Optimizing Silicon Chip Thickness and Pixel Activation Threshold in Scanning Transmission Electron Microscope Detectors

CNF Summer Student: Himani Anilkumar Mishra
Student Affiliation: School of Applied and Engineering Physics, Cornell University

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Principal Investigator(s): David A. Muller, School of Applied and Engineering Physics, Cornell University

Mentor(s): Steven E. Zeltmann, Platform for the Accelerated Realization, Analysis, and Discovery of Interface Materials (PARADIM), Cornell University

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Contact: ham74@cornell.edu, steven.zeltmann@cornell.edu, david.a.muller@cornell.edu

Summer Program Website(s): https://cnf.cornell.edu/education/reu

Research Group Website: https://muller.research.engineering.cornell.edu/

Abstract:

Electron ptychography is a scanning transmission electron microscopy (STEM) technique used to achieve high-quality three-dimensional characterization of rapidly shrinking semiconductor devices[1]. We aim to design dose-efficient STEM detectors that use the maximal amount of generated signal. In STEM, a focused beam of electrons are either transmitted and/or scattered by our material of interest. The transmitted electrons then encounter a pixel array detector that is composed of a sensor layer, which is bump-bonded to an ASIC[2,3]. The silicon sensor layer is divided into pixels that record the amount of energy deposited by the electrons. Each pixel has a threshold of activation. If an electron deposits energy greater than the threshold, the pixel is activated. The problem lies in when the electron lands on the intersection of pixels. If the threshold is low, all pixels are triggered, leading to overcounting, but if the threshold is high, no pixels are triggered, leading to undercounting. Therefore, we must find the optimal pixel activation threshold value. We also test different thicknesses for the sensor layer to avoid the problem of oversaturation. We use a Monte Carlo simulation to track the trajectories and energies deposited by an incident beam of electrons in the sensor layer. From this, we analyze energy distributions and calculate the modulation transfer function (MTF) and detective quantum efficiency (DQE)[4,6] to evaluate the performance of different thickness levels and pixel activation thresholds. Careful thresholding in conjunction with thickness optimization will enable dose-efficient STEM for the high-quality characterization of next-generation semiconductors.

Summary of Research:

The pixel array detector is a type of electron microscope detector that offers high-speed data collection due to its parallel pixel readout and sensitivity to signal changes. It is composed of two layers: a sensor layer and CMOS Integrated Chip. The sensor layer is sectioned into square pixels. This layer is then bump-bonded to the IC. When the energy deposited in a given pixel by an electron is greater than the pixel activation threshold value, the pixel is activated. The problem lies in when an electron lands on the intersection of pixels. A low pixel activation threshold will lead to the electron depositing enough energy in all the pixels and activating all of them, resulting in overcounting. A high threshold will lead to the electron not depositing enough energy in any of the pixels and activating none of them, resulting in undercounting.

To study the relationships between sensor layer thickness and pixel activation threshold on the modulation transfer function (MTF) and detective quantum efficiency (DQE) of our system, we modeled the spread of electrons using a Monte Carlo simulation in a 500-micron deep silicon layer. We set varying initial beam voltages, from 60keV to 300keV. We created lateral and depth energy spread distributions, tracking electron energy at each location.

Summing over the Y and Z direction (Z direction is the beam direction, X-Y is the lateral plane) of the silicon, we created a line spread function, plotting the energy as a function of X position. Taking the Fourier transform of the LSF produces the MTF3. Then, we analyze the relationship between different silicon thickness and activation thresholds, performing the simulation for different pairs and plotting the MTF at Nyquist frequency (contrast for the smallest features) and DQE at 0 frequency (noise for the largest features).

We are also interested in studying the behavior of the Timepix4, a thinner detector, with a 300µm-deep Si layer. Using this depth and a 150 keV threshold, we analyze the relationship between beam radius and pixel size. We choose this threshold because it produces a good MTF. A 150 keV threshold corresponds to around 72.7% of the total energy deposition. This energy is contained in a radius of around 244µm, or 4.5 pixels. We map counts for each triggered pixel.

The origin receives the most energy, resulting in the greatest counts. Fewer pixels are triggered near the edge. At a low threshold, a higher ratio of beam radius to pixel width is favored and at high threshold, a lower ratio of beam radius to pixel width is favored. I also create a pixel activation map for a 300-micron-deep silicon layer (depth of the Timepix4 sensor layer)5, and 150keV threshold and look at the relationship between the initial beam spread and the pixel width.

