MPI semiconductor laboratory of the Max-Planck-Institutes for physics and extraterrestrial physics

Nils Kimmel
04/24/2007

pnCCDs: simulations and reality

N. Kimmel, R. Hartmann, P. Holl, N. Meidinger, R. Richter and L.Strüder

- pnCCDs produced in the MPI semiconductor lab
- Motivation for a detailed device analysis
- The mesh experiment
- Data analysis and pixel reconstruction
- Comparison of measurements and device simulations
- Simulations and measurements of photon absorption in the register structure
- Summary and conclusion

pnCCDs produced in the MPI semiconductor lab

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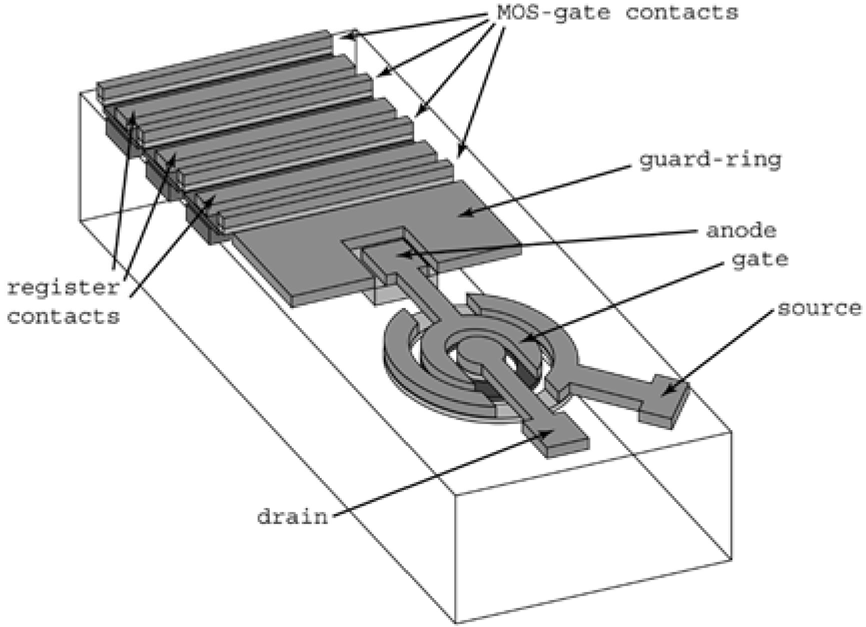
- pnCCD: principle of charge transfer like in conventional MOS-CCD with three registers [1]



- Basic structure is a double sided pn diode [2] with p+ contacts on both sides of the substrate, MOS-gates define fixed potential of p+ register contacts
  → Depletion of shallow n doped bulk silicon with n+ contact at the rim
  → High quantum efficiency from near Infrared to X-ray
  → Fast parallel column readout with low noise down to $2e^-$

pnCCDs produced in the MPI semiconductor lab

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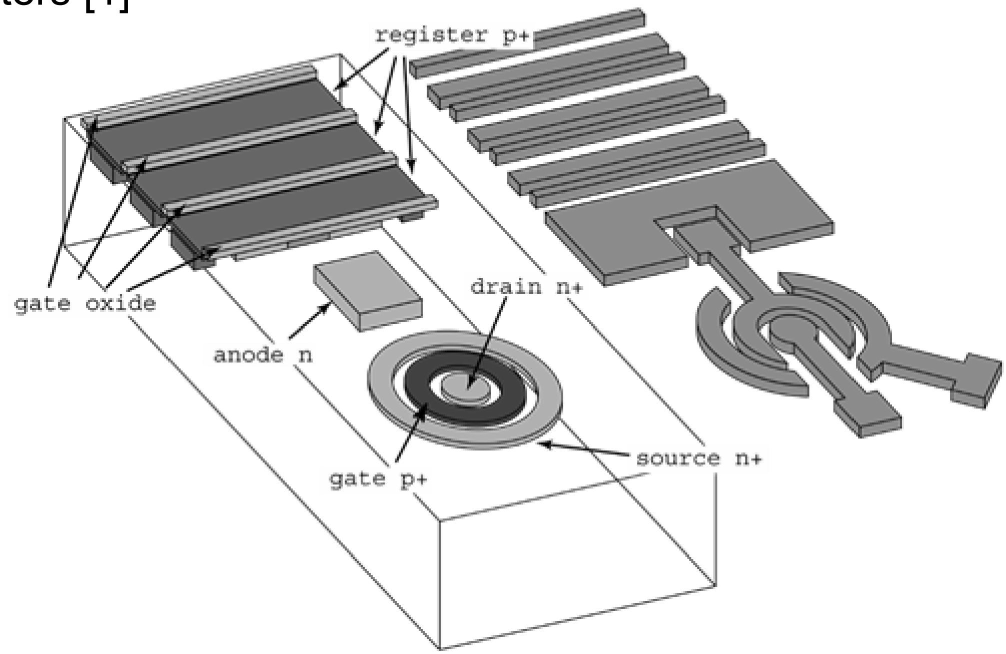

