulations and they should be used as a trend</i>	

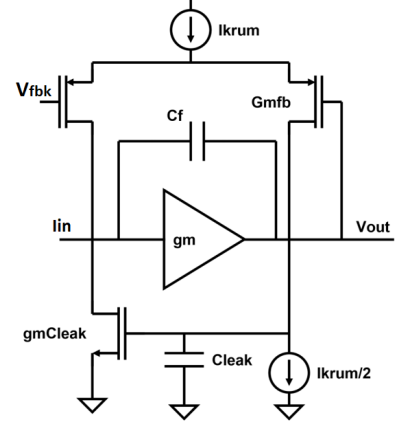


Figure 4.7: *Krummenacher circuit and it's characteristics as implemented in the Timepix analog front end. Taken from the Timepix User Manual⁷.*

4.3.2 “Surrogate” Digital Calibration Model

A key modification made to the Allpix² source files was the addition of a “surrogate” charge conversion model, which is used by both Advacam, Oy with their commercial devices and NASA on Timepix-based space radiation tracking detectors^{22;24;78}. This model accounts for the non-linear response of the Timepix analog front-end to and low pixel charges. This is necessary to convert charge induced at the pixel bump bond (Q_{Ind}) to the Timepix reported time-over threshold value (Q_{ADC}). The conversion model takes the form:

$$Q_{ADC} = \frac{Q_{Ind}}{A} + B + \frac{C}{Q_{Ind} - T} \quad , \quad (4.8)$$

where A , B , C , and T are fitted constants which describe a given device. Note that the parameter T is effectively the energy threshold of the sensor. This model is of particular importance for x-rays below approximately 30 keV, where the ToT non-linearity is most prominent. These parameters are required input for properly matching simulated charge results to the ADC properties of real devices.

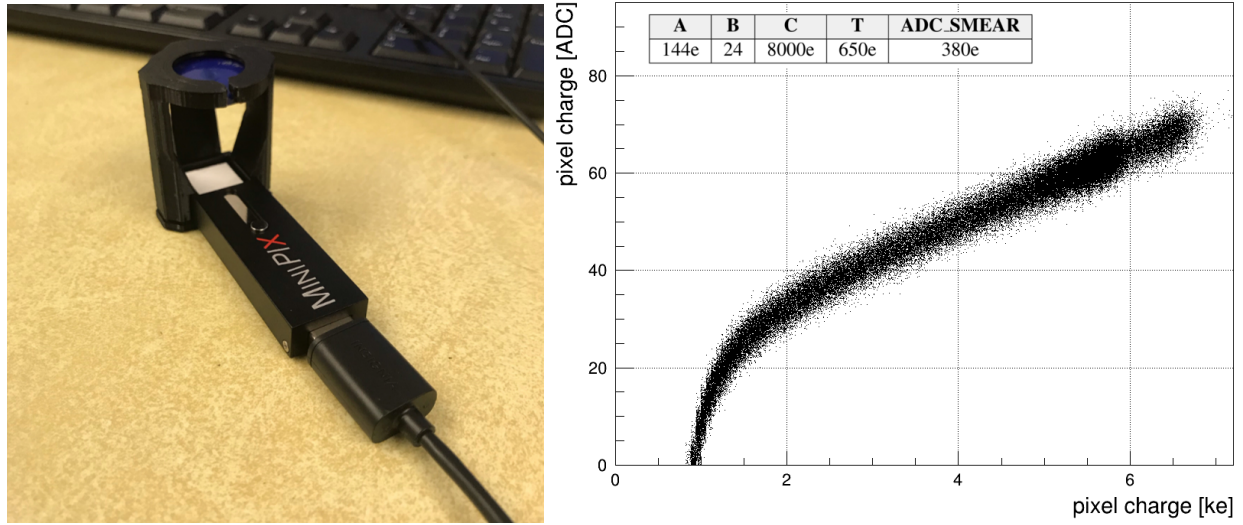


Figure 4.8: *Left: Advacam Minipix sensor in a 3D printed cradle which holds a radioactive ^{109}Cd source at a fixed stand-off distance. Right: Pixel charge converted to ADC counts for simulated MiniPIX device exposed to ^{109}Cd X-rays. The surrogate model coefficients are given in the inset table.*

4.4 Model Validation with MiniPIX Sensors

To validate the modeling method described above, a complete simulation of a commercially available Timepix hybrid detector was performed prior to the micro-structured device simulations. MiniPIX devices are manufactured by Advacam s.r.o., are available with 500 μm thick sensors both bare and ^6LiF coated, and function similarly to the proposed X-MSND devices. The devices operate at 200 V reverse bias, and are configured to collect holes at the pixel contacts. The experimental setup for this data collection is shown in Figure 4.8. To ensure that the exposure conditions could be duplicated in simulation, a 3D printed caddy held an isotropically emitting radioactive disk source at a fixed distance of 5 cm above the center of the sensor. The radioactive sources considered were an 88 keV x-ray emitting ^{109}Cd source and a ^{137}Cs source emitting 662 keV gamma rays.

The results of the pixel and cluster charge matching for MiniPIX devices exposed to ^{109}Cd are shown in Figures 4.8. The surrogate model coefficients used to convert the charge values are found in the table inset in Figure 4.8. These coefficients were found manually by estimating the threshold coefficient for that Timepix sensor first, then scaling the linear

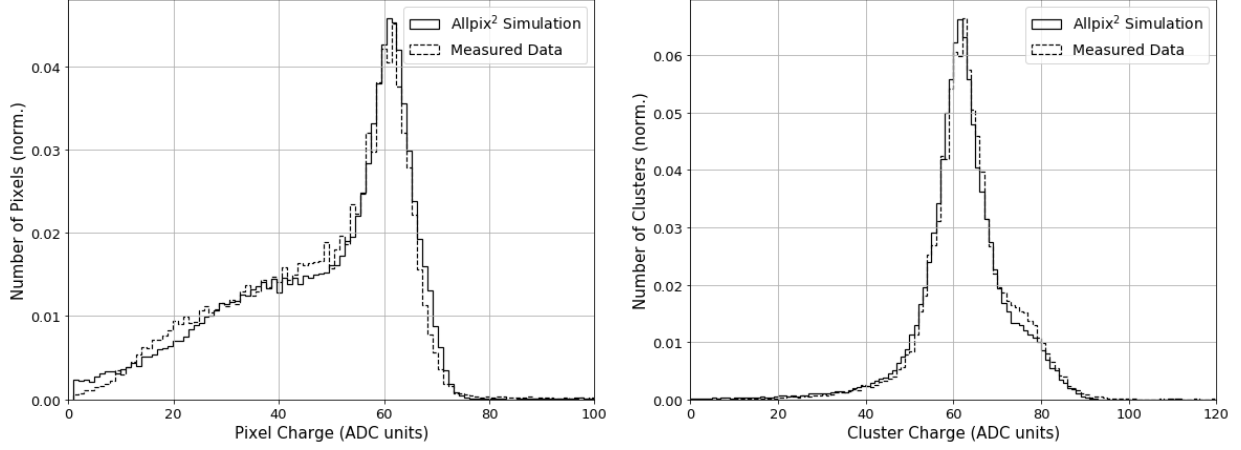


Figure 4.9: *Distribution of pixel charge (left) and cluster charge (right) for the simulated and measured clusters from a MiniPIX device exposed to ^{109}Cd X-rays.*

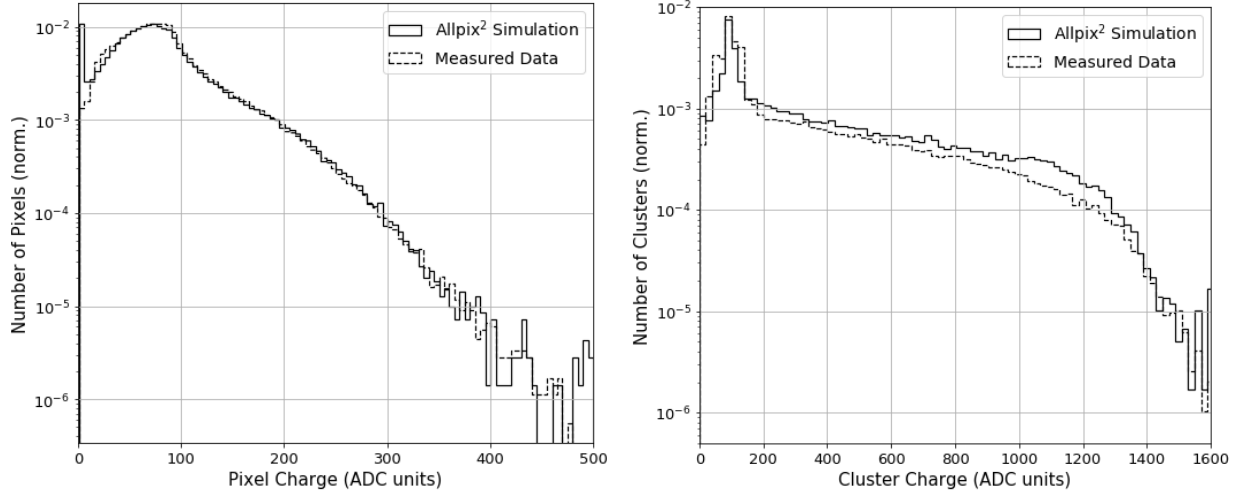


Figure 4.10: *Distribution of pixel charge (left) and cluster charge (right) for the simulated and measured clusters from a MiniPIX device exposed to ^{137}Cs x-rays and gamma rays.*

conversion coefficients (A and B) such that the mean pixel and cluster charge values matched between the simulated and measured data. The non-linear coefficient C was then iterably adjusted with A and B to match the low energy pixel charge data.

Histograms of the accumulated pixel charge and cluster charge for both simulated and collected clusters are given in Figures 4.9 and 4.10 for ^{109}Cd and ^{137}Cs exposure, respectively. These plots indicate that the results from the simulation workflow agree well with the measured data, with the relative magnitude and scale of features in the histograms agreeing. In Figure 4.9, the mean energy of the pixel charge corresponds to the mean energy of the

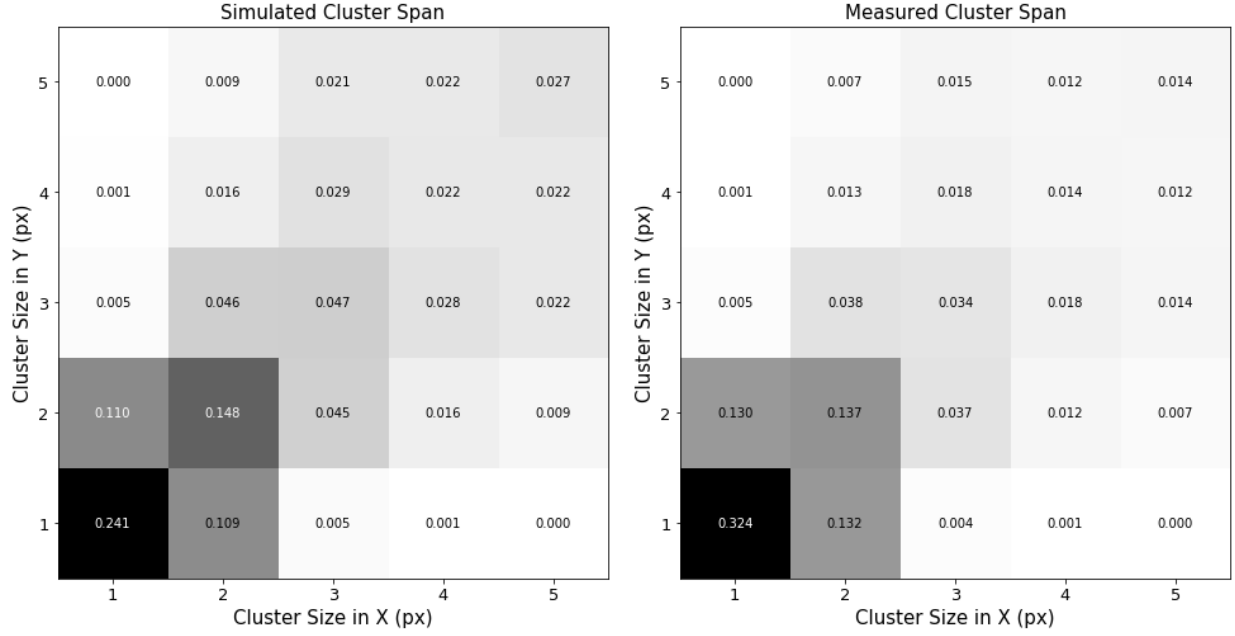


Figure 4.11: Span of clusters produced in (left) and cluster charge (right) for the simulated and measured clusters from a MiniPIX device exposed to ^{137}Cs x-rays and gamma rays.

cluster charge, implying that the majority of clusters are single pixels.

The wide distribution of pixel and cluster charges shown in Figure 4.10 is a result of Compton scattering of the energetic 662 keV gamma rays. These scatters produce long narrow clusters of pixels, with pixel charges that are generally much smaller than the total charge of the cluster, which is supported by the greater charge range in the cluster charge plot compared to the pixel charge plot. The azimuthal scatter angle of these electrons is random, and so the average span of these clusters should be symmetric over a large data set. This is supported by Figure 4.11, which indicates that clusters do not bias in either the x - or y -direction. A minor difference between simulations and measurements in this plot is that the span of simulated clusters tends to be larger than the span of measured clusters. This is likely due to a mismatch in the pixel threshold allowing more low-energy pixels to artificially increase the simulated cluster size, supported by the pixel charge plot of Figure 4.10, which indicates that the simulated pixel charge distributions agrees well with the measured pixel charge except at the very low end of the distribution.

Chapter 5

Hardware Fabrication and Evaluation

The fabrication of functioning X-MSND/Timepix assemblies was a collaborative effort among several research groups at KSU, domestic and international industrial partners, and international research groups. Fabrication of the X-MSND sensors was performed largely by RDT, with parametric design support from REAL and RSIL. The processes used in the production of X-MSND sensors are conventional MEMS photolithography techniques; spin-on deposition of photoresist, UV development, metal lift-off, and wet etching of silicon are all used over the course of fabrication, and will be described in detail. The Electronics Design Laboratory (EDL) of KSU assisted in the design of custom printed circuit boards to which the X-MSND/Timepix assemblies are mounted. External to facilities located at KSU, various industrial manufacturing partners who specialize in VLSI and micro-fabrication assembly processes were also contracted to perform the specialized assembly processes required in assembling the full X-MSND/Timepix systems.

5.1 X-MSND Fabrication Details

The X-MSND sensor fabrication process follows many of the same process steps as typical MSND devices. A high resistivity ($8\text{ k}\Omega\text{ cm}$) n -type $\langle 110 \rangle$ silicon wafer with a diameter of 100 mm is used as the base substrate, wherein high aspect-ratio trenches are wet etched along

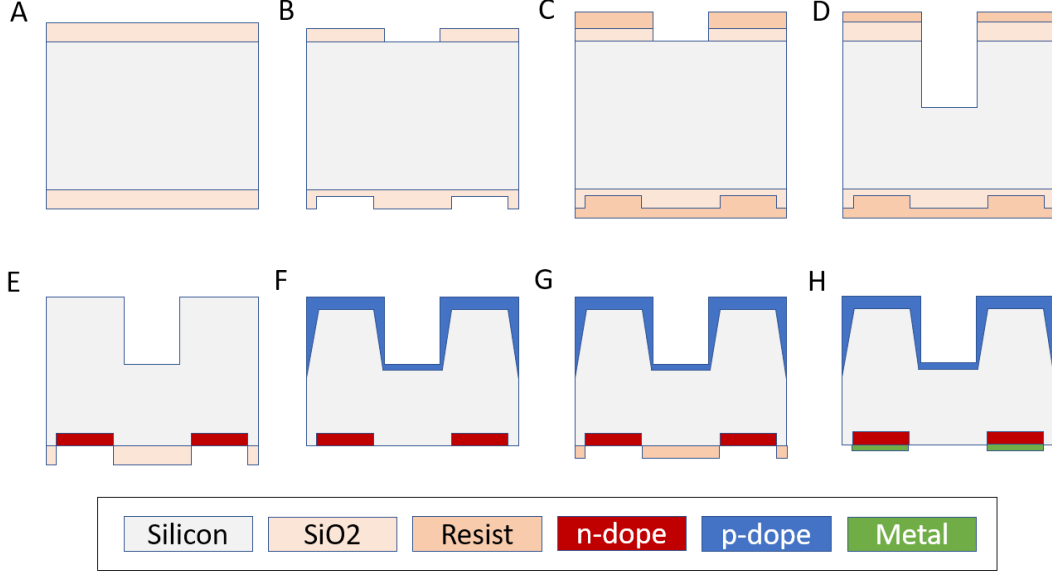


Figure 5.1: *Illustration of X-MSND fabrication steps.*

the (111) plane, forming a trench-fin micro-structure^{29;79}. The major steps in the fabrication of the X-MSND sensor are performed as follows, with Figure 5.1 illustrating these steps:

1. A 3 μm -thick thermal wet oxide is grown on all surfaces of the the silicon wafer to provide a diffusion mask for all future processes (Fig. 5.1-A).
2. A microstructure trench photolithographic pattern is aligned to the (110) Si primary flat, which is aligned to the (111) plane of the Si. The pattern is transferred into the Si with buffered oxide etch (BOE) with 1 μm of oxide left in the trench. A second diffusion window mask is aligned to the trench pattern and the oxide across the entire diffusion window, including the trenches, is etched with 1 μm of oxide removal (Fig. 5.1-B). The backside (pixel side) is patterned with photoresist (PR) and the pixel array pattern is aligned to the top-side trench pattern. PR is placed on the trench side and the backside pattern is etched with 1 μm of oxide removal in BOE (Fig. 5.1-C). Therefore, when the topside diffusion widow is etched down to bare Si after trench etching, the backside will also be etched down to bare silicon and is ready for contact diffusion. As such, the trench pattern has been etched down to bare Si. During these two etch processes the backside (n -type) has been protected from BOE with a thick coating of

PR.