Conclusions and Future Steps:

Higher initial beam voltages have LSF's with broad tails, as the electrons spread further, both laterally and in depth. Smaller initial beam voltages have sharper LSF's, as the electrons don't have as much lateral or depth spread. Lower beam energies are closer to the ideal MTF because they trigger fewer pixels, producing greater contrast. Lower sensor layer thickness and higher threshold (up to an optimal point) favor higher MTF for the same reason.

Lower thicknesses obtain a better MTF for low thickness, because the electrons' spread is limited, resulting in a smaller radius of energy deposition. Each electron activates only a few pixels, resulting in better contrast. The optimal threshold for a good MTF appears to be around 125 keV for 100, 200, 400 and 500-µm depth, after which point the MTF decreases for higher thresholds. 300-um depth seems to have the optimal MTF around 150keV. Thus, there is an optimal point for the threshold, around 100-150keV, for most thicknesses between 100 to 500 µm.

Meanwhile, DQE is favored by higher sensor layer thickness, because a greater depth allows us to capture the entire spread of the electron, resulting in greater signal acquisition. A higher DQE is also favored by a lower pixel activation threshold because it allows each electron to consistently activate many pixels, producing less noise. At a low threshold, a higher ratio of beam radius to pixel width is favored and at high threshold, a lower ratio of beam radius to pixel width is favored. Thus, MTF and DQE are favored by opposite trends in thickness and threshold. It is important to assess these metrics for each distinct detector design to find the optimal conditions for both metrics. In the future, we will perform the Monte Carlo simulation with more electrons (at least 100,000) for a more detailed understanding of the relationship between thickness and threshold.

We may also consider how detectors with fewer pixels can attain maximal signal capture, as MTF and DQE may be easier to optimize for fewer pixels. Additionally, we can quantify the maximal usable imaging speed (MUIS), in addition to MTF and DQE, to assess different detector designs.

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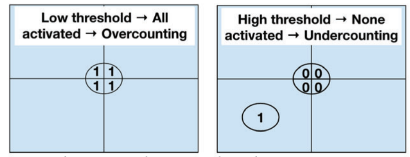

Figure 1: When an electron lands on intersection of pixels, there may be overcounting if the pixel activation threshold is too low and undercounting if the threshold is too high.

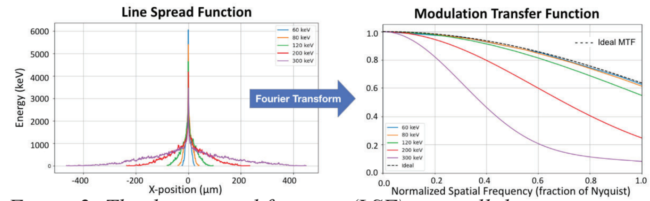

Figure 2: This line spread function (LSF) sums all the energy deposited from 1000 electrons in the Y and Z directions and plots the energy distribution as a function of X position. The Fourier transform of the LSF is the MTF.

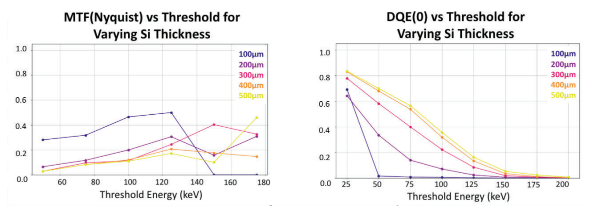

Figure 3: MTF at Nyquist frequency and DQE at zero frequency for varying silicon thicknesses and pixel activation thresholds.

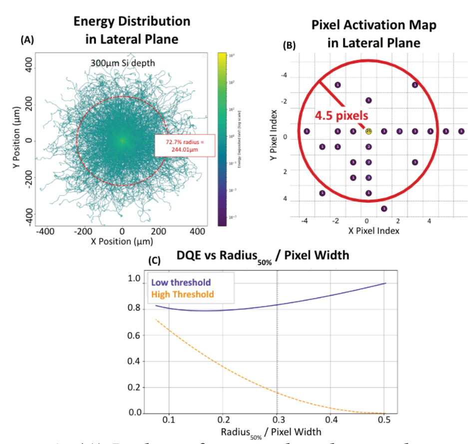

Figure 4: (A) Radius of energy distribution that corresponds to a 150keV threshold. (B) Pixel activation map for 300-µm thick silicon layer. (C) Relationship between ratio of radius where 50% of energy is distributed to pixel width and DQE.