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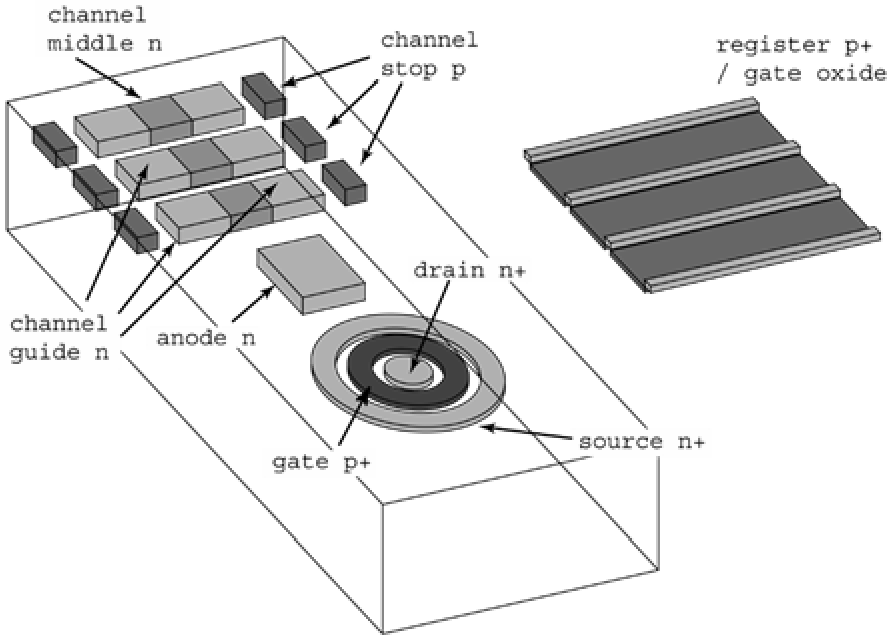

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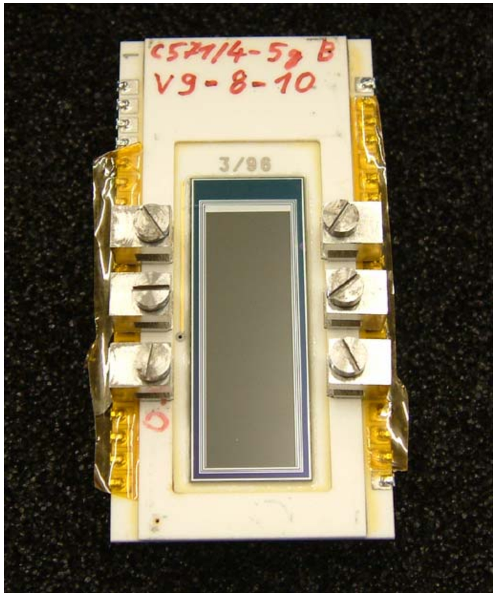
pnCCDs produced in the MPI semiconductor lab

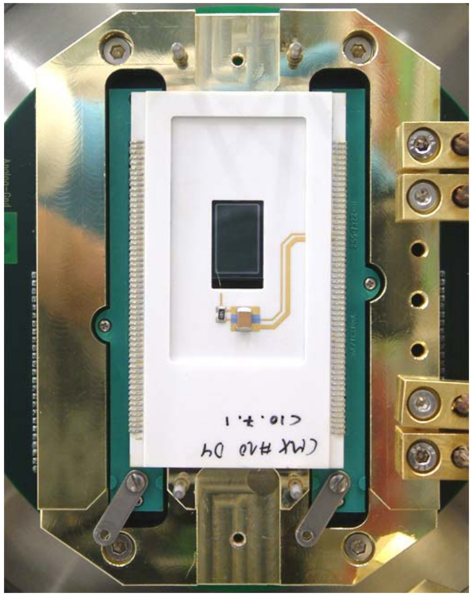
» Different pixel sizes and wafer thicknesses

→ Wafer sizes from 4”/280µm to 6”/450µm for devices of current production

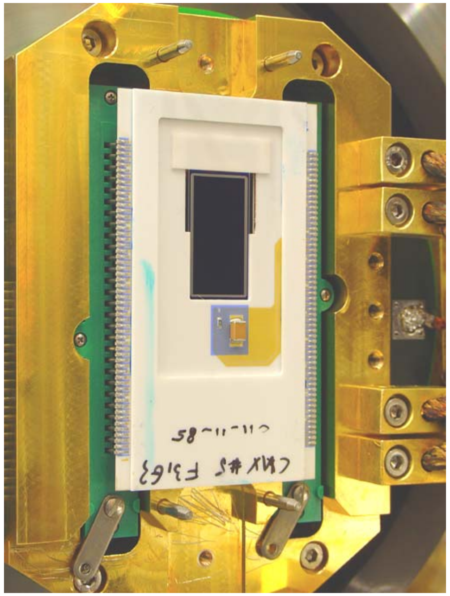
→ Pixel sizes of 150µm, 75µm, 51µm and 36µm with up to 264x264 pixels