3. The wafer is placed in aqueous KOH (50% by weight) at 55 °C and etched to 200 μm in depth to form the trenches (Fig. 5.1-D).
4. The wafer is cleaned, and the trench side diffusion window is further etched in BOE to remove the residual oxide trench mask to open up the diffusion window contact area. The pixel (*n*-type) side is then dry source diffused with phosphorus to a surface concentration of to $1 \times 10^{20} \text{ cm}^{-3}$. A dummy wafer in contact with the trench side is used to protect against *n*-type diffusion on the p-type contact side (Fig. 5.1-E).
5. The wafer is BOE cleaned and then the trench side is diffused to a surface concentration of about $5 \times 10^{19} \text{ cm}^{-3}$ in the same manner as the previous step, except the trench side faces a boron nitride (BN) diffusion source (Fig. 5.1-F). Boron oxide is produced from the BN in a wet environment at 800 °C, which serves to seal the seam between the X-MSND wafer and a dummy wafer before the material can diffuse into the inner portion of the wafer.
6. The wafer is again BOE cleaned of diffusant residue and patterned with liftoff PR and the respective diffusion window and pixel bond-pad patterns are aligned to the same diffused patterns on each side (Fig. 5.1-G). The wafer is then metalized with 2000 Å Al, 500 Å Ti, 2000 Å Pt, and 1000 Å Au (Fig. 5.1-H). After both sides have been metalized, the PR is dissolved and lifted, and the metal pattern is tested for adhesion with a tape-pull test.

The wafer was singulated with a dicing saw after mounting to dicing tape, and the individual X-MSNDs were then tested for electronic properties and graded according to leakage current and capacitance. The trenches of the highest grade sensors were then back-filled with neutron converting material to make the devices neutron sensitive, in this case 96% enriched ^6LiF nano-grain powder with a fill fraction of 0.50 or better. To encapsulate the LiF powder, a thin layer of dry film photoresist was applied to the trenched side of the X-MSND and cured. The 20 μm thick solid epoxy film is able to tent overtop the X-MSND

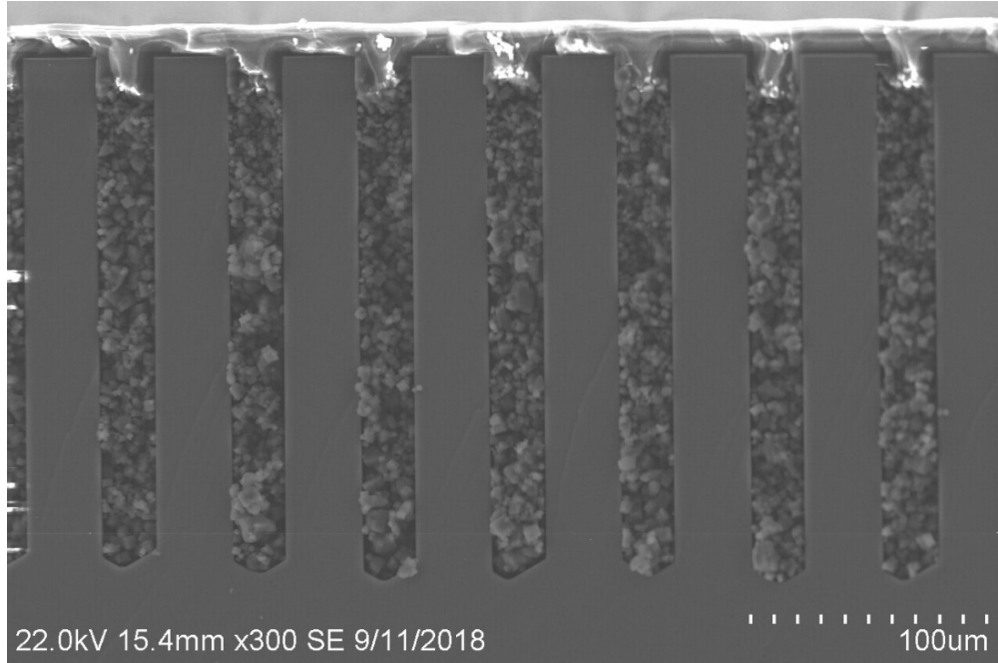


Figure 5.2: *Diced cross-section of X-MSND sensor.*

trenches, containing the ^6LiF within the trenches of the sensor, and was cured to a glassy hardness after a multi-hour oven cure at 300-400°F.

Several variants of X-MSNDs were fabricated in order to provide a large diversity of manufactured sensors. This helped to identify the limitations of the X-MSND and flip-chip bonding compatibility. A total of 10 wafers of diode sensors were produced with the following variations, which included both trench and untrenched sensors:

- 2 wafers planar type, PIN diode (pixels are N-type dopant)
- 2 wafers planar type, NIP diode (pixels are P-type dopant)
- 2 wafers trench X-MSND, PIN diode, no LiF backfill
- 2 wafers trench X-MSND, PIN diode, pre-backfilled with LiF
- 2 wafers trench X-MSND, NIP diode, both non- and pre-backfilled

Additionally, two variations of the pixel bond pad mask were generated to address potential issues with bond pad integrity. Half of each wafer contained standard 20 μm diameter

bond pads, and the other half contains larger 40 μm diameter bond pads (see Figure 5.3). During the wafer fabrication photoresist development, it was noted that smaller bump-bond pads were not clearly formed; bubbles would occasionally reside on the 20 μm diameter photoresist windows, limiting developer chemical interaction. This effect can be seen in Figure 5.4. The larger 40 μm pads will prevent this from occurring. Further, a DI rinse wetting step was added to the usual developer dipping to eliminate the instances of bubbles forming.

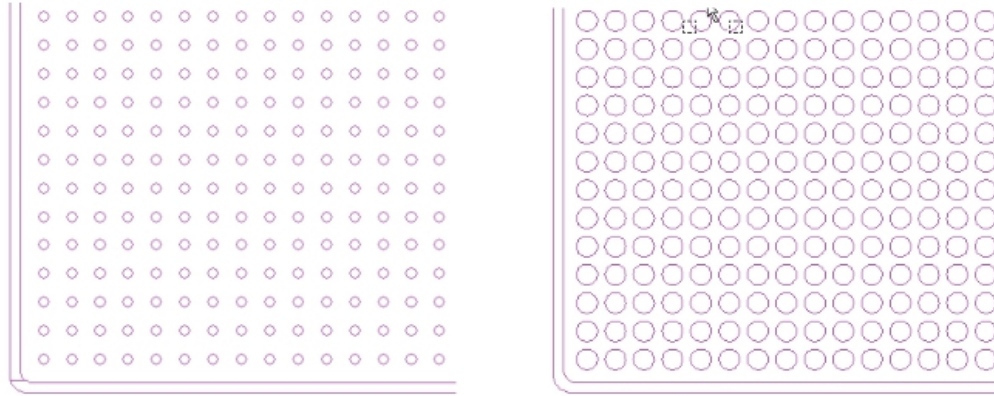


Figure 5.3: *Comparison of photoresist mask for the two sizes of pixel bond pads*

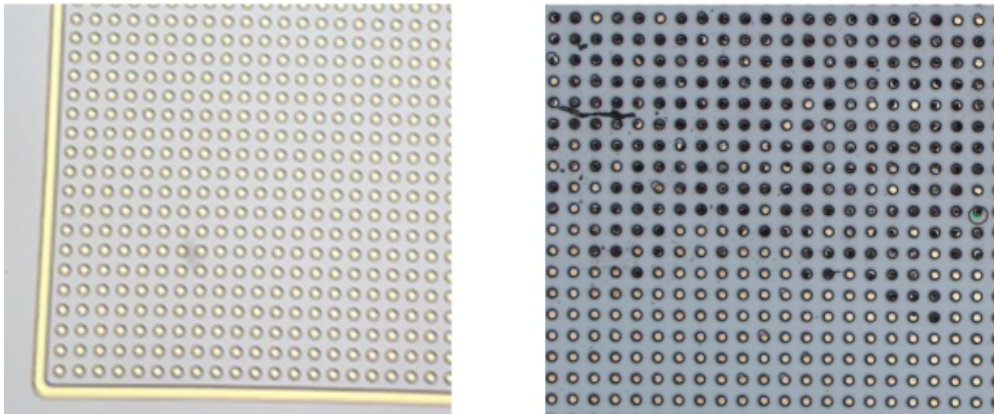


Figure 5.4: *Comparison of properly developed metallized bond pads (left) and metallized bond pads with undeveloped photoresist (right).*

5.1.1 X-MSND/Timepix Assembly

The highest graded X-MSND sensors were serialized and shipped to commercial microelectronics processing companies for assembly with Timepix ASICs. The X-MSND/Timepix

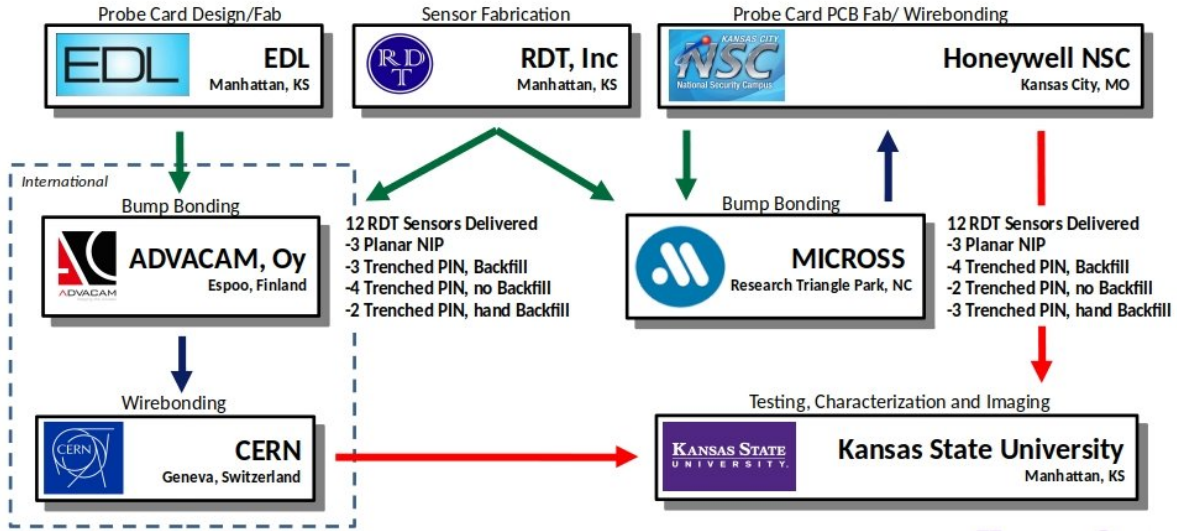


Figure 5.5: Flow chart illustrating the fabrication steps and their locations required to produce the Rev.2 X-MSND sensor probe cards. Intermediate steps include sensor and probe card hardware delivery (green), delivery for final assembly (blue), and delivery for testing and evaluation (red).

assembly process involves three distinct sub-processes: Flip-chip bump-bonding, sensor PCB mounting, and wire-bonding. These processes are all highly specialized and require task specific equipment and expertise to ensure repeatable results and yields, necessitating that these tasks be outsourced to several facilities outside of KSU. Figure 5.5 gives a flow chart of the assembly locations and sensor quantities, split into a majority-international and a domestic only process flow.

Two variants of the PCB card which carries the X-MSND were used during the assembly process; the Medipix style adapter card developed at CERN for planar diode sensors, and a modified variant of that card developed at Kansas State University. This card was designed by KSU's Electronics Design Laboratory under director Timothy J. Sobering. All changes to the original Medipix2 schematic were limited to the inclusion or removal of passive surface mount components, and some layout features of the PCB. Certain changes were also made to pinning labels and connections to more accurately match the Timepix layout and nomenclature, which differs slightly. A summary list of all major changes to the board design is below, followed by additional details.

- Conditioning components were added to voltage supply lines (VCC_IN, VDD_LVDS_IN, AVDD_IN, and VDD_IN). This includes adding ferrite beads for noise reduction and additional decoupling capacitor to ground.
- The high voltage input was reconfigured to match X-MSND device specifications. The LEMO connector (bias input) along with R1 and C1 were moved to the bottom of the PCB to accomodate an X-MSND radiofrequency shield.
- The size and voltage specification of various surface mount capacitors were changed.
- Several connections from the main card connector were reconfigured from the Medipix schematic to match Timepix pins. This includes removal of some surface mount components and changes to the wirebond specification.
- Components near the wirebond pads of the Timepix were moved to the bottom of the PCB and moved closer to the Timepix chip. This reduces decoupling inductance, even with the additional vias, while providing better clearance between components and the wirebonding wedge.
- Several ground planes were made accessible on the top of the PCB, including ground pads around the mounting holes and a rectangular ground border around the sensor itself. This border was designed to allow a metal RF and visible light shield to be soldered over the sensor.

Pictures of the two card variants can be seen side-by-side in Figure 5.6. The X-MSND/Timepix sensor assembly can be seen mounted and wire-bonded on the upper half of the adapter cards.

5.2 Sensor Testing and Evaluation

A fully portable, light-tight test system was designed and constructed for the purpose of operating X-MSND/Timepix chips with a FitPIX driver module manufactured by Advacam,

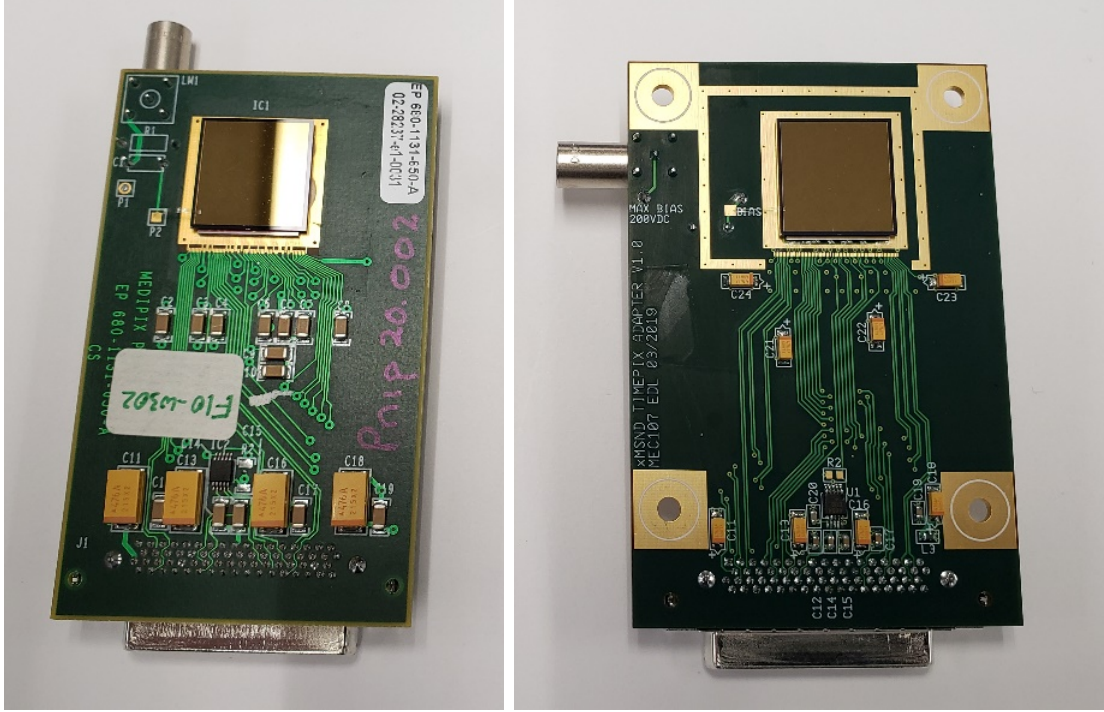


Figure 5.6: X-MSND Timepix sensors on probe cards. Left is the standard CERN design, right is the modified design produced by the KSU Electronics Design Lab (EDL).

Oy. The two test boxes, seen in Figure 5.7, are constructed of enameled cast aluminum and feature gaskets for light-proofing. Included in the construction are isolated BNC feed-throughs for application of X-MSND bias voltage, transistor-transistor logic (TTL) level trigger input and output signals, and 12 V power and USB communications for the FitPIX module to a host computer. The Timepix chip was powered by the FitPIX directly, while the X-MSND bias and current monitoring was supplied by a Keithley 2400 Sourcemeter. The test boxes feature dual 2 mil (0.051 mm) thick Mylar windows centered over the X-MSND/Timepix assembly. This window allows normally incident radiation to interact with the X-MSND chip while blocking ambient light. The unbiased ambient light current of the device while in the test box was measured to be around 2 nA on average, well below the leakage current level of the devices at operating voltage, which can be as high as several hundred micro-amps.

Prior to collecting data with the X-MSND sensors, the whole chip and per-pixel energy thresholds must be determined using a routine called “threshold equalization” that is in-



Figure 5.7: *Light-tight probe card test boxes with Mylar window and feed-throughs. One test box is a redundant test vehicle. The sourcemeter for external negative bias is shown on the far right.*

cluded in the FitPIX interface software called PixetPro, also developed by Advacam. This process varies the compensating current of each pixel such that the noise level is equal for all pixels, then sets the global threshold just above the noise level of the most sensitive pixels. Pixels with excessively high noise levels are masked. The threshold equalization routine was performed on all chips with the FitPIX and probe cards fully installed in the test boxes to reduce the baseline noise current level.

