

## Spatial Resolution Smaller Than the Pixel Size? Yes we can!

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When considering cameras for spectroscopic or imaging applications, one of the first questions asked is, "How many pixels does it have?" It is assumed that the smallest resolvable feature in any camera is equal to the pixel size. Unfortunately, cameras and imagers with many thousands of pixels are expensive, and the rate that data are produced can be difficult to manage. In X-ray imaging, whether for diffraction, fluorescence, microscopy or absorption spectroscopy, imaging systems must carefully balance frame rate, pixel size, camera size and incoming photon flux. If, for instance, the incoming photon flux is too high given the camera's potential charge well, then the resulting image quality will be poor due to charge spilling out into neighboring pixels (i.e., image smearing). Increasing the charge well to account for this may require a redesign of the X-ray detector itself. Assuming that users only want to buy one camera for X-ray work, the best solution is to have a camera that is flexible, and can, for instance, change the effective resolution as the experiment requires.

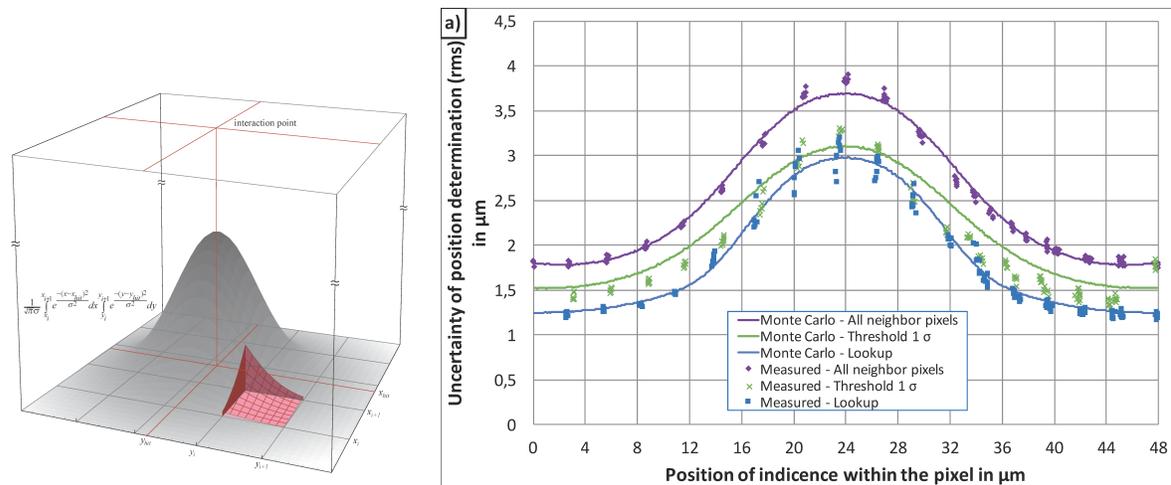
pnCCDs are radiation detectors on high resistivity 450  $\mu\text{m}$  thick fully sensitive silicon [1]. They are back-illuminated devices with an ultra-thin, homogeneous radiation entrance window, enabling the direct detection of X-rays from 100 eV up to 30 keV with high quantum efficiency. When pnCCDs are hit by X-rays, the incoming photons are converted into electron-hole pairs through the photoelectric effect. The photoelectron ionizes silicon atoms in the vicinity until all its energy is dissipated. At an X-ray energy of 1320 eV,  $360 \pm 7$  signal electrons are generated within a radius of less than 1  $\mu\text{m}$ . Then, due to electrostatic repulsion and diffusion, the signal charge cloud widens during its drift from the conversion point inside the silicon into the potential minimum of the pixels. The charge cloud expands to approximately a radius of 13  $\mu\text{m}$  (for an X-ray energy of 1320 eV) once arriving in the potential well of the pixel structure (see Figure 1).

This widening of the electron cloud causes single X-ray events to appear as a collection of charges in two or more pixels. While this may seem detrimental to the overall position resolution of the camera, this is actually an opportunity to resolve the initial location of the X-ray event to smaller than the size of one pixel. Calculating the center of gravity of a multi-pixel event, and knowing that the charge distribution has a Gaussian profile given electrostatic repulsion theory, the actual location of the X-ray event can be calculated with extremely high accuracy. We have demonstrated with the help of simulations and measurements (see Fig. 2) that a position precision of better than 3  $\mu\text{m}$  (rms) at an X-ray energy of 1320 eV can be achieved with a pixel size of 48  $\mu\text{m}$  [2]. In these experiments, an X-ray beam was focused on the pnCCD entrance window with a spot size of approximately 0.8  $\mu\text{m}$  and scanned over the pixel area with a step size of 3  $\mu\text{m}$  in the x direction and 10  $\mu\text{m}$  in the y direction. For X-rays of 1.3 keV, a position accuracy of 2.55  $\mu\text{m}$  is achieved, which is in excellent agreement with the simulations. For higher energies like 6 keV the position accuracy improves to 0.8  $\mu\text{m}$  because more signal electrons (1625 e<sup>-</sup>) spread over a larger area with a better signal-to-noise ratio. In terms of practical application, this means that the pnCCD, which has an array of

264 x 264 pixels with a 48  $\mu\text{m}$  pitch can be used as a detector with an equivalent of over 4200 x 4200 pixels. This enables the flexibility to change the data rate and resolution of the camera without making any physical adjustments to the pnCCD. This flexibility is achieved entirely through software, using an understanding of charge distribution within the pnCCD and careful post processing and reconstruction of each X-ray event. We will present this method in detail, along with laboratory applications of sub pixels resolution.

#### References:

- [1] I. Ordavo et al., NIMA 654, (2011), 250 - 257  
 [2] S. Ihle, P. Holl *et al*, Direct measurement of the position accuracy for low energy X-ray photons with a pnCCD. Journal of Instrumentation, **12** (2017)



**Figure 1: (Left)** At X-ray energies below 10 keV the electron-hole pairs are generated within a radius of less than 1  $\mu\text{m}$  in silicon. Due to electrostatic repulsion and diffusion, the signal charge cloud widens during its drift from the conversion point into the potential minimum of the pixels. This distribution is Gaussian in nature, and, as a result, the center of gravity can be very precisely calculated.

**Figure 2: (Right)** Uncertainty of position determination in x direction over the pixel. The width of the illumination spot ( $\sigma = 0.8 \mu\text{m}$ ) is included in the plotted values. The measured values (data points) are plotted at the corresponding position from the border of the pixel. The Monte Carlo simulation values are plotted as solid lines. The measured uncertainty of the position determination in x – direction is in good agreement with the Monte Carlo simulation. The three colors represent three different algorithms for the reconstruction of the point of interaction: (magenta) all neighboring pixel next to the seed pixels are taken into account, (green) a 1  $\sigma$  threshold is applied, (blue) only physically reasonable pixels are taken into account with the help of a look-up table.