150µm pixel XMM type pnCCD, 64x200 pixels frame size, 290µm thickness



75µm pixel frame store pnCCD [3], 128x125 pixels img. area, 280µm thickness



51µm pixel frame store pnCCD, 264x264 pixels img. area, 450µm thickness

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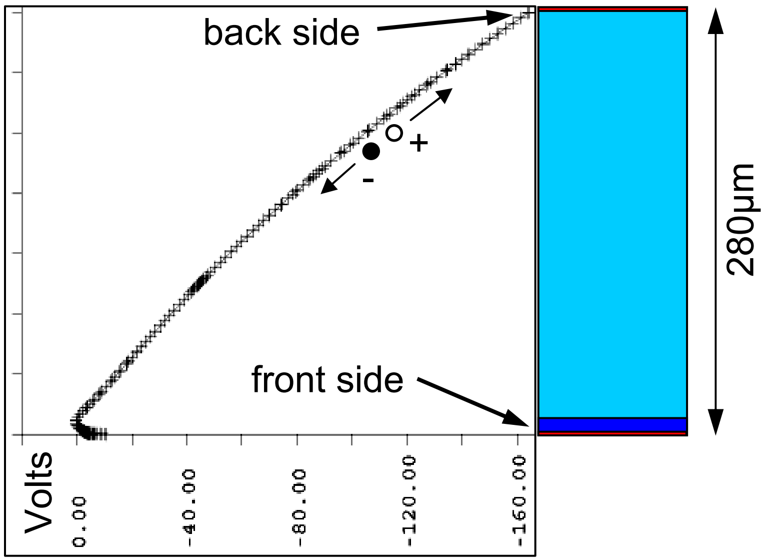
Motivation for a detailed device analysis

» Fully depleted bulk with high back contact voltage (E-field 4000V/cm and more) → Drift dominated charge collection, drift times around 1.5ns



X-ray photons generate electron-hole cloud

electrons and holes are separated in the drift field

holes enter p+ contact on the back side

electrons drift to potential minimum at the front side

p+ silicon   n- silicon   n silicon

» Electron cloud expands during drift time due to electrostatic repulsion and diffusion; for low X-ray photon energies, diffusion is the dominating effect.
→ 1e$^-$ per 3.65eV: 486e$^-$ for W-M (1774eV) or 1236e$^-$ for Ti-Kα (4510eV)

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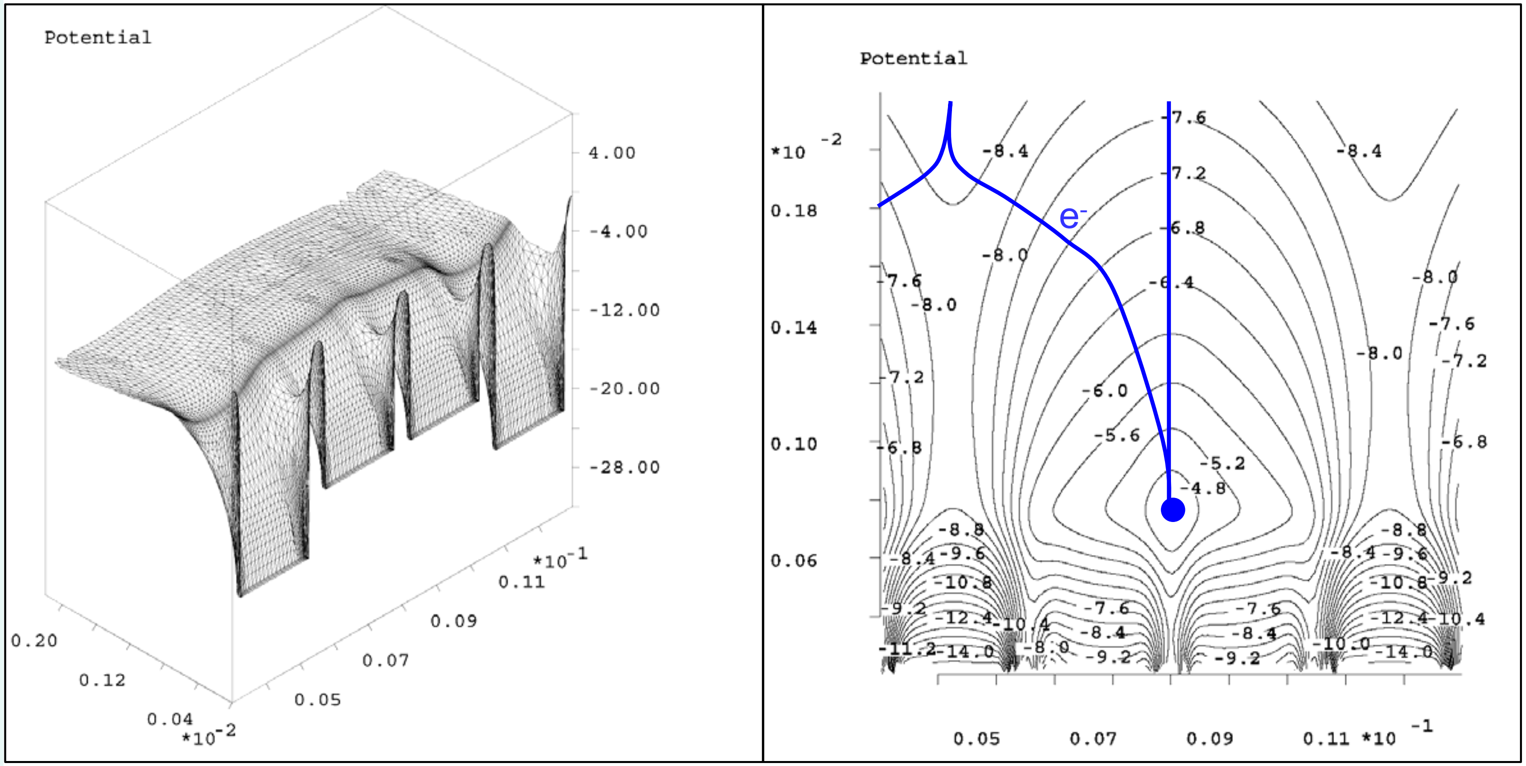
Motivation for a detailed device analysis

» El. potential determines process of charge collection



Electric potential in pnCCD with 75µm pixels, a region of 100µm width and 20µm depth with four registers is shown.