5.2.1 Early Sensor Data Collection and Problem Diagnosis

Flip-chip bonding was identified early in the fabrication process as the most failure-prone step. This step is completed by aligning the X-MSND pixel solder pads with the pre-populated solder balls on the Timepix chip, then applying heat with a small amount of pressure to wet and bond the solder balls to both chips. Minor deviations in the flatness and parallelism of the X-MSND dryfilm coating resulted in minute canting of the sensor, which can result in inconsistent bump-bonding across the sensor. Additional problems were encountered in the heating of the lead-tin solder balls; in some cases, not enough heat could

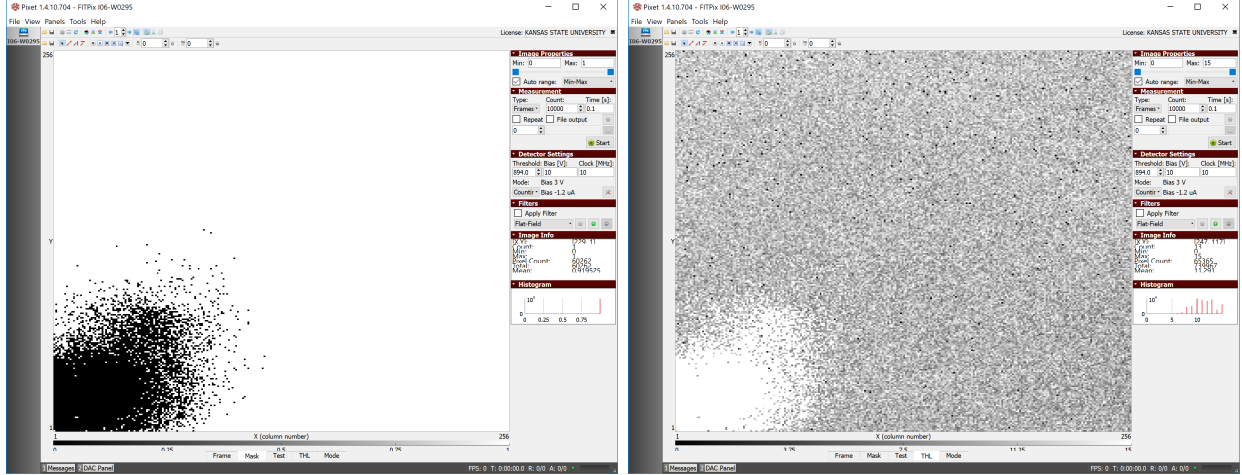


Figure 5.8: *Threshold equalization results of chip assembly IO6. Masked pixels (left) appear black. Only unmasked pixels completed threshold equalization and given a THL value (right)*

not be properly transferred underneath the sensor to melt the solder, forming a weak bond. In two early prototype examples, the bond was weak enough that the sensors completely detached from the Timepix.

Figure 5.8 shows an example of pixel masks and per-pixel THL values for assembly CERN-I06 after threshold equalization, prior to the sensor and Timepix chip detaching. This sensor represents the first test batch of sensor assemblies. The masked corner off CERN-I06 visible in Figure 5.8 corresponds with the wetted corner in Figure 5.10. These images support the conclusion that the corner masked by the threshold equalization routine are areas are bump bonded, but are experiencing excessive current due to large un-bonded regions, which was confirmed by scanning electron microscope (SEM) imaging. In all cases where threshold equalization completed, a large portion of the pixels were automatically masked by the FitPIX software. This indicates pixels which read excessive current or are generally unresponsive to threshold adjustments. In some cases, the unresponsive regions were too large for the threshold equalization routine to automatically mask, and portions of the array needed to be masked manually. It was initially assumed that the masked regions were insensitive due to poor solder connections. Testing revealed that the unmasked regions were largely insensitive to both alpha and neutron radiation. Exposing the X-MSND to ambient light confirmed that current produced in the X-MSND silicon was not being transmitted to

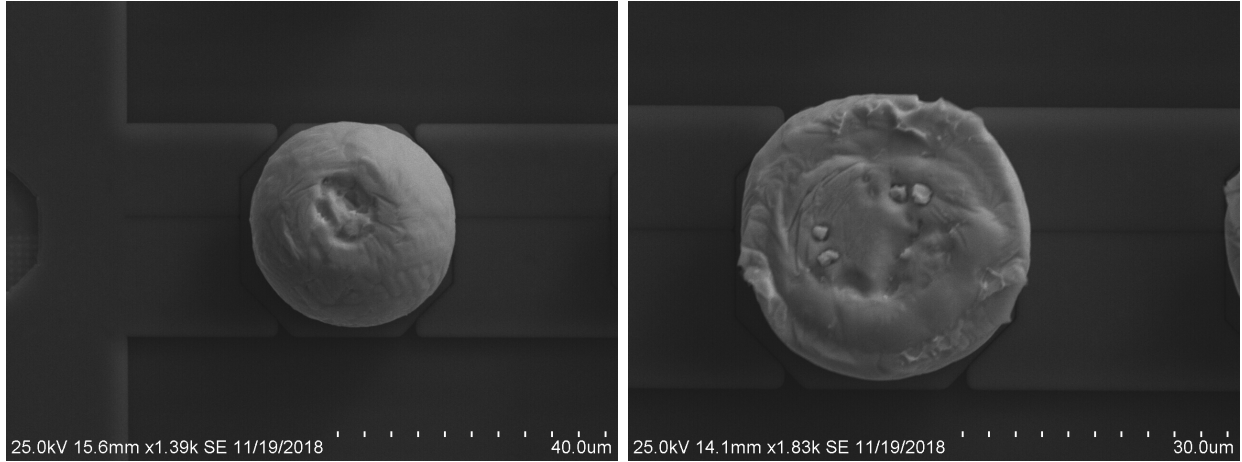


Figure 5.9: *SEM images of Timepix side solder balls after X-MSND detachment. Majority of solder balls are untouched or show signs of pressure (left), with few balls appearing to have melted (right).*

the corresponding Timepix pixels. Flickering in pixels surrounding the masked section when exposed to light suggested that only these regions were passing current to the Timepix, and that the excessive current was due to an absence of good metal contacts at the X-MSND/Timepix interface.

The detachment of the X-MSND sensors from the Timepix chip was treated as an opportunity to inspect the bump bonding and confirm the cause of failure. Both the metal contact side of the X-MSND and solder ball side of the Timepix chip were imaged using a SEM at the Kansas State Micro-Analysis Laboratory (KSMAL). Several noticeable inconsistencies were observed across the devices. The majority of metal contacts and corresponding solder balls on the silicon devices appear to have been untouched or otherwise not melted. In some cases, it was evident that pressure was applied to the chips significant enough to flatten tops of the solder ball tops (necessary for uniform flip chip bonding), but the solder balls did not appear to melt and form the solder bond. Some instances of wetted solder balls and corresponding contacts were found near the corners of the chips. SEM images of chips from probe card CERN-I06, shown in Figure 5.9 with close-up images of individual solder balls shown in Figure 5.10, illustrate the contrast between successfully or partially wetted/bonded solder regions and unwetted regions.

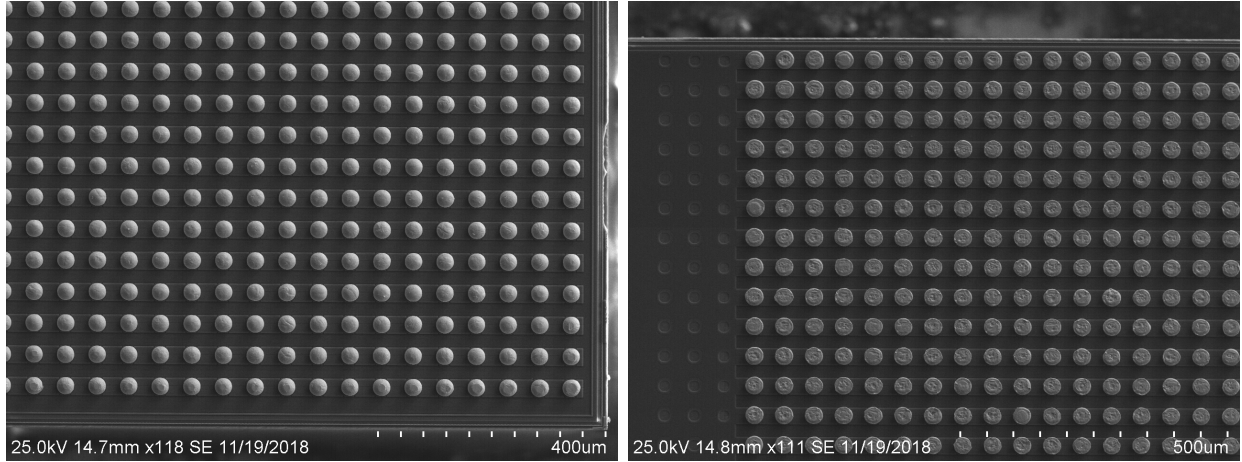


Figure 5.10: *SEM images of Timepix with solder balls taken from two regions of a chip where the X-MSND sensor detached. Left is the lower-right corner of the chip showing no wetting of balls. The tops of the solder balls were also flattened, indicating pressure was applied to the sensor, but not enough heat was available to melt the solder balls. Right is the upper-left corner of the sensor where the balls were melted and deformed.*

Sensor Revisions

In order to address the problems encountered with the flip-chip bonding, several major changes were made to the fabrication process. First, the solder ball material was changed from lead-tin to indium-tin. This reduced the solder melting temperature from 220°C to 117°C, improving the probability that all the solder balls melted and bonded to the solder pads, as well as lowering tool temperatures and reducing the probability that the dry film will glass transition and adhere to the flip-chip tooling. The dry-film was also oven cured for significantly longer to prevent tool adhesion during the flip chip bonding process. The metal stack-up of the pixel bump bonds was revised from Ti-Ni-Au to Ti-Pt-Au. This avoids the use of nickel metal, which may introduce problems with oxidation and poor adhesion/contact of the conductive gold to the silicon sensor. Furthermore, greater emphasis was placed on cleanliness and surface preparation of the sensor surface.

5.2.2 General Sensor Performance

Table 5.1 provides a summary of the basic metrics determining yield and performance of the delivered probe card sensors. Of the 12 sensors delivered to Advacam, 2 probe cards

	Advacam, Oy	Micross Components
Probecard Design	Medipix	X-MSND EDL Custom
Sensors Delivered	12 (9 X-MSND)	12 (9 X-MSND)
Probe Cards Dead/Undelivered	2	4 (3 repaired)
Functioning Yield	7 Cards (3 X-MSND)	8 Cards (5 X-MSND)
Avg % Masked Px	5.5%	3.5%

Table 5.1: *Comparison of Probe Cards bump bonded by Micross and Advacam*

were either not-delivered or dead on arrival. These issues were attributed to an accidental dislodging of the X-MSND/Timepix assembly from the probe card PCB, and an unresponsive or malfunctioning Timepix ASIC, respectively. Of the 12 sensors delivered to Micross, one probe card remained undelivered due to severely damaged wire bonds. An additional three cards were rendered un-usable upon arrival due to improperly placed SMT capacitors (reversed polarity). These cards were repaired by EDL personnel on site at KSU without issue.

To be considered as part of the functioning yield of cards, the cards must have had all necessary wirebond connections to allow Timepix readout and sensor biasing, must have been able to communicate with the PixetPro software via the FitPIX driver module USB, and must be capable of passing a threshold equalization routine within the maximum tolerated operating parameters. For all tests, the maximum negative bias allowed was 320 V with an Ikrumm value of 15 DAC. The most common error preventing sensors from functioning was a failed threshold equalization, generally caused by a significant amount of pixels reporting high current or simply unresponsive to variation in threshold. All sensors that successfully equalized contained some masked pixels, however, none of the functional yield sensors contained clusters of dead pixels that would prohibit effective dead pixel interpolation.

In general, standard planar sensors performed the best of all variants, with only one sensor dead on arrival due to an unrelated failure of the Timepix chip. X-MSND sensors that were not coated with dry-film, whether they were backfilled before or after the flip-chip bonding process, had a functioning yield rate on par with the planar devices. This was observed for both flip-chip assemblers, as reported in Table 5.1. Furthermore, Micross has delivered X-MSND/Timepix assemblies with functioning yields similar to the quality

of Advacam assemblies, and is the only provider to successfully bond a dry-film coated X-MSND to a Timepix that counts toward the functioning yield of cards. These observations support the conclusion that the dry-film epoxy layer is the root cause of early problems with bump-bonding, and revising the fabrication to accommodate trench backfilling after bump-bonding would yield the best results.

Chapter 6

Data Collection and Imaging

The highest performing subset of fabricated X-MSND sensors was used to generate radiographs of various multi-material objects, and to collect the cluster data used to validate the simulation method presented in this study. To facilitate this, pre-existing x-ray and neutron imaging facilities at KSU were utilized with as minimal modifications as possible. Those images were generated using cluster analysis and image processing scripts developed at KSU. The methods and results of these techniques yielded reasonably high quality images as illustrated here.

6.1 Radiation Testing Methods

6.1.1 Evaluation with Check Sources

To qualitatively verify radiation sensitivity and observe the clusters formed in X-MSNDs, the micro-structured devices with no dry-film were exposed to photon emitting check sources. Several clusters from these exposures can be seen in Figure 6.1, which includes ^{109}Cd , ^{137}Cs , and ^{60}Co . These sources vary significantly in photon energy as shown in Table 6.1, and subsequently generate different sized clusters from photoelectric and scattered electrons produced in the silicon. Clusters from the photon emitting sources were not malformed and characteristically similar to clusters collected from standard planar sensors. Cluster size was

Radioactive Source	Emission Type	Energy
^{109}Cd	x-ray	88 keV
^{137}Cs	x-ray	32 keV
	gamma	662 keV
^{60}Co	gamma	1173 keV
	gamma	1333 keV
^{241}Am	x-ray	59 keV
	alpha	5486 keV

Table 6.1: *Radioactive sources used for X-MSND evaluation*

also observed to increase with increasing source photon energy.

An alpha particle emitting ^{241}Am source was also used emulate the ionization of silicon expected by neutron detection events. These alpha particles have a short range in silicon and the LiF backfill material, and so placing the ^{241}Am source directly on the X-MSND sensor results in alpha particles only ionize the uppermost part of the fins. The clusters collected from the ^{241}Am source were the first clearly observed instances of cluster elongation due to interactions in the fins, and are shown in Figure 6.2. These clusters had a very high aspect ratio, generally only being one pixel wide and up to 10 or more pixels long.

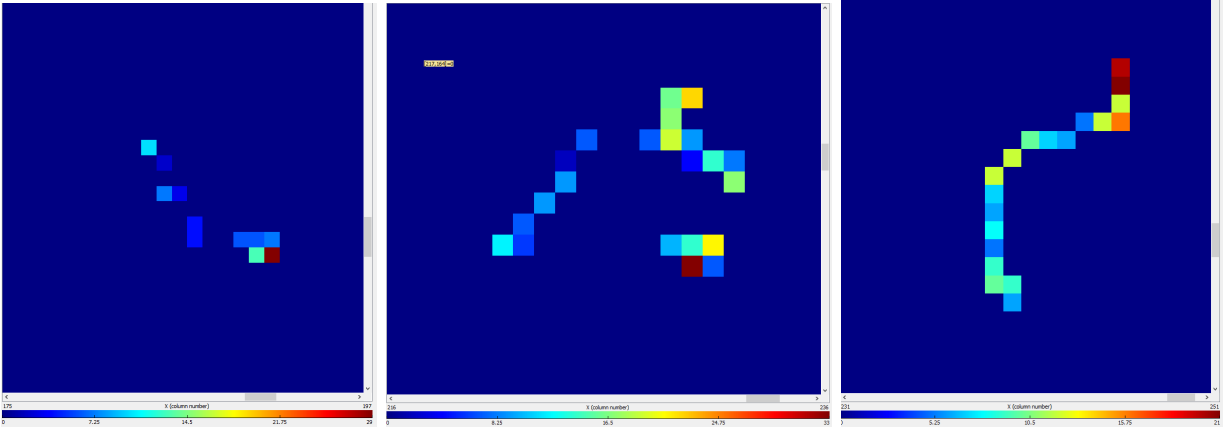


Figure 6.1: *Clusters collected with X-MSND from gamma and x-ray emitting check sources. Ordered least to most energetic: ^{109}Cd (left), ^{137}Cs (middle), and ^{60}Co (right).*

6.1.2 Neutron Testing Facilities

For neutron testing and imaging, the KSU TRIGA MkII research reactor was used as a strong source of collimated neutrons. Both the northwest (radial NWBP) and southeast (tangential

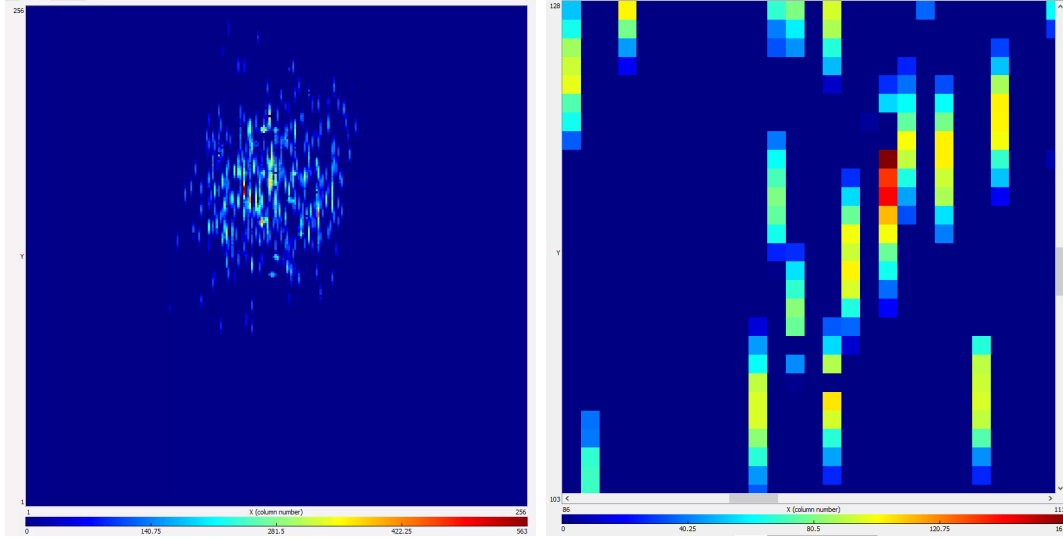


Figure 6.2: *A full frame and a zoomed frame showing elongated clusters from ^{241}Am alpha particles ionizing the tips of X-MSND fins.*

SEBP) beam ports of the reactor were used (see Figure 6.3). The exit antechamber of the NWBP contains a pyrralitic graphite neutron monochromator which reflects neutrons according to their energy dependent Bragg diffraction angle⁸⁰. A second collimator obliquely placed in the scattered neutron field generates a thermal neutron beam line with highly uniform neutron energy selected to optimize detection efficiency with a He^3 proportional counter.