» Voltages of surface contacts and implantation doses + profiles determine el. potential inside pnCCD. Electron cloud is split at potential barrier of pixel.

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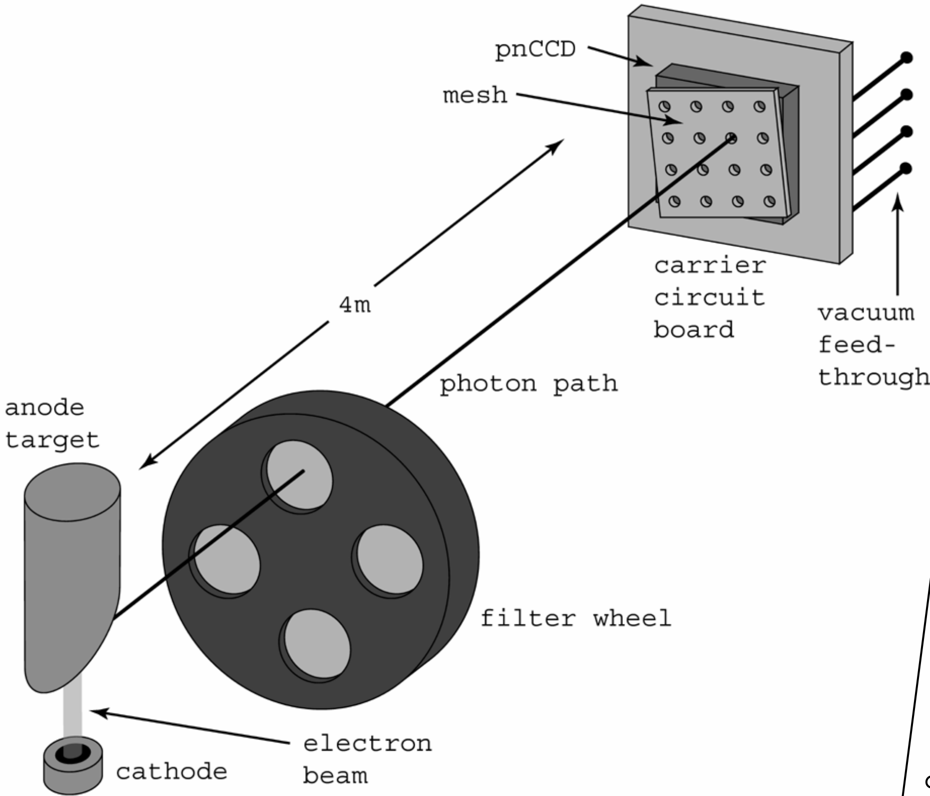
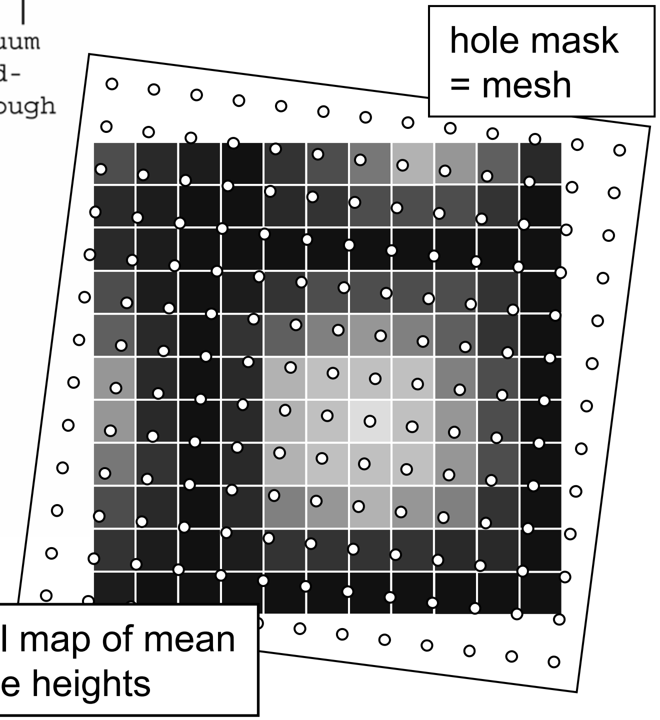
The mesh experiment [4]

» Scanning of a pixel gives data on response to photon conversion position in pixel → scanning with resolution in µm range too difficult, use mesh method!



- Solution: use gold foil with holes on a square grid
- hole distance ≥ pixel size
- Slight rotation: every hole has different position in pixel below



- We used a gold mesh with 10µm thick-ness, 5µm hole diameter, 150µm hole distance: max usable X-ray energy Cr-Kα 5415eV