It was determined through preliminary cluster collection that the NWBP beam diameter was slightly smaller than the X-MSND sensor chip width, preventing a flat field capture for imaging purposes. The SEBP, having a larger beam diameter, was instead used for imaging. The SEBP emits a softer neutron spectrum with lower gamma ray contamination than all other beam ports (measured at the beam port shutter) due to being orientated tangentially to the core reflector and having a 2 in thick lead gamma filter within the beam column, just past the core reflector. The NWBP with the reactor operated at operated at 10 kW(th) was reserved for thermal neutron testing (efficiency, cluster analysis etc.). The SEBP was operated at a power of 5-25 kW(th), giving it an approximate thermal neutron flux of $1 \times 10^4 \text{ cm}^{-2} \text{ s}^{-1}$ to $5 \times 10^4 \text{ cm}^{-2} \text{ s}^{-1}$, and an estimated epithermal neutron flux of $2.5 \times 10^3 \text{ cm}^{-2} \text{ s}^{-1}$ to $12.5 \times 10^4 \text{ cm}^{-2} \text{ s}^{-1}$ based on known prior measurements⁸.

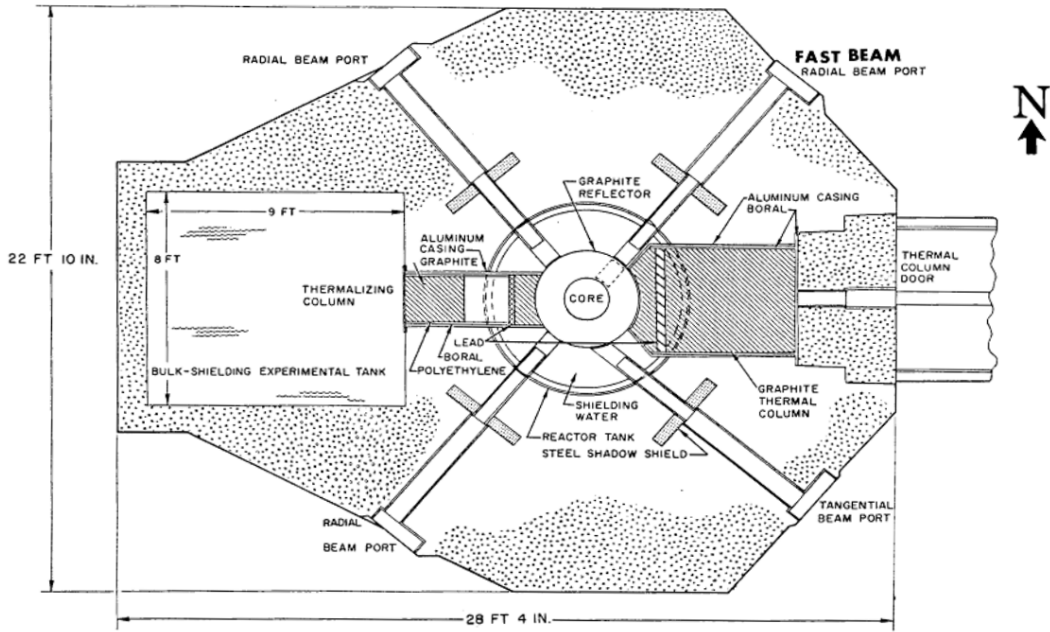


Figure 6.3: *Layout of TRIGA MkII reactor and beam port configuration. The northwest radial beam port (with supporting pyrolytic graphite diffractor) and southeast tangential beamport are used for X-MSND thermal neutron testing and neutron imaging, respectively⁸.*

6.1.3 X-ray Testing Source

X-ray testing and imaging was carried out using a custom RadSource RS1800 X-ray generator operated by the KSU REAL laboratory, shown in Figure 6.4. The generator is a custom unit allowing for general flexibility of the x-ray tube operation parameters, and is equipped with a lead lined irradiation chamber and a shielded cable feed-through door. The generator emits from a variable current (1-10 mA) and variable potential (10-130 kV) tungsten anode x-ray tube with an anode angle of 30 degrees. To optimize x-ray transmission through the image subject, the generator was operated at its minimum current setting of 1 mA, and a potential range of 40-60 kV, depending on target composition. A 3D printed occluder made from ColorFabb nGen polystyrene was designed for x-ray imaging applications, also visible in Figure 6.4. The occluder serves to partially collimate the x-ray output flux, but primarily prevents excessive dose being imparted on peripheral components of the sensor PCB.



Figure 6.4: *Left: Custom RS-1800 X-ray generator located in the Radiological Engineering Analysis Laboratory. Right: An X-MSND sensor card in-situ in the RS1800 and close up picture showing X-MSND/Timepix assembly. The card is aligned with the 3D printed x-ray occluder, directly in line with the RS1800 conical x-ray output.*



Figure 6.5: *3D printed PLA cross, xy oriented, 100% infilled. Cross has 1.5 mm thick arms with a 1 mm radius fillet on all junctions, 15 mm thick (right). Nylon M4 Phillips head screw with brass threaded insert, nylon washer, steel washer, and nylon nut (middle). Female BNC bulkhead feed-through; zinc and copper construction with Teflon insulator between conductors (right).*

6.2 Imaging Subjects

Several radiography imaging subjects were made or identified that would exemplify the bimodal imaging capabilities of the X-MSND sensors. All subjects contain some amount of hydrogenous material to provide contrast for neutron imaging. Figure 6.5 identifies the subjects and describes their material composition and are referred to in the text as the “Cross”, “Screw”, and “BNC” subjects, named from left to right as shown. The cross subject is a 3D printed subject made from polylactic acid (PLA) plastic, and the remaining two subjects are objects of plastic and metal construction chosen for their mixture of large and small feature sizes.

6.3 Data Acquisition and Image Processing

6.3.1 Frame Data Processing

A general purpose MATLAB script was written to perform all of the necessary frame processing and image reconstruction routines, relying on the Image Processing Toolbox for cluster identification and analysis. The script reads integer array-formatted frame text files from a selected directory, and sequentially analyzes the identified clusters; parameters of inter-

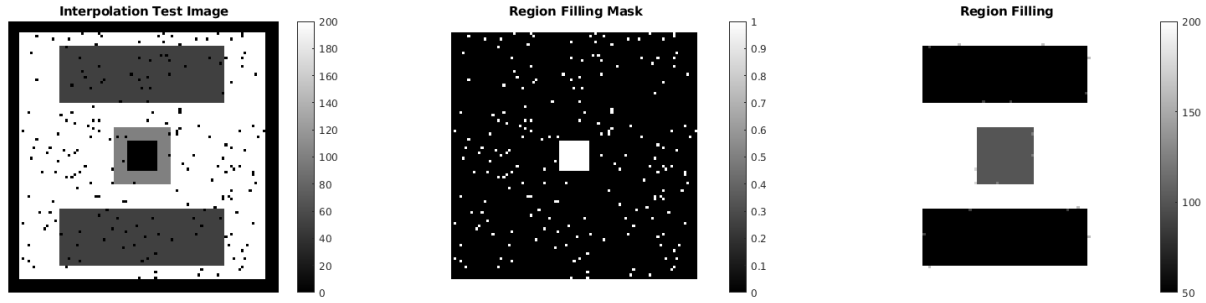


Figure 6.6: *Pixel interpolation demonstration, 100-by-100 pixels. Left: Test image imitating 3 imaged objects interrupted by randomly dispersed dead pixels with a large patch of dead pixels in the center object and the sensor edges dead. Middle: binary mask showing dead pixels to be filled. Right: Final corrected image (note the shift in color scale).*

est include Pixel and Cluster Charge, total Cluster Size span both in the x- and y-axis, Eccentricity (effectively the cluster roundness), and the Cluster Centroid position, both unweighted and weighted against per-pixel charge⁸¹. The script is capable of outputting all cluster and pixel data to either text-readable or compressed binary files for rapid recall of cluster metrics and images.

To account for dead pixels in the completed image, inward interpolation is performed on the zero pixels using the smooth 2D Laplace method. This problem is a type of Dirichlet boundary value problem, where the discrete boundary conditions are the values of the unmasked pixels⁸². An example of this technique being used on a small test image is shown in Figure 6.6. This type of region filling has the added benefit of filling dead sensor boundary pixels via extrapolation, which can not be accurately filled with linear interpolation or extrapolation alone.

Radiographs in the post processing code are generated via two possible methods. The first and simplest method of producing images is by generating a chargemap, where frames (and therefore full clusters) are overlaid atop each other, with their constituent pixels having a value equal to the ToT value reported by the PixetPro software. A byproduct of using full clusters is that non-uniformities in pixel front-end response across the sensor can produce artifacts in the final image; the threshold equalization does not account for variations that occur at energies higher than the baseline noise level, such as nonlinear pixel response near

the sensor boundaries for large clusters, variations caused by silicon etching defects, etc.. This necessitates that a “flat-field” correction be applied to the clusters. This is done by collecting a single integral frame of the particular radiological environment the image is to be collected in, but with no intervening material present. This collection should be done over a long period of time, such that the frame represents the sensor wide pixel response to a uniform field. Each frame collected for imaging is then corrected by pixel-wise multiplying each frame with the mean-normalized inverse of the flat field (i.e., a pixel with exactly mean sensitivity and flat field intensity will have a correction factor of one, less sensitive pixels will have a correction greater than one, and more sensitive pixels will have a correction less than one).

The second imaging type generates a hitmap by overlaying the weighted cluster centroid data, where each cluster per frame contributes unity weight given to a single pixel at the weighted centroid coordinate. The frames used in this type of imaging are also flat-field corrected, as variations in pixel ToT can skew the calculated cluster centroid toward more sensitive pixels active in the cluster. Depending on cluster size, this method allows for subpixel imaging as the cluster centroid coordinates can be calculated with subpixel accuracy, so long as the cluster has a span greater than a single pixel in either dimension. Integer multiples of the actual sensor dimensions are currently supported by the algorithm (512-by-512 subpixels, etc).

For easy loading and recalling of cluster data, the data processing algorithms were wrapped in a MATLAB application GUI, a screenshot of which can be seen in Figure 6.7. The GUI handles the input of cluster frames and processing of either frames in a directory, or can re-display frame data saved as a preprocessed binary file. The chargemap, hitmaps with various subpixel and interpolation schemes, pixel and cluster charge histograms, and cluster size metrics are also plotted. The interpreted MATLAB code can be found in Appendix B for both the multicore frame processing and GUI wrapper scripts.

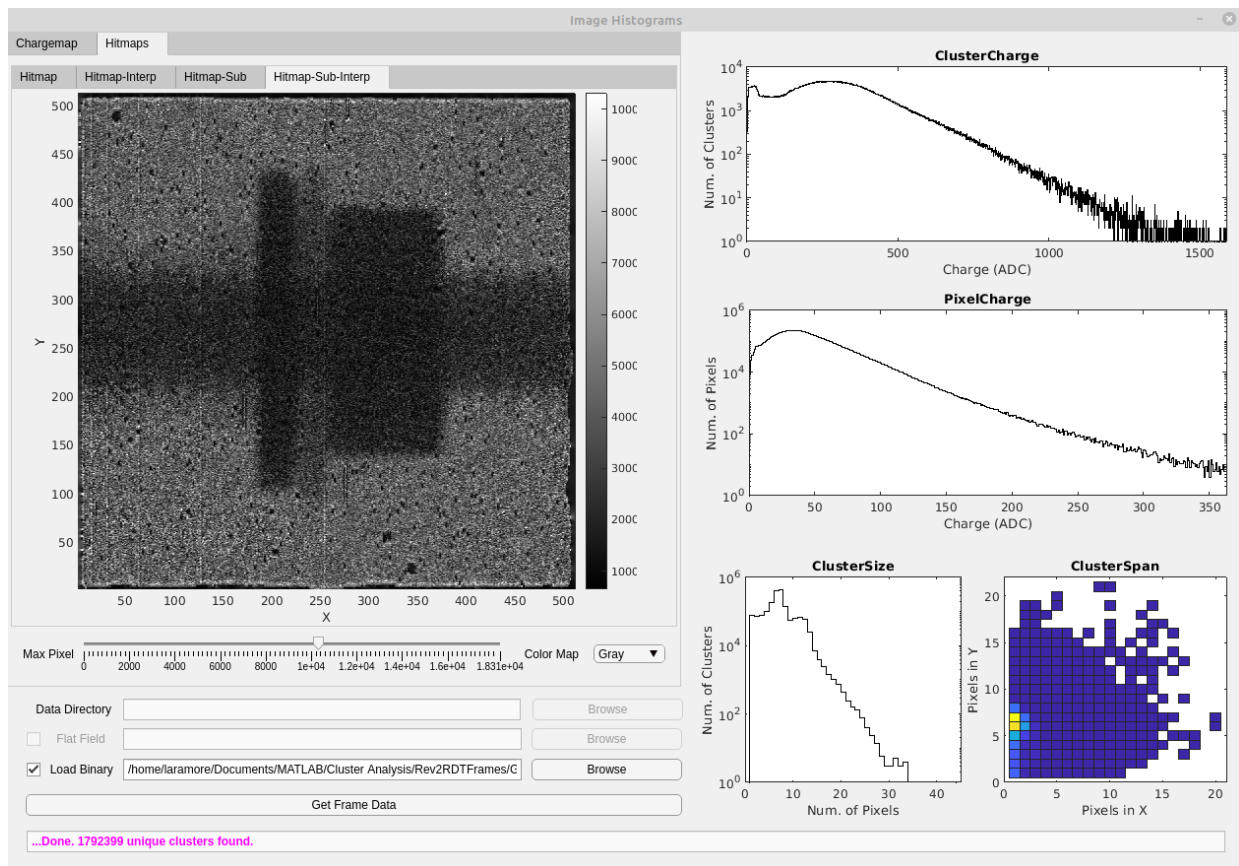


Figure 6.7: *MATLAB frame processing GUI, with a reconstructed neutron radiograph of the nylon screw subject loaded. The data was recalled as a binary file from a previous data processing.*

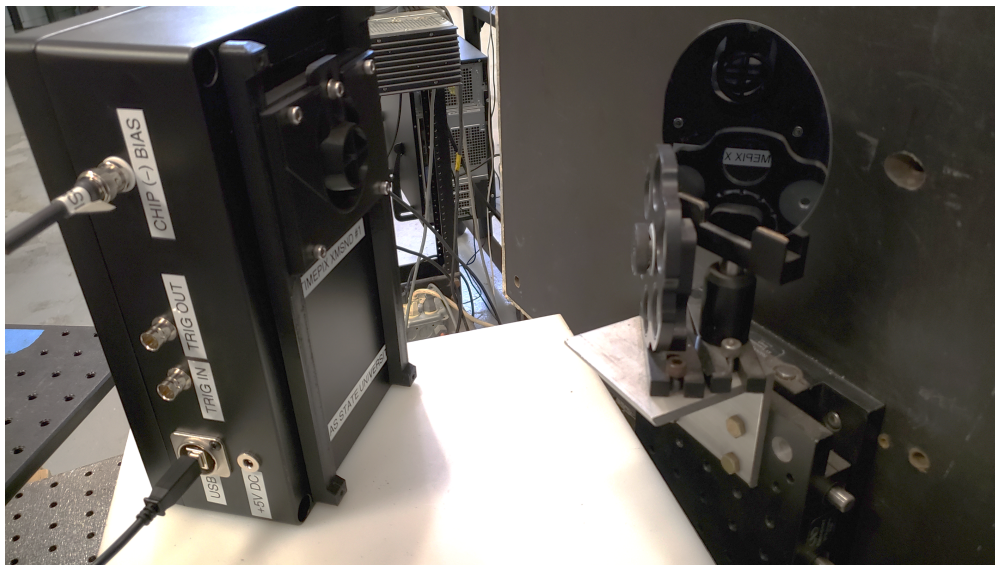


Figure 6.8: *Testing configuration of the X-MSND probecards at the NWBP during the first imaging test. The light tight test vehicle can be seen to the left, with the PLA cross subject affixed in front of the Mylar window.*

6.3.2 X-MSND Imaging Results

Following early functional testing with Revision 1 sensors fabricated in FY18, several changes were made to the typical operating parameters of the sensors. The trenched sensors were operated at a reverse bias of 300 V rather than the 200 V typical of Timepix sensors of this size. This change was supported by revised diode depletion simulations in COMSOL, as well as feedback from Advacam with respect to onsite X-MSND/Timepix assembly functional checks of Revision 2 sensors. Additionally, all trenched sensors were operated with an Ikcrumm feedback current of 10-15 DAC (approximately 1.6-2.3 nA/px).

Cluster data collected with X-MSND devices at the SEBP were captured at 10 ms per frame. Assuming a theoretical detection efficiency of 14% for X-MSND devices as determined in simulation, this gives a rough estimate of 27 neutron interactions resulting in clusters per frame while in the SEBP field. 50,000 frames were collected per object imaged per device to provide substantial data.

The first neutron images taken with the backfilled X-MSND sensors were acquired in the NWBP of the KSU TRIGA Reactor. Images were taken of the simple PLA cross subject. The physical configuration at the beamport can be seen in Figure 6.8. For this acquisition, the

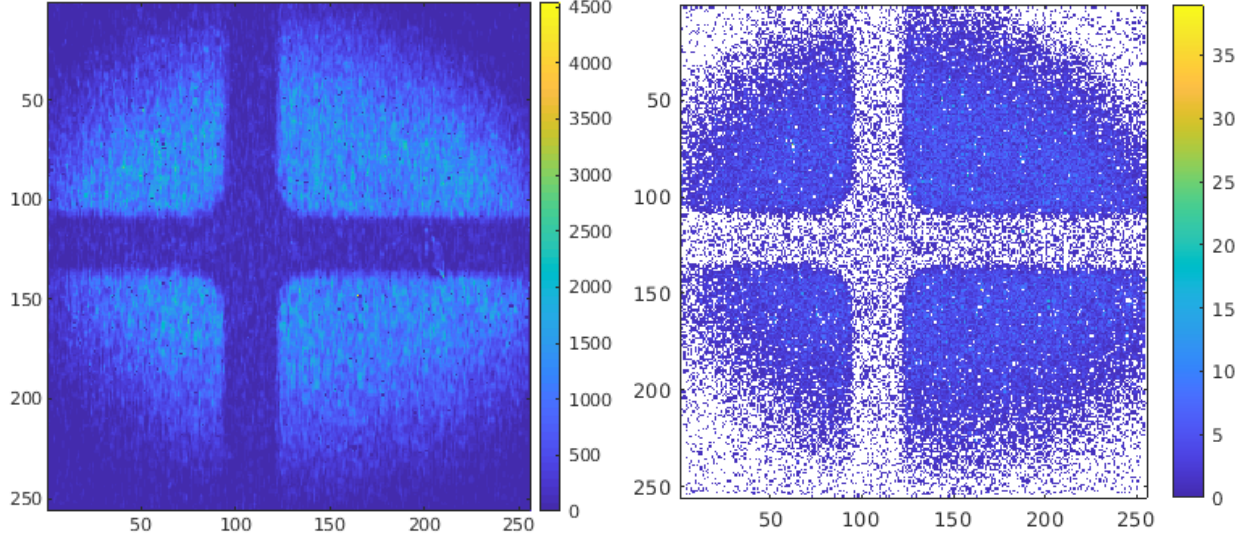


Figure 6.9: *Neutron images taken of the PLA cross subject. The effect of elongated clusters can be seen in the chargemap (left). The hitmap is generated by calculating the weighted centroid of each cluster and tallying it in the image map (right).*

reactor was operated at a conservative power of 10 kW(th), and 20,000 frames were collected with a frame acquisition time of 100 ms per frame. The resulting chargemap can be seen in Figure 6.9. This image was collected without flat field correction, and a small artifact can be seen approximately centered at coordinate 210, 170. Using cluster centroiding, the complimentary hitmap can be seen beside its chargemap in the same figure. In these first images, it was observed that the diameter of the neutron beam coming from the NWBP was slightly smaller than the chip dimensions. This left a large portion of the chip unusable, and would make post-processing significantly more difficult. This prompted moving the neutron imaging efforts to the wider SEBP for radiography of the remaining subjects.

The remaining neutron images were taken at the SEBP. First, a flat field image was collected in the neutron beam with no subject to provide a flat field correction map. This was used to correct for differences in the chip sensitivity across all pixels, and for spacial differences in the neutron field intensity at the SEBP. The flat-field image is collected in integral mode until a peak pixel intensity of 10^5 is observed. Then the BNC subject and the nylon screw subject were imaged at a reactor power of 25 kW(th). These were collected with a frame time of 50 ms for 50,000 frames each. The hitmaps generated by one of these chips

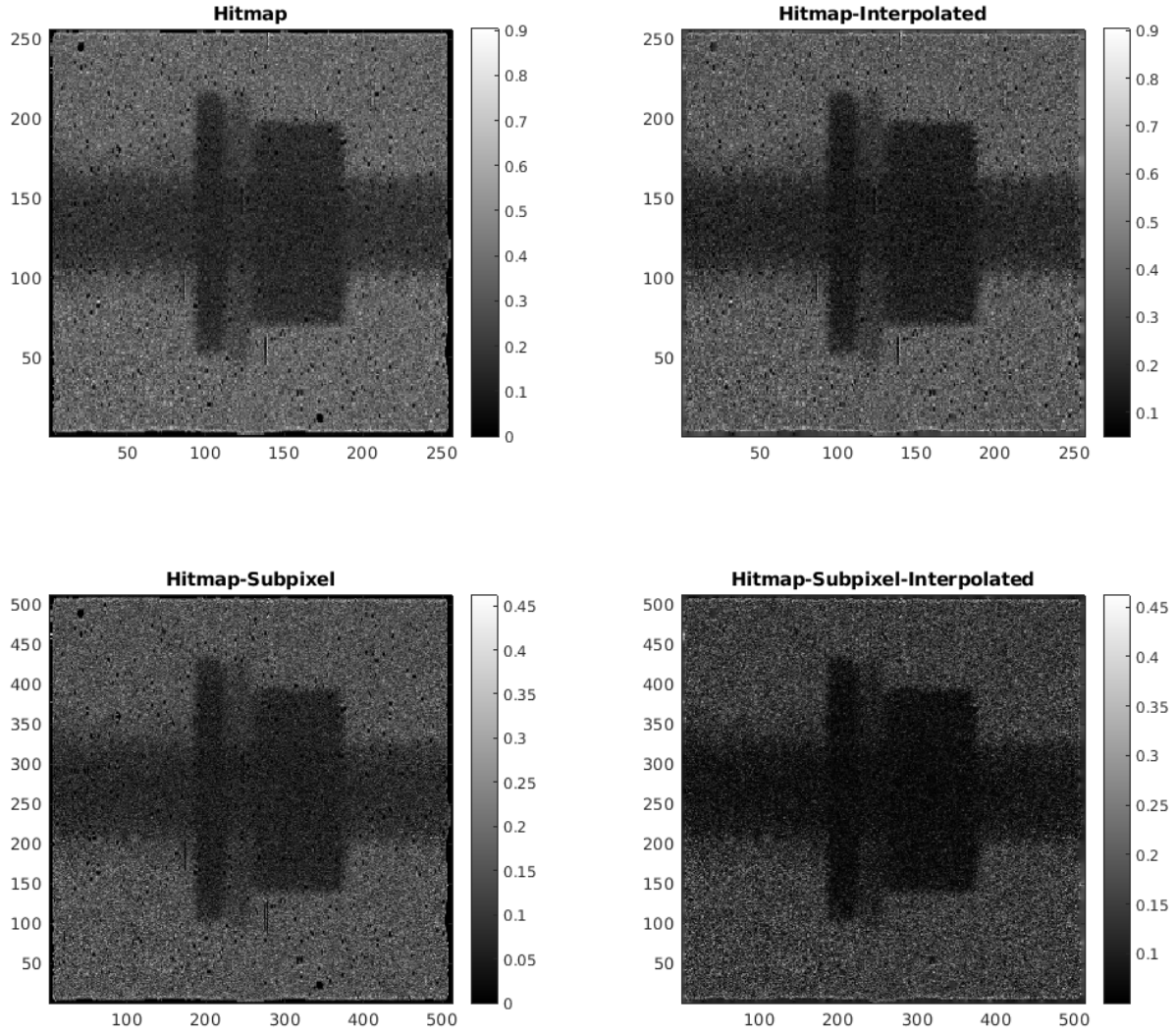


Figure 6.10: Neutron images taken of the nylon screw subject from figure 6.5. Interpolated images show the effect of Laplace inward interpolation in compensating for dead pixels.

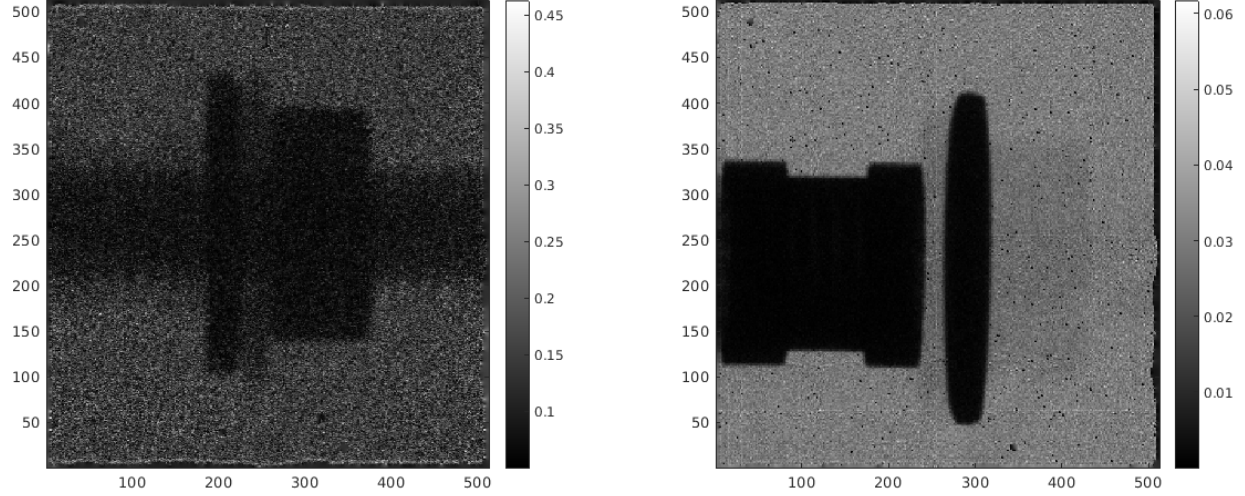


Figure 6.11: *Comparison of neutron picture (left) and x-ray picture (right) taken of the nylon screw subject. Nylon features contrast inversely to the brass and stainless between the images.*

for the nylon screw subject can be seen in Figure 6.10. The threads of the plastic screw can be seen in the image, as well as the nylon nut and washer. The brass threaded insert and steel washer were not seen in the images, as expected.

An important difference between the collection of neutron-induced clusters compared to x-ray clusters is that neutrons will generally require many more frames to image the same subject as with x-rays. This is due to the much larger cluster size resulting from the neutron induced interactions and the limitations of the cluster identification software. Accurate calculation of the cluster centroid relies on clear separation between clusters, which necessitates an increased frame rate or reduced neutron flux. However, the frame rate of the acquisition software is limited by the generation and saving of frame files, reducing the practical upper limit of frame rate to just under 100 frames per second saved.

X-Ray Data Collection and Imaging

X-ray images of the same subjects were also acquired. The optimal operating potential of the x-ray generator was found to be 60 kV, as this produced images with good contrast and optimal penetration into small, high- Z objects, without exposing the sensor and surrounding electronics to high-intensity radiation. A lead occluder was installed in the RS1800 to

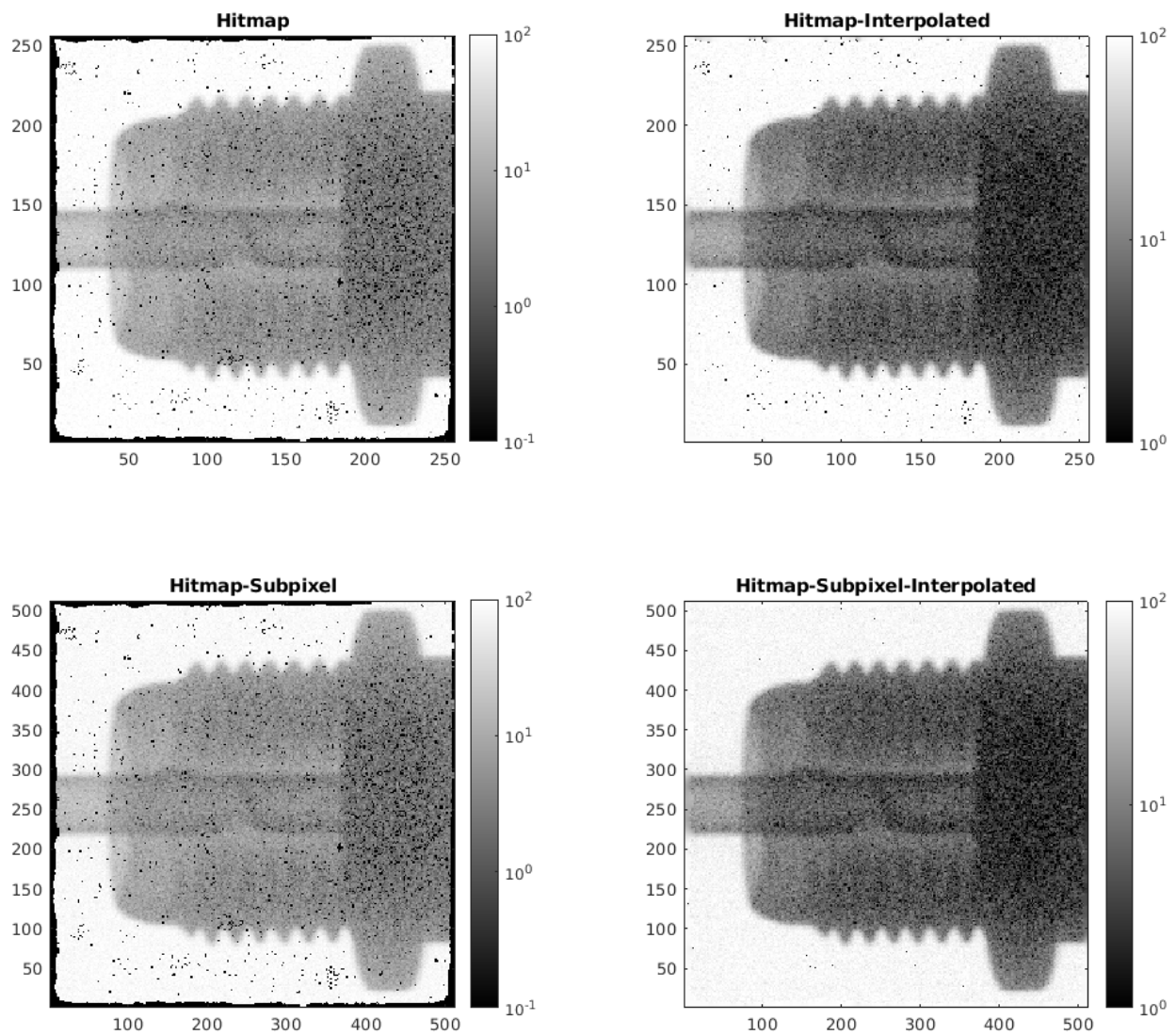


Figure 6.12: X-ray images of the BNC connector generated from x-ray cluster hitmap data. Subpixels are one-quarter full pixel size. Colormap is in log scale to improve visibility of interior features.

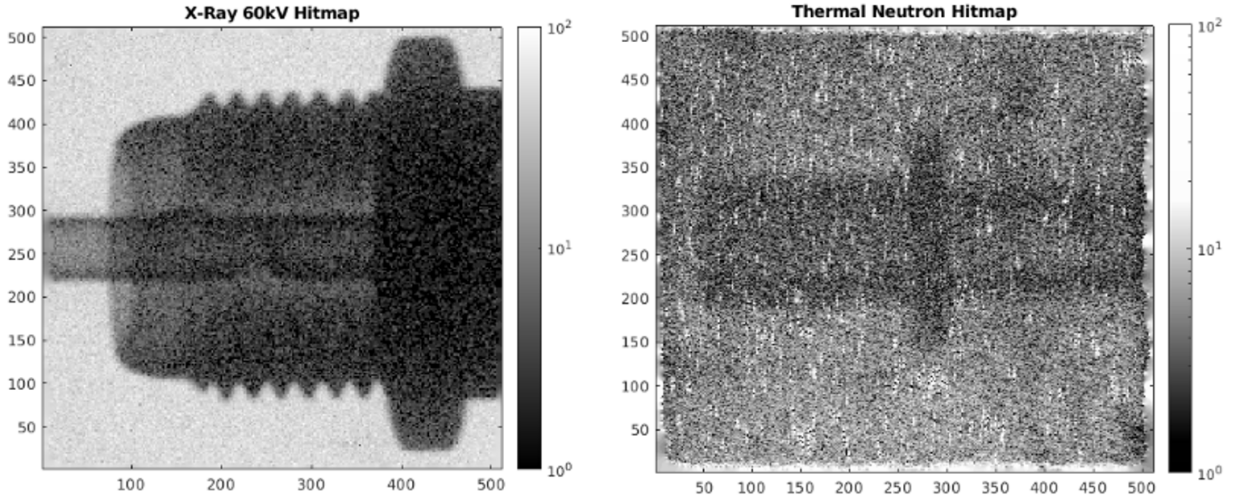


Figure 6.13: Comparison of *x-ray picture (left) neutron picture (right)* taken of the BNC subject. *Delrin plastic insulator is visible in the neutron image only.*

partially collimate the x-rays, provide a structure to hold imaging subjects, and to further reduce the dose imparted on non-imaging components of the sensor assembly. A flat-field image was also taken in the RS1800 with no subject, and used to correct for variation in pixel sensitivity and beam intensity. A comparison of images taken with neutron and x-rays of the nylon screw subject is shown in Figure 6.11. The structure of the nylon features are almost completely invisible in the x-ray image, which exhibits high contrast for the brass and stainless parts. The comparison is stark with the neutron image, in which the plastic components provide the greatest contrast. Images taken in the x-ray field of the BNC connector subject can be seen in Figure 6.12. The metallic construction of the connector provides good contrast with the plastic insulator in the interior of the subject. The central copper conductor can be seen easily through the outer zinc body, and minor features such as the crimp in the central conductor are also seen. Dark fringing at the outer edges of tubular components, such as the central conductor, correctly imply that the object is hollow. The threads of the BNC feedthrough are very clearly visible in the image as well. A comparison of neutron and x-ray images taken of the BNC feedthrough are shown in Figure 6.13. In the neutron image, the plastic insulator that separates the inner conductor and metallic housing of the connector is clearly visible as a hollow structure. In contrast to x-ray image,

no metallic components of the BNC connector are visible in the neutron image

6.4 Comparison of Simulation Results with Data

Cluster charge and pixel charge data was compiled for several of the trenched X-MSND sensors and compared to the raw simulated charge data. The surrogate model was then applied to match the simulated data to the measured for each serialized sensor; the determined coefficients and the resulting charge map for a subset of clusters is shown in Figure 6.14, corresponding to data collected with Timepix sensor D10-W0302. The final results of the ADC model for this assembly can be seen in Figure 6.15. The simulation and ADC model thus far shows good agreement with the measured data. It was found that there is some non-linearity in the very energetic pixel charges. Specifically, the simulation tended to overestimate the energy of the most energetic pixels. This could in part be explained by the Timepix flattening effect, where the ToT value of very energetic pixels is under-reported compared to the theoretical energy deposited^{78;83}. This effect is observed in electron collecting sensors, whereas hole collecting sensors experience a similar, more severe effect called the volcano effect. In flattening, the pixel energy across a cluster appears to have a flat top, rather than a rounded gaussian-like distribution as expected.

More cluster analysis will need to be performed in order to confirm if clusters produced in X-MSNDs exhibit similar, non-linear characteristics as other electron collecting hybrid Timepix sensors. It is also possible that the slow diffusion of the electrons is introducing non-linear ToT characteristics and ballistic deficit due to the long peaking time of the Timepix preamplifier. The diffusion may also introduce some level of sensor depth dependence, where interactions occurring closer to the top of the fin will diffuse slower than those occurring nearer to the bottom.