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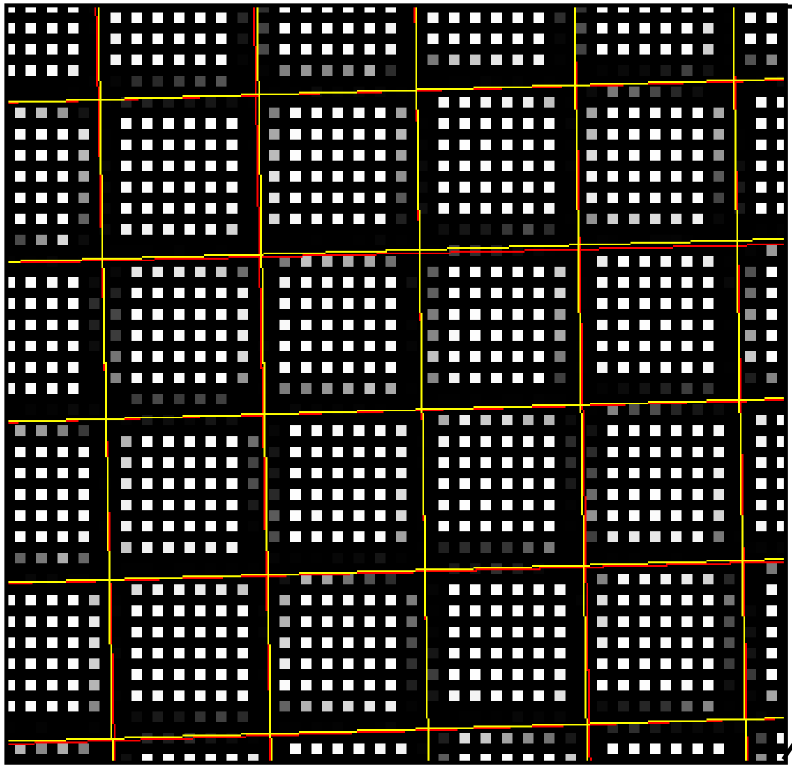
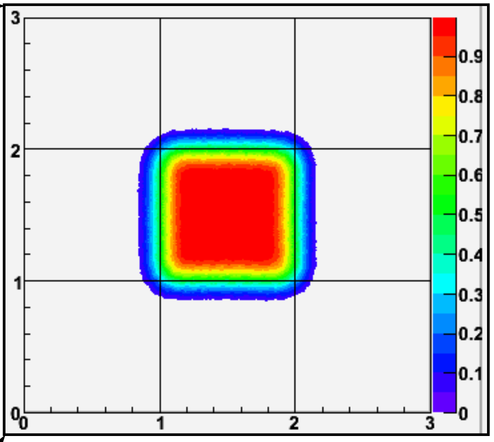
Data analysis and pixel reconstruction

» Photons detected as pulse height patterns of one up to four pixels → pulse heights represent spreading of charge cloud over pixels



● Map of pixels with single events, pixels are bright where holes lie near center of pixel
● Yellow lines are parameterization of moiré pattern: distance, angle and offset to lower left corner define position of the mesh



● Projection of frame data into a "virtual" pixel, the reconstruction of an average pixel

● Map showing the relative amount of collected charge in an area of 3x3 pixels: charge collection function

● Map showing the count rate in an area of 1 pixel: count map

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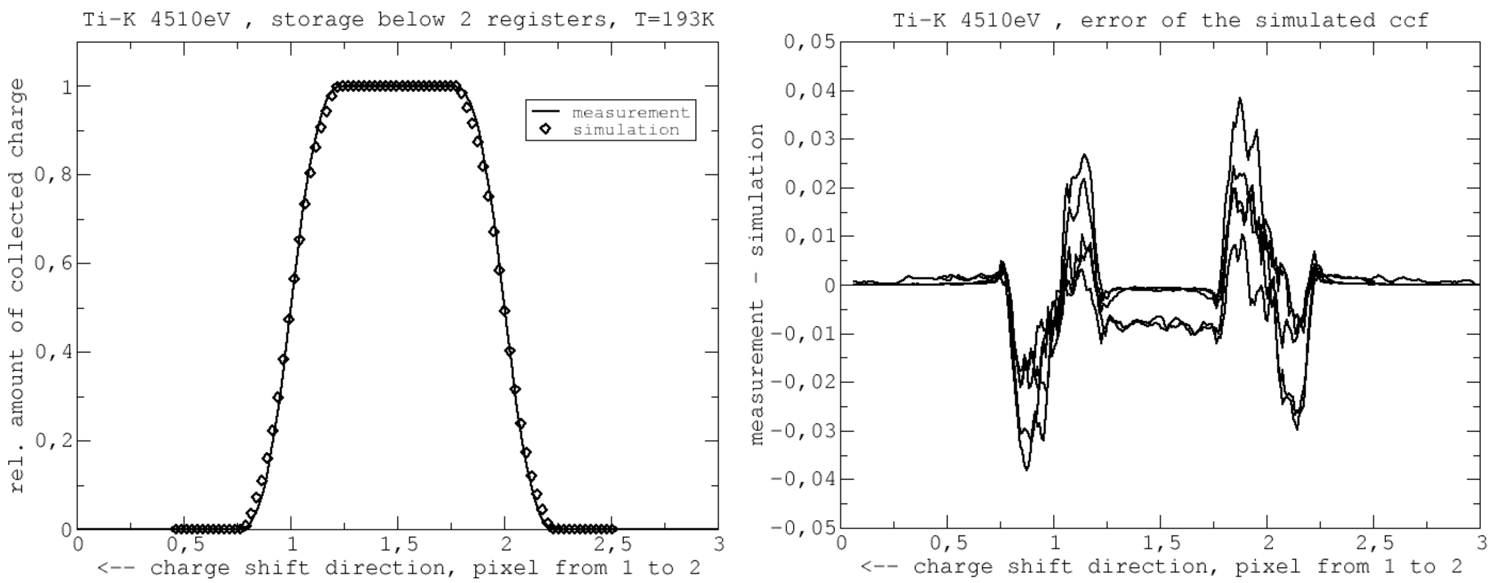
Comparison of measurements and device simulations