The span of the accumulated clusters is also shown in Figure 6.16 for both simulated and measured clusters, with both having a mean span of six pixels in the y -direction and only one pixel in the x -direction. One distinction between the measured and simulated is that the simulation overestimates the occurrence of pixels symmetric (odd numbered span)

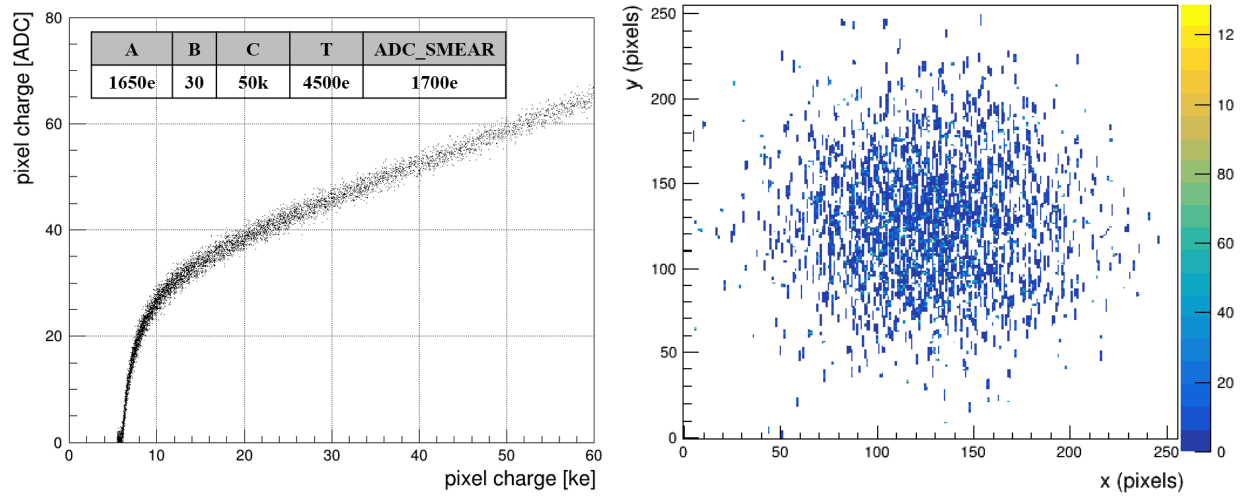


Figure 6.14: ADC calibration plot for X-MSNDs from neutron detection events for sensor chip D10-W0302 (left). The resultant clusters and charge are also shown in units of 1000's of charges for simulating the same sensor (right).

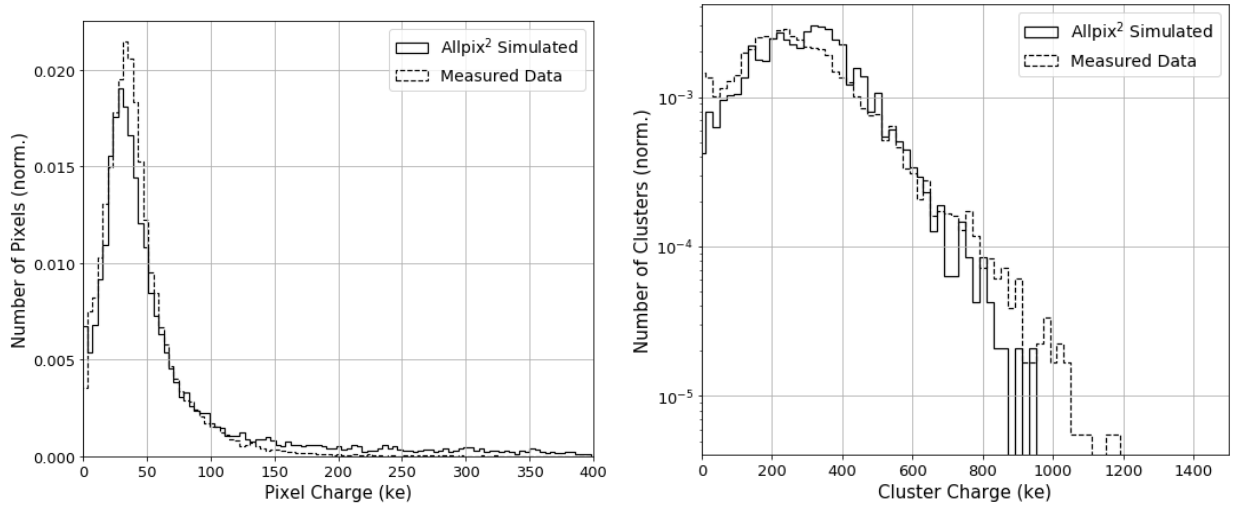


Figure 6.15: Drift time recorded for all electrons (left). This is accumulated and normalized to determine that the total drift time needed to collect 95% of the charges for a given event is just under 1000 ns (right).

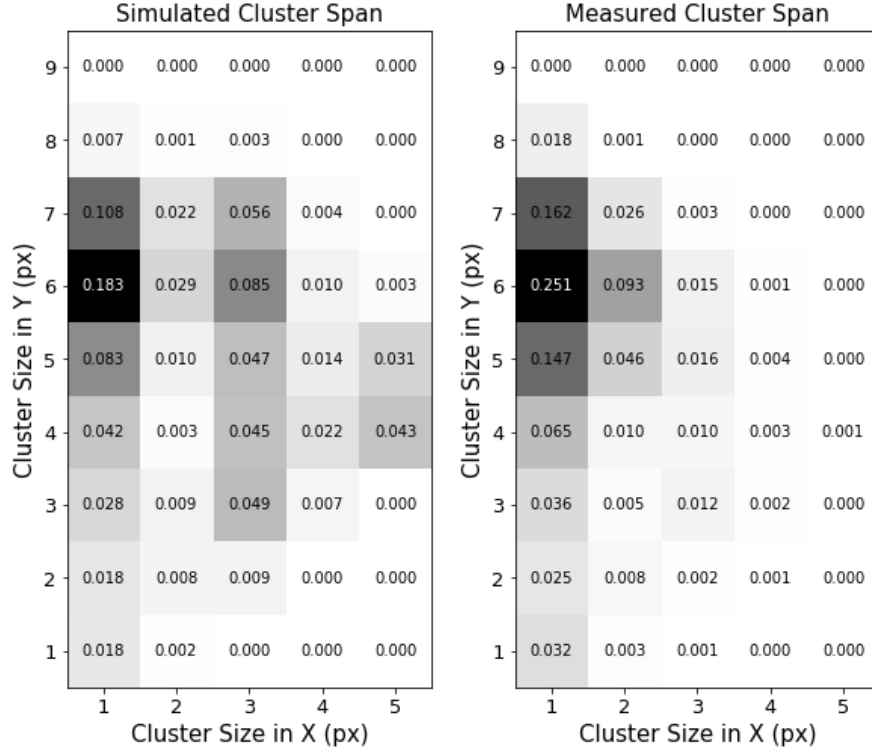


Figure 6.16: *The measured and simulated cluster span is also shown, where the strong elongation is evident in both.*

in the x -axis. This is likely a byproduct of the small symmetric weighting potential solution used in the simulation, which always calculates charge induction for five pixels along both axis. Alternatively, these results may imply that the X-MSND sensors are under producing round clusters.

Chapter 7

Discussions and Conclusion

7.1 Discussion of Simulation Methods and Successes

The simulation workflow outlined here showed significant success in simulating the detection characteristics of the X-MSND sensors, particularly in its ability to accurately model neutron induced clusters. The importance of implementing a physics based charge transport method is most evident in the capability of this simulation scheme to predict the elongated clusters generated by neutron detection events. This unique characteristic of conformally doped trenched sensors could not have been modeled by simple charge projection alone, as this feature requires treatment of the electric field in the trenches and fins separately. This feature was simulated before it was observed in actual sensors, lending credence to the importance of physics based simulation in the development of new technologies. Further, the explicit charge carrier drift is necessary in order to estimate the recombination losses of charge carriers diffusing into the fin sidewalls. These losses can be prominent in the low field regions of the fin depending, depending on the location of the interaction.

The inclusion of “surrogate” model correction of the non-linear energy response characteristic in simulations of Timepix hybrid sensors aided in producing pixel and cluster charge distributions that well replicated measured data. However, the charge carrier drift timing characteristics revealed another source of non-linearity that is unique to the conformally

doped micro-structured sensors: the nearly 1000 ns drift time of a potentially large fraction of the charge carriers is significantly longer than the 110 ns peaking time of the Timepix analog front end. The result of this is that the pixel charge will skew disproportionately higher depending on the location of the detection event; a more “spread out” charge cloud caused by slow diffusion near the top end of the fin will artificially increase the pulse pixel ToT. To properly model this phenomenon, transient simulations of charge transport that simulate induced current with respect to time at the pixel should be generated and processed. The ability to predict induced current with respect to time is a feature currently in development for Allpix² at the time of this writing. These current tables can then be convolved with the expected response of the Timepix analog front end to better predict the TOT per pixel.

7.2 Sensor Fabrication

The fabrication of the X-MSND sensors resulted in reasonable levels of success during the final set of manufactured devices. The percent yield of functional X-MSND assemblies was found to be between 33%-56%, depending on the processing company. The complex assembly process of such a detector requires several independent facilities and research groups, which necessarily introduces multiple points of failure. Further, determining the causes of failures with minimal diagnostic tooling required that a large number of changes be made to eliminate possible causes of failure.

The flip chip bonding process was determined to be the most likely cause of assembly failure, as the process requires a high level of precision and ideal chip conditions, with relatively little feedback through the process. It was determined that the surface conditions of the X-MSND, namely parallelism and flatness, were the features most likely to cause failures in the X-MSND flip-chip bonding process. This was evidenced in the canting of the sensors as a result of deviations in parallelism, which produced consistent failures or partial failures of devices. The disproportionately high success rate of non-encapsulated sensors helped to confirm this, as the lack of dry-film on the sensors exposed the flat-polished silicon surfaces on the trenched side of the sensor. Some research has begun on improving the surface conditions

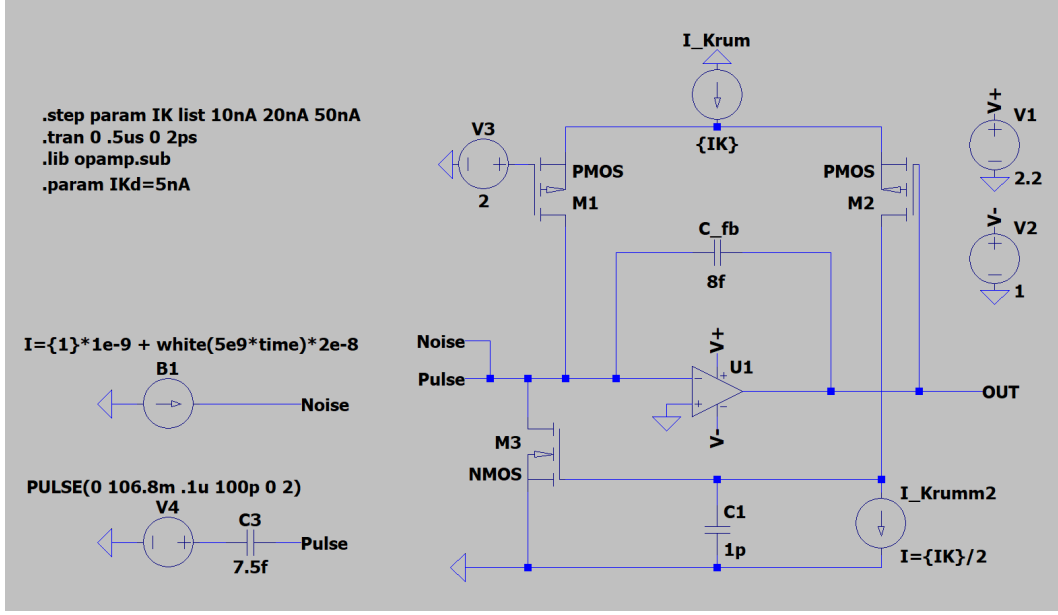


Figure 7.1: *LTSpice model of the Timepix single-pixel Krummenacher CSA circuit. Model supports variations in leakage current and pixel noise, and supports test pulses as shown, or an arbitrary input current waveform.*

of the dry-film epoxy by post application processes (extending cure time, polishing, etc.). Future developments in micro-structured Timepix sensors should correspondingly emphasize upper surface conditions to repeat the success found in this endeavor.

7.3 Future Work and Developments

7.3.1 Timepix Circuit Modelling

The potential significance of modeling the Krummenacher CSA circuit of the Timepix analog front-end was identified early in the X-MSND simulation process, a concern that was bolstered when the long charge collection time of the X-MSND sensor was predicted. As this simulation workflow is carried forward in future research endeavors, a greater emphasis will be put toward simulating the full Timepix CSA circuit as part of the ADC conversion function. Circuit analysis programs such as LTSpice or Matlab Simulink are capable of simulating the expected time-dependent characteristics and transfer function of an arbitrary circuit. An example of a simplified LTSpice model of the CSA circuit implemented in the

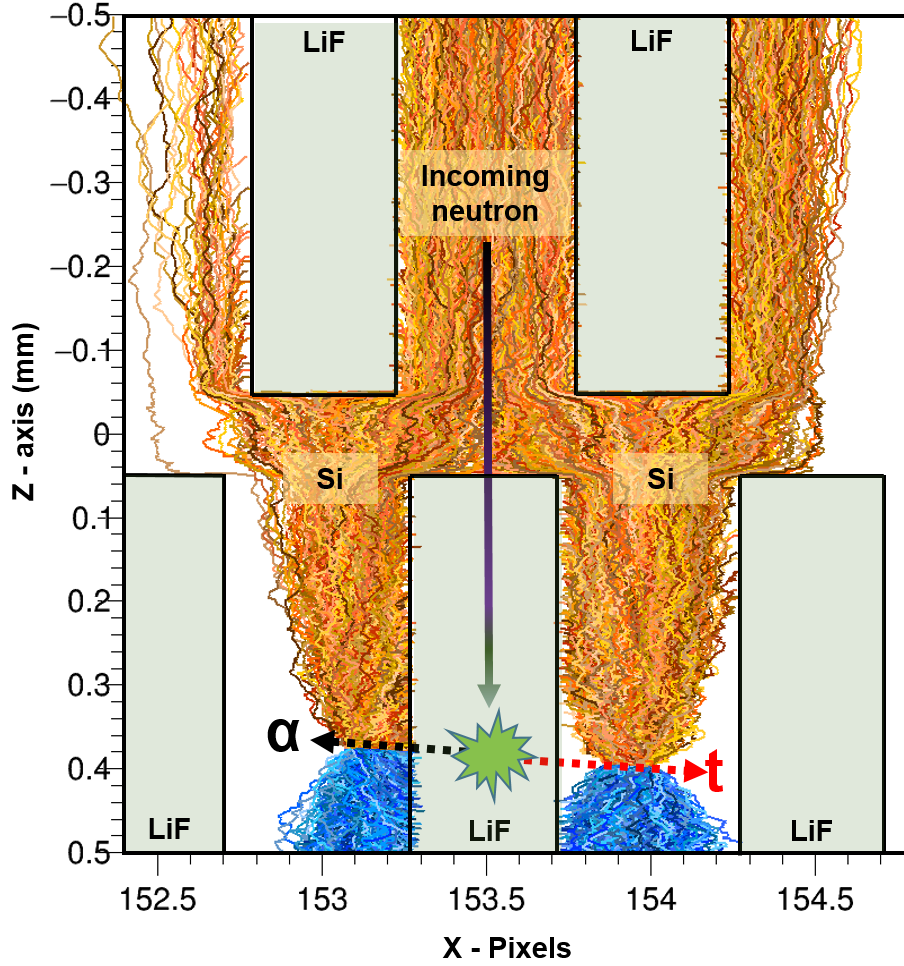


Figure 7.2: An X-DS-MSND sensor simulated in Allpix² undergoing a neutron detection event. Electron and hole tracks can be seen drifting towards their respective electrodes.

Timepix chip is shown in Figure 7.1.

7.3.2 Advanced Sensor Concepts

Advancements in X-MSND/Timepix technologies have continued beyond the original bi-modal sensor concept. A 1000 μm thick, dual sided variant of the MSND has been under development by RDT, Inc., and the KSU S.M.A.R.T. Laboratory, which is intended to have a significantly higher thermal neutron detection efficiency than conventional single sided MSNDs^{84–86}. A pixelated version of this sensor has been devised by the KSU X-MSND research group that will have a designed 60% thermal neutron detection efficiency, but forgoes

x-ray detection capabilities. The neutron counting sensors in development by RDT have been shown to have gamma rejection rates of one count in 10^6 gammas.

This fully trenched sensor requires significantly different boundary conditions to the single sided sensors, as conformally doped sidewalls along the entire thickness of the sensor would reduce the electric field in the majority of the sensor to near zero. Simulations of these sensors which follow a workflow similar to the one outlined in the body of this body are currently ongoing. A simulation of this X-DS-MSND sensor in operation can be seen in Figure 7.2, with the full X-MSND charge carrier transport workflow being implemented. This device will employ the Timepix 3 ASIC, which has is a data-driven rather than frame-driven readout that allows for significantly higher data throughput and provides operation modes for simultaneous time of arrival and time over threshold measurements.

7.3.3 Concluding Statement

The successful fabrication of the X-MSND imager represents an unprecedented increase in the neutron imaging efficiency of small profile neutron cameras. Furthermore, it has proven at least in part that micro-structured devices are capable of being integrated with pixelated readout sensors like the Timepix, which had not been demonstrated prior to this work.

The simulation workflow described here has shown to be successful in modeling the response of pixelated semiconductor detectors while relying minimally on empirical fitting. As such, this type of workflow is best suited to inform on the development and fabrication of novel imagers. Further, this workflow's independence of empirical data and inclusion of generic geometry modeling tools allows it to model any general configuration of sensor, micro-structured or otherwise.