» Charge collection function can be simulated as a profile in line and transfer direction



- Simulations have a good accuracy with an error of 4% to max. 10%
- Charge collection function profile is parameterized as an error function with a specific charge cloud σ
- Error of the simulated σ is below 10%
- Value of σ typically 7μm in studied 75μm pixel device

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Comparison of measurements and device simulations

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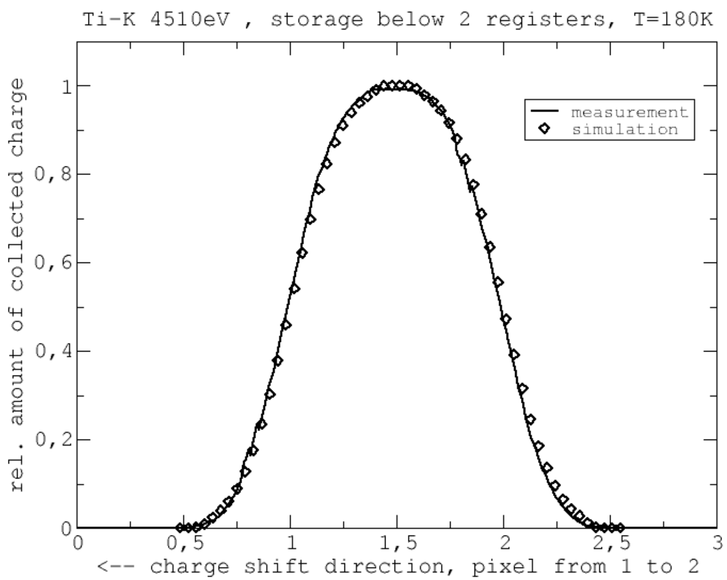

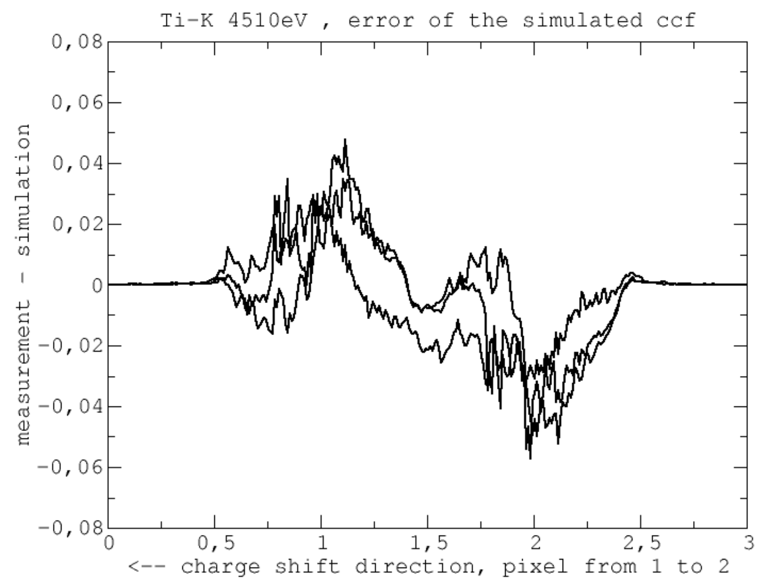

- Simulations have a good accuracy with an error of 4% to max. 10%
- Charge collection function profile is parameterized as an error function with a specific charge cloud σ.
- Error of the simulated σ is below 10%
- Value of σ typically 9µm in studied 51µm pixel device

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Comparison of measurements and device simulations