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Appendix A

Additional Equations

A.1 Complimentary Error Function

The complimentary error function (sometimes called the Gaussian error function) describes the dopant profile as a function of depth in silicon for a substrate under a fixed surface dose. The error function is given as

$$\operatorname{erf}(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-t^2} dt \quad . \quad (\text{A.1})$$

The complimentary error function $\operatorname{erfc}(z)$ is simply

$$\operatorname{erfc}(z) = 1 - \operatorname{erf}(z) \quad . \quad (\text{A.2})$$

The error function, its argument z and its compliment may be complex, but are always real for the purposes of calculating a dopant profile.

A.2 Gaussian PDF for Sampling Thermal Diffusion

The displacement of a charge carrier due to Einstein diffusion can be randomly sampled from normal distribution centered at zero and having a standard deviation derived from the diffusion length of the charge carrier in the substrate being considered

$$\sigma_{diff} = \sqrt{\frac{2k_B T}{q} \mu_q t_s} \quad , \quad (\text{A.3})$$

where σ_{diff} is the standard deviation of the diffusion displacement, q is the total charge of the transport group, T is the absolute temperature of the substrate, k_B is Boltzmann's constant, μ_q is the mobility of the charge, and t_s is the incremented timestep. The normal distribution can therefore be expressed as

$$g(\sigma_{diff}, x) = \frac{1}{\sigma_{diff} \sqrt{2\pi}} e^{-\frac{1}{2} \left(\frac{x}{\sigma_{diff}} \right)^2} \quad (\text{A.4})$$

To sample this function, the inverse cumulative distribution function (CDF) of the normal distribution can be evaluated for a random number N between 0 and 1,

$$|s_{diff}| = CDF^{-1}(\sigma_{diff}, N) = \sigma_{diff} \sqrt{2} \operatorname{erfc}(2N - 1) \quad . \quad (\text{A.5})$$

where $|s_{diff}|$ is the magnitude of the charge carrier's displacement.

Appendix B

MATLAB Frame Processing Scripts

B.1 Frame Analysis Script

```
function [clusternum,CC,CS,CSX,CSY,PC,Roundness,Centroids,chargemap] = AnalyzeFrames(frame_dir, bin_file, flatfield_dir)

    if ~strcmp(flatfield_dir,'')
        flatfield = dlmread(flatfield_dir);
        flatfield2 = ones(256)./flatfield;
        flatfield2(flatfield2==Inf)=0;
        flatfield = flatfield2*mean(flatfield(flatfield>0));
    else
        flatfield = ones(256);
    end
    %%
    if isstring(bin_file)
        load(bin_file,'CC','CS','CSX','CSY','PC','Roundness','Centroids','chargemap');
        clusternum=size(CC);
    else
        filesin1 = dir(fullfile(frame_dir,'*.txt'));
        filesin2 = dir(fullfile(frame_dir,'*.pbf'));
        dinfo = vertcat(filesin1,filesin2);
        framenum = length(dinfo);
        clusternum = 0;chargemap = zeros(256);
        CC = cell(framenum,1);
        CS = cell(framenum,1);
        CSX = cell(framenum,1);
        CSY = cell(framenum,1);
        PC = cell(framenum,1);
        Roundness = cell(framenum,1);
        Centroids = cell(framenum,1);
        parpool(44);
        WaitMessage = parfor_wait(length(dinfo), 'Waitbar', true); ME=[];
        try
            parfor K = 1 : framenum
                thisfilename = [dinfo(K).folder '/' dinfo(K).name];
                if strcmp(dinfo(K).name(end-3:end),'.txt')
```

```

        frame=dlmread(thisfilename)
elseif strcmp(dinfo(K).name(end-3:end),'.pbf')
    fileID = fopen(thisfilename);
    frame = fread(fileID,[256 256], 'uint16');
    fclose(fileID);
end
if any(frame,"all")
    frame = frame.*flatfield;
    chargemap = chargemap + frame;
    BW = frame > 0;
    stats = regionprops('table',BW,frame,{'PixelValues','BoundingBox','WeightedCentroid','Eccentricity','Area','MeanIntensity'});
    clusternum = clusternum + height(stats);
    CC{K}=double(stats.Area.*stats.MeanIntensity);
    CS{K}=uint16(stats.Area);
    CSX{K}=uint16(stats.BoundingBox(:,3));
    CSY{K}=uint16(stats.BoundingBox(:,4));
    Roundness{K}=stats.Eccentricity;
    Centroids{K} = stats.WeightedCentroid;
    try
        PC{K}=double(cell2mat(stats.PixelValues));
    catch
        PC{K}=double(stats.PixelValues);
    end
end
end
WaitMessage.Send;
end
clusternum=max(clusternum);
CC = vertcat(CC{:}); CS = vertcat(CS{:});CSX = vertcat(CSX{:});
CSY = vertcat(CSY{:}); Roundness = vertcat(Roundness{:});Centroids = vertcat(Centroids{:});PC = vertcat(PC{:});
binout = strcat(frame_dir,'_Processed.mat');
save(binout,'CC','CS','CSX','CSY','PC','Roundness','Centroids','chargemap')
writematrix(chargemap,join([frame_dir "_chargemap.txt"],""));
WaitMessage.Destroy;
pause(0.1)
delete(gcf('nocreate'))
pause(0.1)
catch ME
end
if isempty(ME)
    delete(gcf('nocreate'))
    rethrow(ME)
end
end
end
end

```

B.2 Graphical Interface Script

```
classdef ClusterAnalyzer < matlab.apps.AppBase

% Properties that correspond to app components
properties (Access = public)

    UIFigure                matlab.ui.Figure
    PCAxes                  matlab.ui.control.UIAxes
    CSAxes                  matlab.ui.control.UIAxes
    LoadButton              matlab.ui.control.Button
    CCAxes                  matlab.ui.control.UIAxes
    TabGroup                 matlab.ui.container.TabGroup
    ChagemapTab              matlab.ui.container.Tab
    GridLayout2              matlab.ui.container.GridLayout
    ChargeMapAxes            matlab.ui.control.UIAxes
    Panel                    matlab.ui.container.Panel
    ColorMapDropDownLabel    matlab.ui.control.Label
    ColorMapDropDown         matlab.ui.control.DropDown
    MaxPixelLabel            matlab.ui.control.Label
    MaxPixelSlider           matlab.ui.control.Slider
    HitmapsTab               matlab.ui.container.Tab
    GridLayout               matlab.ui.container.GridLayout
    TabGroup2                matlab.ui.container.TabGroup
    HitmapTab                matlab.ui.container.Tab
    GridLayout3              matlab.ui.container.GridLayout
    HitmapAxes               matlab.ui.control.UIAxes
    HitmapInterpTab          matlab.ui.container.Tab
    GridLayout3_2            matlab.ui.container.GridLayout
    HitmapInterpAxes         matlab.ui.control.UIAxes
    HitmapSubTab             matlab.ui.container.Tab
    GridLayout3_3            matlab.ui.container.GridLayout
    HitmapSubAxes            matlab.ui.control.UIAxes
    HitmapSubInterpTab       matlab.ui.container.Tab
    GridLayout3_4            matlab.ui.container.GridLayout
    HitmapSubInterpAxes      matlab.ui.control.UIAxes
    Panel_2                  matlab.ui.container.Panel
    Panel_3                  matlab.ui.container.Panel
    ColorMapDropDown_2Label  matlab.ui.control.Label
    ColorMapDropDown_2       matlab.ui.control.DropDown
    MaxPixelLabel_2          matlab.ui.control.Label
    RangeSlider2             matlab.ui.control.Slider
    DataDirectoryEditFieldLabel matlab.ui.control.Label
    DataDirectoryEditField   matlab.ui.control.EditField
    LoadButton_2            matlab.ui.control.Button
    FlatFieldFileEditField   matlab.ui.control.EditField
    FlatFieldCheckBox        matlab.ui.control.CheckBox
    GetFrameDataButton       matlab.ui.control.Button
    LoadBinaryCheckBox      matlab.ui.control.CheckBox
    LoadBinaryField         matlab.ui.control.EditField
    LoadButton_3            matlab.ui.control.Button
    CSpanAxes                matlab.ui.control.UIAxes
    StatusField              matlab.ui.control.EditField
end

properties (Access = private)
    clusternum=0;
    ChagemapRaw = [];
    HitmapRaw=[];HitmapSubRaw=[]
end
```

```

CC=[];PC;
CS=[];CSX=[];CSY=[];
Roundness=[];
Centroids=[];
HighestPixel = 100000000;
HighestPixel2 = 100000000;
ChosenMap = gray(256)
ChosenMap2 = gray(256)
end
methods (Access = private)
function makehitmap(app)
    app.StatusField.Value = 'Generating Hitmaps...';
    pause(0.1)
    subpixeling = 2;
    hitmap = zeros(256);
    hitmapsub = zeros(256*subpixeling);
    for i = 1:app.clusternum
        x = ceil(app.Centroids(i,1)); y = ceil(app.Centroids(i,2));
        xsub = ceil(subpixeling*app.Centroids(i,1)-1); ysub= ceil(subpixeling*app.Centroids(i,2)-1);
        val = app.CC(i);
        hitmap(x,y) = hitmap(x,y) + val;
        if app.CSX(i) == 1 && app.CSY(i) == 1
            hitmapsub(xsub:xsub+subpixeling-1,ysub:ysub+subpixeling-1) = hitmapsub(xsub:xsub+subpixeling-1,ysub:ysub+subpixeling-1) + val;
        elseif app.CSX(i) == 1
            hitmapsub(xsub:xsub+subpixeling-1,ysub) = hitmapsub(xsub:xsub+subpixeling-1,ysub) + val;
        elseif app.CSY(i) == 1
            hitmapsub(xsub,ysub:ysub+subpixeling-1) = hitmapsub(xsub,ysub:ysub+subpixeling-1) + val;
        else
            hitmapsub(xsub,ysub) = hitmapsub(xsub,ysub) + val;
        end
    end
end
pctl = @(v,p) interp1(linspace(0.5/length(v), 1-0.5/length(v), length(v))', sort(v), p*0.01, 'spline');
clip =pctl(hitmap(:),99.9);
hitmap(hitmap>clip)=clip;
clip = pctl(app.ChargemapRaw(:),99.9);
app.ChargemapRaw(app.ChargemapRaw>clip)=clip;
app.HitmapRaw=hitmap;app.HitmapSubRaw=hitmapsub;
app.MaxPixelSlider.Limits=[0,max(app.ChargemapRaw,[],'all')];app.MaxPixelSlider.Value=max(app.ChargemapRaw,[],'all');
app.RangeSlider2.Limits=[0,max(app.HitmapRaw,[],'all')];app.RangeSlider2.Value=max(app.HitmapRaw,[],'all');
updateimage(app);
end
function updateimage(app)
    pctl = @(v,p) interp1(linspace(0.5/length(v), 1-0.5/length(v), length(v))', sort(v), p*0.01, 'spline');
    chargemap = app.ChargemapRaw;
    hitmap = app.HitmapRaw;
    hitmapsub = app.HitmapSubRaw;
    chargemap(chargemap>app.HighestPixel)=app.HighestPixel;
    hitmap(hitmap>app.HighestPixel2)=app.HighestPixel2;
    hitmapsub(hitmapsub>app.HighestPixel2)=app.HighestPixel2;
    hitmapfill = regionfill(hitmap',(hitmap<pctl(hitmap(:),5))');
    hitmapsubfill = regionfill(hitmapsub',(hitmapsub<pctl(hitmapsub(:),5))');
    app.StatusField.Value = 'Generating Plots...';
    imagesc(app.ChargeMapAxes,chargemap);set(app.ChargeMapAxes,'YDir','normal');app.ChargeMapAxes.XLim=[1,256];app.ChargeMapAxes.YLim=[1,256];
    imagesc(app.HitmapAxes,hitmap);app.HitmapAxes.XLim=[1,256];app.HitmapAxes.YLim=[1,256];set(app.HitmapAxes,'YDir','normal');
    imagesc(app.HitmapSubAxes,hitmapsub');app.HitmapSubAxes.XLim=[1,512];app.HitmapSubAxes.YLim=[1,512];set(app.HitmapSubAxes,'YDir','normal');
    imagesc(app.HitmapInterAxes,hitmapfill);app.HitmapInterAxes.XLim=[1,256];app.HitmapInterAxes.YLim=[1,256];set(app.HitmapInterAxes,'YDir','normal');

```

```

imagesc(app.HitmapSubInterpAxes,hitmapsubfill);app.HitmapSubInterpAxes.XLim=[1,512];app.HitmapSubInterpAxes.YLim=[1,512];set(app.HitmapSubInterpAxes,'YDir','n');
app.ChargeMapAxes.Colormap = app.ChosenMap;
app.HitmapAxes.Colormap = app.ChosenMap2;
app.HitmapSubAxes.Colormap = app.ChosenMap2;
app.HitmapInterpAxes.Colormap = app.ChosenMap2;
app.HitmapSubInterpAxes.Colormap = app.ChosenMap2;
colorbar(app.ChargeMapAxes);colorbar(app.HitmapAxes);colorbar(app.HitmapSubAxes);colorbar(app.HitmapInterpAxes);colorbar(app.HitmapSubInterpAxes);
drawnow;pause(0.05);
histogram(app.CCAxes, app.CC,"BinWidth",1,"DisplayStyle","stairs","EdgeColor",[0 0 0]);
histogram(app.PCAxes, app.PC,"BinWidth",1,"DisplayStyle","stairs","EdgeColor",[0 0 0]);
histogram2(app.CSpanAxes, app.CSX,app.CSY,'DisplayStyle','tile','ShowEmptyBins','off');
histogram(app.CSAxes, app.CS,"BinWidth",1,"DisplayStyle","stairs","EdgeColor",[0 0 0]);
drawnow;pause(0.1);
app.CCAxes.XLim = [0 pctl(app.CC,99.995)];
app.PCAxes.XLim = [0 pctl(app.PC,99.995)];
app.CSAxes.XLim = [0 max(app.CS,[],'all')];
app.CSpanAxes.XLim = [0 max(app.CSX,[],'all')+1];
app.CSpanAxes.YLim = [0 max(app.CSY,[],'all')+1];
set(app.CCAxes, 'YScale', 'log')
set(app.PCAxes, 'YScale', 'log')
set(app.CSAxes, 'YScale', 'log')
pause(0.1)
app.StatusField.Value = ['...Done. ' int2str(max(app.clusternum)) ' unique clusters found.'];
app.GetFrameDataButton.Enable=true;
app.ColorMapDropDown.Enable=true;app.ColorMapDropDown_2.Enable=true;
app.MaxPixelSlider.Enable=true;app.RangeSlider2.Enable=true;
drawnow;pause(0.1);
end
end
% Callbacks that handle component events
methods (Access = private)
% Code that executes after component creation
function startupFcn(app)
% Configure image axes
app.ChargeMapAxes.Colormap = app.ChosenMap;
app.HitmapAxes.Colormap = app.ChosenMap2;
app.HitmapSubAxes.Colormap = app.ChosenMap2;
app.HitmapInterpAxes.Colormap = app.ChosenMap2;
app.HitmapSubInterpAxes.Colormap = app.ChosenMap2;
colorbar(app.ChargeMapAxes);colorbar(app.HitmapAxes);colorbar(app.HitmapSubAxes);colorbar(app.HitmapInterpAxes);colorbar(app.HitmapSubInterpAxes);
drawnow;pause(0.1);
end
% Button pushed function: LoadButton
function LoadButtonPushed(app, event)
app.GetFrameDataButton.Enable=false;
% Display uigetfile dialog
dirname = uigetdir;
drawnow;pause(0.05);
% Make sure user didn't cancel uigetfile dialog
if (ischar(dirname))
app.DataDirectoryEditField.Value = dirname;
end
app.GetFrameDataButton.Enable=true;
end
% Button pushed function: LoadButton_2
function LoadButton_2Pushed(app, event)

```

```

app.GetFrameDataButton.Enable=false;
[file,path] = uigetfile('.txt');
drawnow;pause(0.05);
flatfilename = strcat(path,file);
if (ischar(flatfilename))
    app.FlatFieldFileEditField.Value = flatfilename;
end
app.GetFrameDataButton.Enable=true;
drawnow;pause(0.1)
end
% Value changed function: FlatFieldCheckBox
function FlatFieldCheckBoxValueChanged(app, event)
    value = app.FlatFieldCheckBox.Value;
    if (value == 1)
        app.FlatFieldFileEditField.Editable = true;
        app.LoadButton_2.Enable = true;
    else
        app.FlatFieldFileEditField.Editable = false;
        app.LoadButton_2.Enable = false;
    end
end
% Value changed function: LoadBinaryCheckBox
function LoadBinaryCheckBoxValueChanged(app, event)
    value = app.LoadBinaryCheckBox.Value;
    if (value == 1)
        app.FlatFieldCheckBox.Enable = false;
        app.DataDirectoryEditField.Editable = false;
        app.LoadButton.Enable = false;
        app.FlatFieldFileEditField.Editable = false;
        app.LoadButton_2.Enable = false;
        app.LoadBinaryField.Editable = true;
        app.LoadButton_3.Enable = true;
    else
        app.FlatFieldCheckBox.Enable = true;
        app.DataDirectoryEditField.Editable = true;
        app.LoadButton.Enable = true;
        if (app.FlatFieldCheckBox.Value == 1)
            app.FlatFieldFileEditField.Editable = true;
            app.LoadButton_2.Enable = true;
        end
        app.LoadBinaryField.Editable = false;
        app.LoadButton_3.Enable = false;
    end
end
% Button pushed function: GetFrameDataButton
function GetFrameDataButtonPushed(app, event)
    app.GetFrameDataButton.Enable=false;
    Goodpath = false;
    bin_file = convertCharsToStrings(app.LoadBinaryField.Value);
    frame_dir = app.DataDirectoryEditField.Value;
    switch app.LoadBinaryCheckBox.Value
        case 0
            bin_file = 0;
            if strcmp(frame_dir,'')
                app.StatusField.Value = 'No Directory Chosen';
                app.GetFrameDataButton.Enable=true;
            end
        end
    end
end