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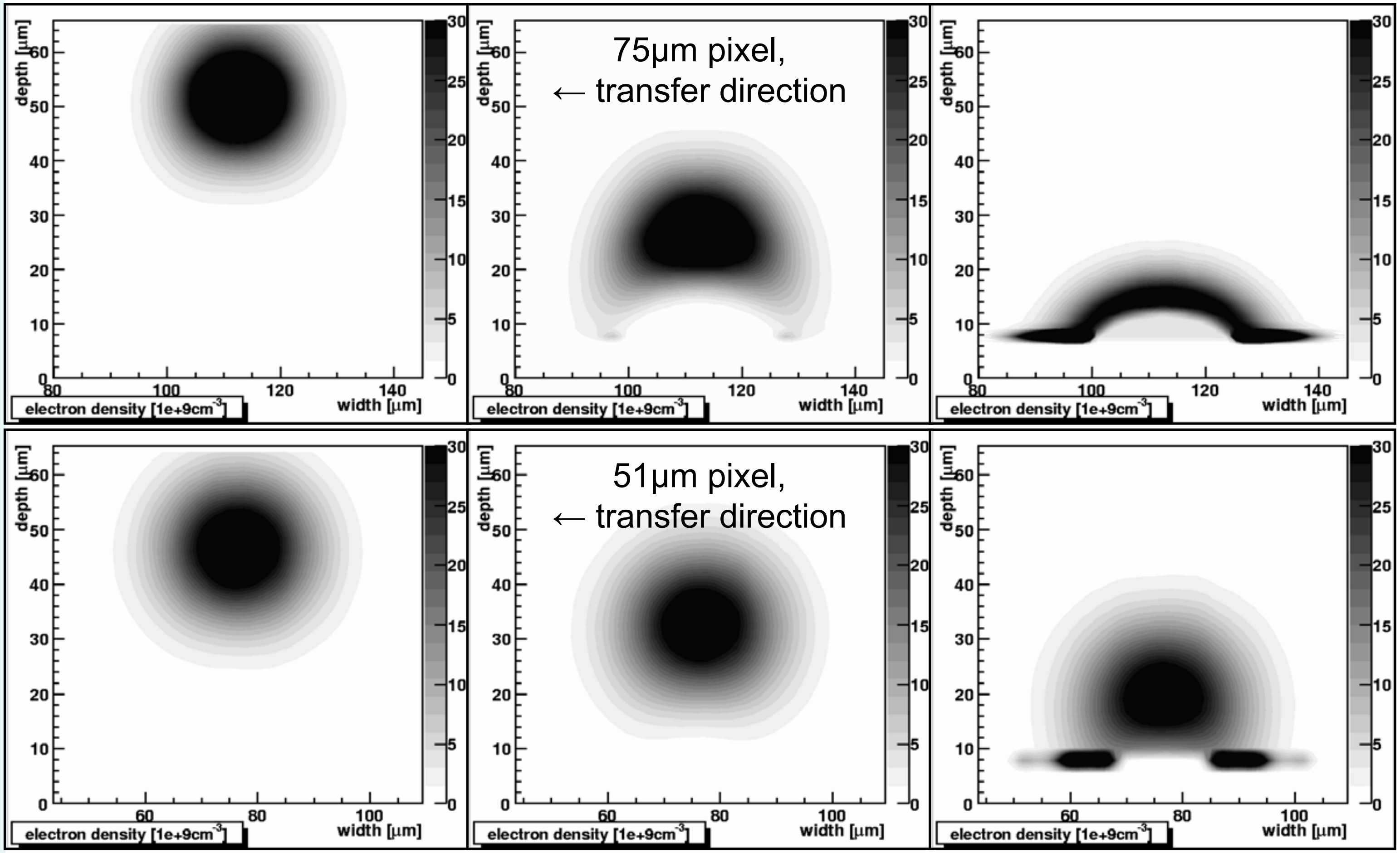
» Depth (time) resolved view of the charge collection simulation shown before:



- Simulations shown here are for a photon energy of 4.5keV / Ti-Kα
- Separation of charge cloud in a depth of approx. 1/3 pixel size = width of one register including the MOS-gate

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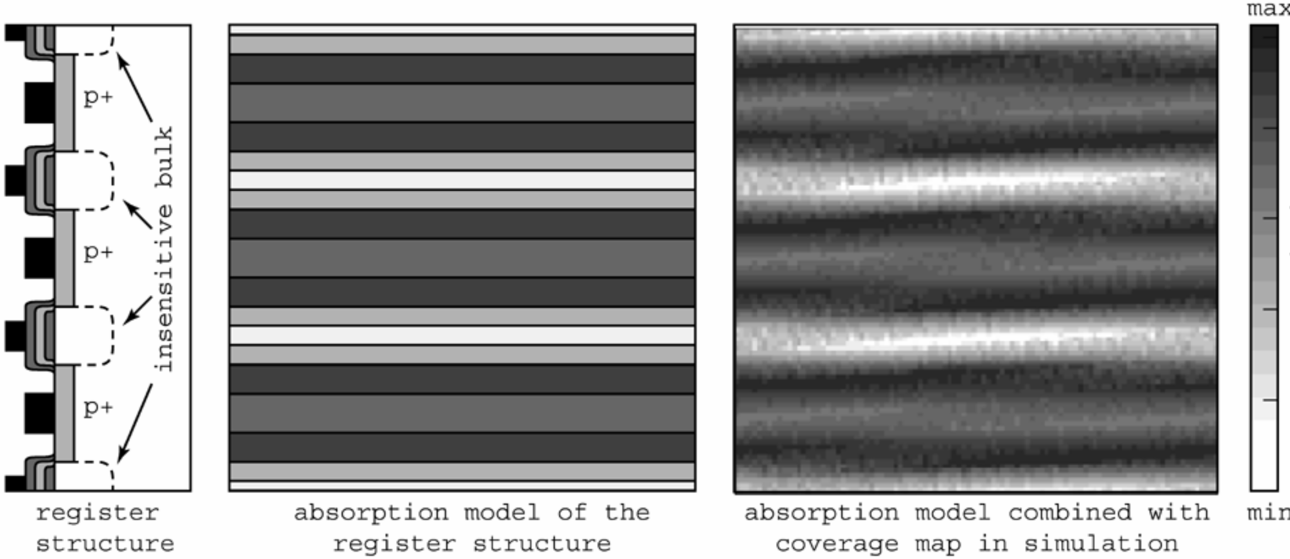
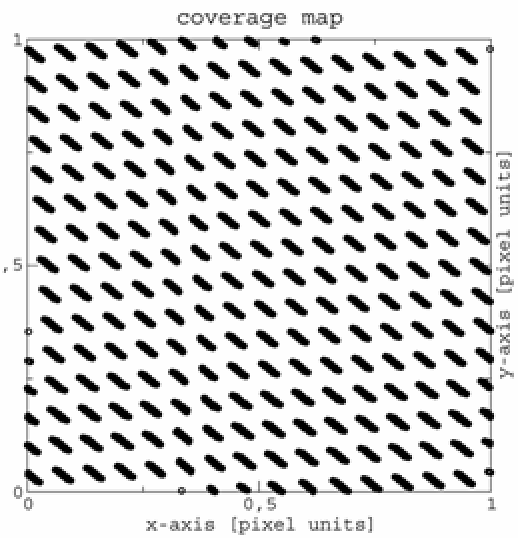
Photon absorption in the register structure

» Analyze the depth of insensitive layers below MOS-gates and in p+ contacts



The thicknesses and widths of the Si-oxide, Si-nitride and the aluminum layers are well known



- Absorption profile is created with geometry and material data of known layers and assumptions on insensitive regions
- Absorption profile is extended to absorption map of a pixel
- Pixel absorption map is combined with measured map of hole positions in Monte-Carlo simulation to create a count map
- Measured and simulated count maps are subtracted to evaluate the square of the difference

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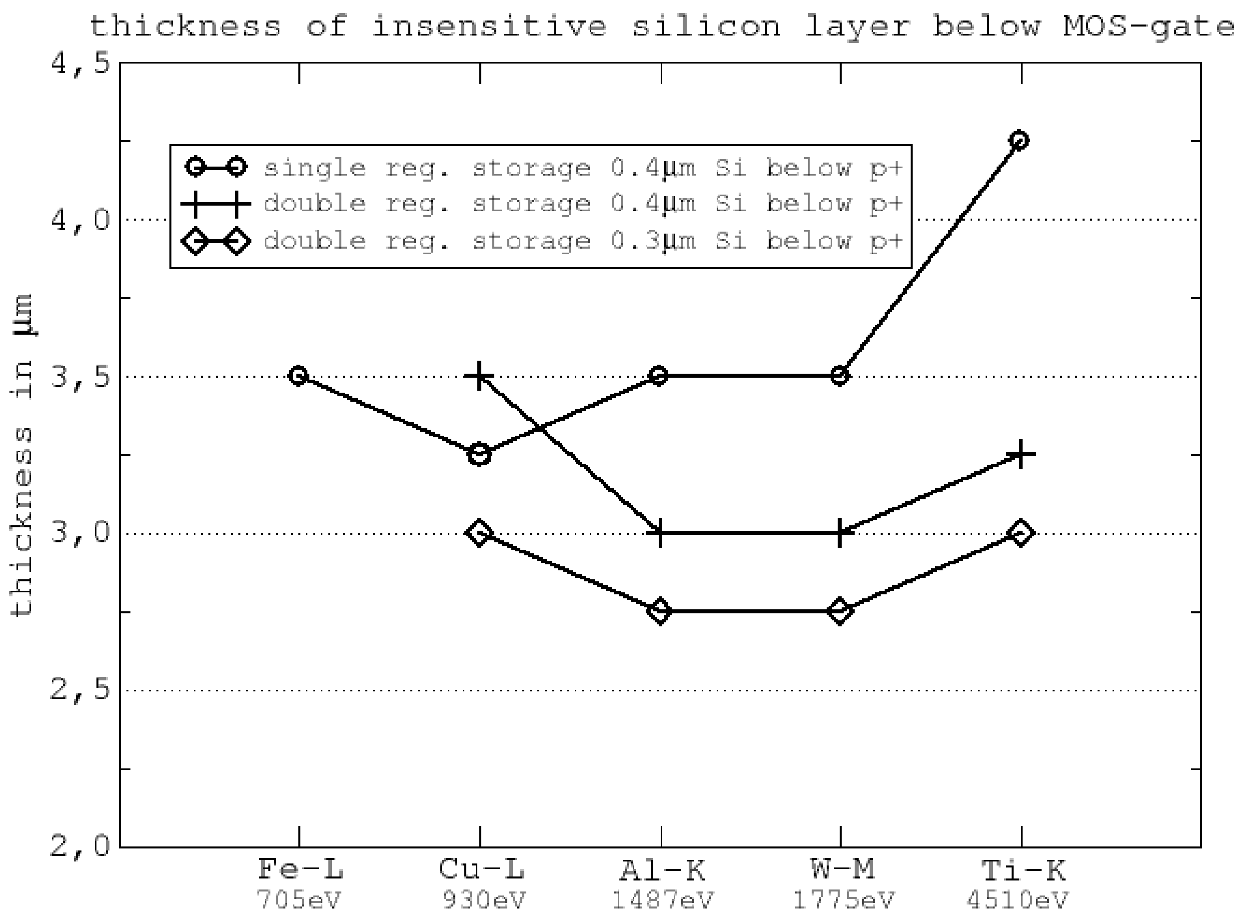
Photon absorption in the register structure

» Lowest square difference of count map data and simulations gives the best fit thicknesses of the insensitive layers for different X-ray energies
» Thickness of insensitive p+ layer is extrapolated from technology data



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Summary and conclusion

» Successful measurements of charge collection and absorption of photons in the front side structure

» New mesh data analysis method was developed and successfully tested

» Charge collection function can be simulated with an accuracy better than 10%

» σ of simulated charge collection function also has an accuracy better than 10% → position reconstruction based on simulations is better than 2.5µm

» Simulations of front side absorption give results for the thickness of an insensitive layer below the MOS-gates → results for different X-ray energies are consistent within an error of 0.5µm

Special thanks to the technology staff and the electronics group of the semiconductor lab!

1) Strüder L., Bräuninger H., et al., Rev. Sci. Instrum. 68 (1997) 4271.
2) Rehak P., Gatti E., et al., NIMA 235 (1985) 224.
3) N. Meidinger, et al., NIMA 512 (2003) 341.
4) H. Tsunemi, K. Yoshita, S. Kitamoto, Jpn. J. Appl. Phys. 36 (1997) 2906.