```

```

        else
            app.StatusField.Value = strcat('Evaluating Frame Data in Directory: ',frame_dir);
            Goodpath=true;
            pause(0.01)
        end
    case 1
        if strcmp(bin_file, '')
            app.StatusField.Value = 'No Binary File Chosen';
            app.GetFrameDataButton.Enable=true;
        else
            Goodpath=true;
            app.StatusField.Value = strcat('Loading Binary Data in File: ',bin_file);
            drawnow;pause(0.01)
        end
    end
end
if Goodpath
    flatfield_dir=app.FlatFieldFileEditField.Value;
    try
        [app.clusternum,app.CC,app.CS,app.CSX,app.CSY,app.PC,app.Roundness,app.Centroids,app.ChargemapRaw]=AnalyzeFrames(frame_dir,bin_file,flatfield_dir);
    catch
        app.StatusField.Value = 'Error with AnalyzeFrames: Bad File Format or Analysis Bug.';
    end
    makehitmap(app)
end
end
% Button pushed function: LoadButton_3
function LoadButton_3Pushed(app, event)
    app.GetFrameDataButton.Enable=false;
    % Display uigetfile dialog
    [file,path] = uigetfile('*.mat');
    drawnow;pause(0.05);
    bin_file = strcat(path,file);
    % Make sure user didn't cancel uigetfile dialog
    if (ischar(bin_file))
        app.LoadBinaryField.Value = bin_file;
    end
    app.GetFrameDataButton.Enable=true;
end
% Value changed function: ColorMapDropDown_2
function ColorMapDropDown_2ValueChanged(app, event)
    Choice = str2num(app.ColorMapDropDown_2.Value);
    switch Choice
        case 1
            app.ChosenMap2 = gray(256);
        case 2
            app.ChosenMap2 = jet(256);
        case 3
            app.ChosenMap2 = parula(256);
    end
    updateimage(app)
end
% Value changed function: ColorMapDropDown
function ColorMapDropDownValueChanged(app, event)
    Choice = str2num(app.ColorMapDropDown.Value);
    switch Choice
        case 1

```



```

        app.ChosenMap = gray(256);
    case 2
        app.ChosenMap = jet(256);
    case 3
        app.ChosenMap = parula(256);
    end
    updateimage(app)
end
% Value changed function: MaxPixelSlider
function MaxPixelSliderValueChanged(app, event)
    pause(0.5)
    app.HighestPixel = app.MaxPixelSlider.Value;
    updateimage(app);
end
% Value changed function: RangeSlider2
function RangeSlider2ValueChanged(app, event)
    pause(0.5)
    app.HighestPixel2 = app.RangeSlider2.Value;
    updateimage(app);
end
% Selection change function: TabGroup, TabGroup2
function TabBufferSelectionChanged(app, event)
    drawnow; pause(0.05);
end
end
% Component initialization
methods (Access = private)
    % Create UIFigure and components
    function createComponents(app)
        % Create UIFigure and hide until all components are created
        app UIFigure = uifigure('Visible', 'off');
        app UIFigure.AutoResizeChildren = 'off';
        app UIFigure.Position = [100 100 1259 855];
        app UIFigure.Name = 'Image Histograms';
        app UIFigure.Resize = 'off';
        % Create PCAxes
        app.PCAxes = uiaxes(app UIFigure);
        title(app.PCAxes, 'PixelCharge')
        xlabel(app.PCAxes, 'Charge (ADC)')
        ylabel(app.PCAxes, 'Num. of Pixels')
        app.PCAxes.XLim = [0 255];
        app.PCAxes.Box = 'on';
        app.PCAxes.Position = [708 348 537 246];
        % Create CSAxes
        app.CSAxes = uiaxes(app UIFigure);
        title(app.CSAxes, 'ClusterSize')
        xlabel(app.CSAxes, 'Num. of Pixels')
        ylabel(app.CSAxes, 'Num. of Clusters')
        app.CSAxes.XLim = [0 255];
        app.CSAxes.Box = 'on';
        app.CSAxes.Position = [704 57 271 266];
        % Create LoadButton
        app.LoadButton = uibutton(app UIFigure, 'push');
        app.LoadButton.ButtonPushedFcn = createCallbackFcn(app, @LoadButtonPushed, true);
        app.LoadButton.Position = [535 157 153 22];
        app.LoadButton.Text = 'Browse';
    end
end

```

```

% Create CCAxes
app.CCAxes = uiaxes(app.UIFigure);
title(app.CCAxes, 'ClusterCharge')
xlabel(app.CCAxes, 'Charge (ADC)')
ylabel(app.CCAxes, 'Num. of Clusters')
app.CCAxes.XLim = [0 1];
app.CCAxes.Box = 'on';
app.CCAxes.Position = [706 606 539 235];
% Create TabGroup
app.TabGroup = uitabgroup(app.UIFigure);
app.TabGroup.AutoResizeChildren = 'off';
app.TabGroup.SelectionChangedFcn = createCallbackFcn(app, @TabBufferSelectionChanged, true);
app.TabGroup.Interruptible = 'off';
app.TabGroup.Position = [1 191 685 665];
% Create ChargemapTab
app.ChargemapTab = uitab(app.TabGroup);
app.ChargemapTab.Title = 'Chargemap';
app.ChargemapTab.BusyAction = 'cancel';
app.ChargemapTab.Interruptible = 'off';
% Create GridLayout2
app.GridLayout2 = uigridlayout(app.ChargemapTab);
app.GridLayout2.ColumnWidth = {'1x'};
app.GridLayout2.RowHeight = {'30x', 40};
% Create ChargeMapAxes
app.ChargeMapAxes = uiaxes(app.GridLayout2);
xlabel(app.ChargeMapAxes, 'X')
ylabel(app.ChargeMapAxes, 'Y')
app.ChargeMapAxes.Box = 'on';
app.ChargeMapAxes.Layout.Row = 1;
app.ChargeMapAxes.Layout.Column = 1;
% Create Panel
app.Panel = uipanel(app.GridLayout2);
app.Panel.BorderType = 'none';
app.Panel.Layout.Row = 2;
app.Panel.Layout.Column = 1;
% Create ColorMapDropDownLabel
app.ColorMapDropDownLabel = uilabel(app.Panel);
app.ColorMapDropDownLabel.HorizontalAlignment = 'right';
app.ColorMapDropDownLabel.Position = [513 8 59 22];
app.ColorMapDropDownLabel.Text = 'Color Map';
% Create ColorMapDropDown
app.ColorMapDropDown = uidropdown(app.Panel);
app.ColorMapDropDown.Items = {'Gray', 'Jet', 'Parula'};
app.ColorMapDropDown.ItemsData = {'1', '2', '3'};
app.ColorMapDropDown.ValueChangedFcn = createCallbackFcn(app, @ColorMapDropDownValueChanged, true);
app.ColorMapDropDown.Enable = 'off';
app.ColorMapDropDown.Position = [586 10 66 19];
app.ColorMapDropDown.Value = '1';
% Create MaxPixelLabel
app.MaxPixelLabel = uilabel(app.Panel);
app.MaxPixelLabel.HorizontalAlignment = 'right';
app.MaxPixelLabel.Position = [9 9 58 22];
app.MaxPixelLabel.Text = 'Max Pixel';
% Create MaxPixelSlider
app.MaxPixelSlider = uislider(app.Panel);
app.MaxPixelSlider.ValueChangedFcn = createCallbackFcn(app, @MaxPixelSliderValueChanged, true);

```

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app.MaxPixelSlider.Enable = 'off';
app.MaxPixelSlider.FontSize = 10;
app.MaxPixelSlider.Position = [82 28 423 3];
% Create HitmapsTab
app.HitmapsTab = uitab(app.TabGroup);
app.HitmapsTab.Title = 'Hitmaps';
app.HitmapsTab.BusyAction = 'cancel';
app.HitmapsTab.Interruptible = 'off';
% Create GridLayout
app.GridLayout = uigridlayout(app.HitmapsTab);
app.GridLayout.ColumnWidth = {'1x'};
app.GridLayout.RowHeight = {'1x', 40};
app.GridLayout.Padding = [3 10 3 10];
% Create TabGroup2
app.TabGroup2 = uitabgroup(app.GridLayout);
app.TabGroup2.SelectionChangedFcn = createCallbackFcn(app, @TabBufferSelectionChanged, true);
app.TabGroup2.Interruptible = 'off';
app.TabGroup2.Layout.Row = 1;
app.TabGroup2.Layout.Column = 1;
% Create HitmapTab
app.HitmapTab = uitab(app.TabGroup2);
app.HitmapTab.Title = 'Hitmap';
app.HitmapTab.BusyAction = 'cancel';
app.HitmapTab.Interruptible = 'off';
% Create GridLayout3
app.GridLayout3 = uigridlayout(app.HitmapTab);
app.GridLayout3.ColumnWidth = {'1x'};
app.GridLayout3.RowHeight = {'1x'};
app.GridLayout3.Padding = [20 0 40 0];
% Create HitmapAxes
app.HitmapAxes = uiaxes(app.GridLayout3);
title(app.HitmapAxes, '')
xlabel(app.HitmapAxes, 'X')
ylabel(app.HitmapAxes, 'Y')
app.HitmapAxes.ClippingStyle = 'rectangle';
app.HitmapAxes.Box = 'on';
app.HitmapAxes.BoxStyle = 'full';
app.HitmapAxes.Layout.Row = 1;
app.HitmapAxes.Layout.Column = 1;
% Create HitmapInterpTab
app.HitmapInterpTab = uitab(app.TabGroup2);
app.HitmapInterpTab.Title = 'Hitmap-Interp';
app.HitmapInterpTab.BusyAction = 'cancel';
app.HitmapInterpTab.Interruptible = 'off';
% Create GridLayout3_2
app.GridLayout3_2 = uigridlayout(app.HitmapInterpTab);
app.GridLayout3_2.ColumnWidth = {'1x'};
app.GridLayout3_2.RowHeight = {'1x'};
app.GridLayout3_2.Padding = [20 0 40 0];
% Create HitmapInterpAxes
app.HitmapInterpAxes = uiaxes(app.GridLayout3_2);
title(app.HitmapInterpAxes, '')
xlabel(app.HitmapInterpAxes, 'X')
ylabel(app.HitmapInterpAxes, 'Y')
app.HitmapInterpAxes.Box = 'on';
app.HitmapInterpAxes.Layout.Row = 1;

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app.HitmapInterAxes.Layout.Column = 1;
% Create HitmapSubTab
app.HitmapSubTab = uitab(app.TabGroup2);
app.HitmapSubTab.Title = 'Hitmap-Sub';
app.HitmapSubTab.BusyAction = 'cancel';
app.HitmapSubTab.Interruptible = 'off';
% Create GridLayout3_3
app.GridLayout3_3 = uigridlayout(app.HitmapSubTab);
app.GridLayout3_3.ColumnWidth = {'1x'};
app.GridLayout3_3.RowHeight = {'1x'};
app.GridLayout3_3.Padding = [20 0 40 0];
% Create HitmapSubAxes
app.HitmapSubAxes = uiaxes(app.GridLayout3_3);
title(app.HitmapSubAxes, '')
xlabel(app.HitmapSubAxes, 'X')
ylabel(app.HitmapSubAxes, 'Y')
app.HitmapSubAxes.Box = 'on';
app.HitmapSubAxes.Layout.Row = 1;
app.HitmapSubAxes.Layout.Column = 1;
% Create HitmapSubInterTab
app.HitmapSubInterTab = uitab(app.TabGroup2);
app.HitmapSubInterTab.Title = 'Hitmap-Sub-Interp';
app.HitmapSubInterTab.BusyAction = 'cancel';
app.HitmapSubInterTab.Interruptible = 'off';
% Create GridLayout3_4
app.GridLayout3_4 = uigridlayout(app.HitmapSubInterTab);
app.GridLayout3_4.ColumnWidth = {'1x'};
app.GridLayout3_4.RowHeight = {'1x'};
app.GridLayout3_4.Padding = [20 0 40 0];
% Create HitmapSubInterAxes
app.HitmapSubInterAxes = uiaxes(app.GridLayout3_4);
title(app.HitmapSubInterAxes, '')
xlabel(app.HitmapSubInterAxes, 'X')
ylabel(app.HitmapSubInterAxes, 'Y')
app.HitmapSubInterAxes.Box = 'on';
app.HitmapSubInterAxes.Layout.Row = 1;
app.HitmapSubInterAxes.Layout.Column = 1;
% Create Panel_2
app.Panel_2 = uipanel(app.GridLayout);
app.Panel_2.BorderType = 'none';
app.Panel_2.Layout.Row = 2;
app.Panel_2.Layout.Column = 1;
% Create Panel_3
app.Panel_3 = uipanel(app.Panel_2);
app.Panel_3.BorderType = 'none';
app.Panel_3.Position = [2 -1 664 45];
% Create ColorMapDropDown_2Label
app.ColorMapDropDown_2Label = uilabel(app.Panel_3);
app.ColorMapDropDown_2Label.HorizontalAlignment = 'right';
app.ColorMapDropDown_2Label.Position = [512 14 65 22];
app.ColorMapDropDown_2Label.Text = 'Color Map';
% Create ColorMapDropDown_2
app.ColorMapDropDown_2 = uidropdown(app.Panel_3);
app.ColorMapDropDown_2.Items = {'Gray', 'Jet', 'Parula'};
app.ColorMapDropDown_2.ItemsData = {'1', '2', '3'};
app.ColorMapDropDown_2.ValueChangedFcn = createCallbackFcn(app, @ColorMapDropDown_2ValueChanged, true);

```

```

app.ColorMapDropDown_2.Enable = 'off';
app.ColorMapDropDown_2.Position = [592 16 73 19];
app.ColorMapDropDown_2.Value = '1';
% Create MaxPixelLabel_2
app.MaxPixelLabel_2 = uilabel(app.Panel_3);
app.MaxPixelLabel_2.HorizontalAlignment = 'right';
app.MaxPixelLabel_2.Position = [6 14 58 22];
app.MaxPixelLabel_2.Text = 'Max Pixel';
% Create RangeSlider2
app.RangeSlider2 = uislider(app.Panel_3);
app.RangeSlider2.ValueChangedFcn = createCallbackFcn(app, @RangeSlider2ValueChanged, true);
app.RangeSlider2.BusyAction = 'cancel';
app.RangeSlider2.Enable = 'off';
app.RangeSlider2.FontSize = 10;
app.RangeSlider2.Position = [74 34 423 3];
% Create DataDirectoryEditFieldLabel
app.DataDirectoryEditFieldLabel = uilabel(app.UIFigure);
app.DataDirectoryEditFieldLabel.HorizontalAlignment = 'right';
app.DataDirectoryEditFieldLabel.Position = [20 157 87 22];
app.DataDirectoryEditFieldLabel.Text = 'Data Directory';
% Create DataDirectoryEditField
app.DataDirectoryEditField = uieditfield(app.UIFigure, 'text');
app.DataDirectoryEditField.Position = [119 157 404 22];
% Create LoadButton_2
app.LoadButton_2 = uibutton(app.UIFigure, 'push');
app.LoadButton_2.ButtonPushedFcn = createCallbackFcn(app, @LoadButton_2Pushed, true);
app.LoadButton_2.Enable = 'off';
app.LoadButton_2.Position = [534 127 153 22];
app.LoadButton_2.Text = 'Browse';
% Create FlatFieldFileEditField
app.FlatFieldFileEditField = uieditfield(app.UIFigure, 'text');
app.FlatFieldFileEditField.Editable = 'off';
app.FlatFieldFileEditField.Position = [119 127 405 22];
% Create FlatFieldCheckBox
app.FlatFieldCheckBox = uicheckbox(app.UIFigure);
app.FlatFieldCheckBox.ValueChangedFcn = createCallbackFcn(app, @FlatFieldCheckBoxValueChanged, true);
app.FlatFieldCheckBox.Text = 'Flat Field';
app.FlatFieldCheckBox.Position = [21 127 89 22];
% Create GetFrameDataButton
app.GetFrameDataButton = uibutton(app.UIFigure, 'push');
app.GetFrameDataButton.ButtonPushedFcn = createCallbackFcn(app, @GetFrameDataButtonPushed, true);
app.GetFrameDataButton.Position = [20 60 667 22];
app.GetFrameDataButton.Text = 'Get Frame Data';
% Create LoadBinaryCheckBox
app.LoadBinaryCheckBox = uicheckbox(app.UIFigure);
app.LoadBinaryCheckBox.ValueChangedFcn = createCallbackFcn(app, @LoadBinaryCheckBoxValueChanged, true);
app.LoadBinaryCheckBox.Text = 'Load Binary';
app.LoadBinaryCheckBox.Position = [21 96 95 22];
% Create LoadBinaryField
app.LoadBinaryField = uieditfield(app.UIFigure, 'text');
app.LoadBinaryField.Editable = 'off';
app.LoadBinaryField.Position = [119 96 405 22];
% Create LoadButton_3
app.LoadButton_3 = uibutton(app.UIFigure, 'push');
app.LoadButton_3.ButtonPushedFcn = createCallbackFcn(app, @LoadButton_3Pushed, true);
app.LoadButton_3.Enable = 'off';

```

```

        app.LoadButton_3.Position = [534 96 153 22];
        app.LoadButton_3.Text = 'Browse';
        % Create CSpanAxes
        app.CSpanAxes = uiaxes(app.UIFigure);
        title(app.CSpanAxes, 'ClusterSpan')
        xlabel(app.CSpanAxes, 'Pixels in X')
        ylabel(app.CSpanAxes, 'Pixels in Y')
        app.CSpanAxes.XLim = [0 1];
        app.CSpanAxes.Box = 'on';
        app.CSpanAxes.Position = [974 57 271 266];
        % Create StatusField
        app.StatusField = uieditfield(app.UIFigure, 'text');
        app.StatusField.Editable = 'off';
        app.StatusField.FontWeight = 'bold';
        app.StatusField.FontColor = [1 0 1];
        app.StatusField.Position = [21 23 1218 22];
        % Show the figure after all components are created
        app.UIFigure.Visible = 'on';
    end
end

% App creation and deletion
methods (Access = public)
    % Construct app
    function app = ClusterAnalyzer
        % Create UIFigure and components
        createComponents(app)

        % Register the app with App Designer
        registerApp(app, app.UIFigure)

        % Execute the startup function
        runStartupFcn(app, @startupFcn)
        if nargin == 0
            clear app
        end
    end

    % Code that executes before app deletion
    function delete(app)
        % Delete UIFigure when app is deleted
        delete(app.UIFigure)
    end
end
end
end

```