Subpixel Response of Double-SOI Pixel Detectors for X-ray Astronomy

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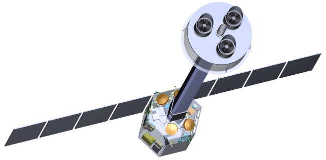
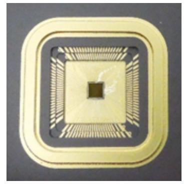
Hideaki Matsumura (Kavli IPMU), Koji Mori, Ayaki Takeda, Yusuke Nishioka, Kohei Fukuda, Takahiro Hida, Masataka Yukumoto (Univ. of Miyazaki)
Yasuo Arai, Shunji Kishimoto, Ikuo Kurachi (KEK)

PIXEL2018 @Activity Center of Academia Sinica in Taipei

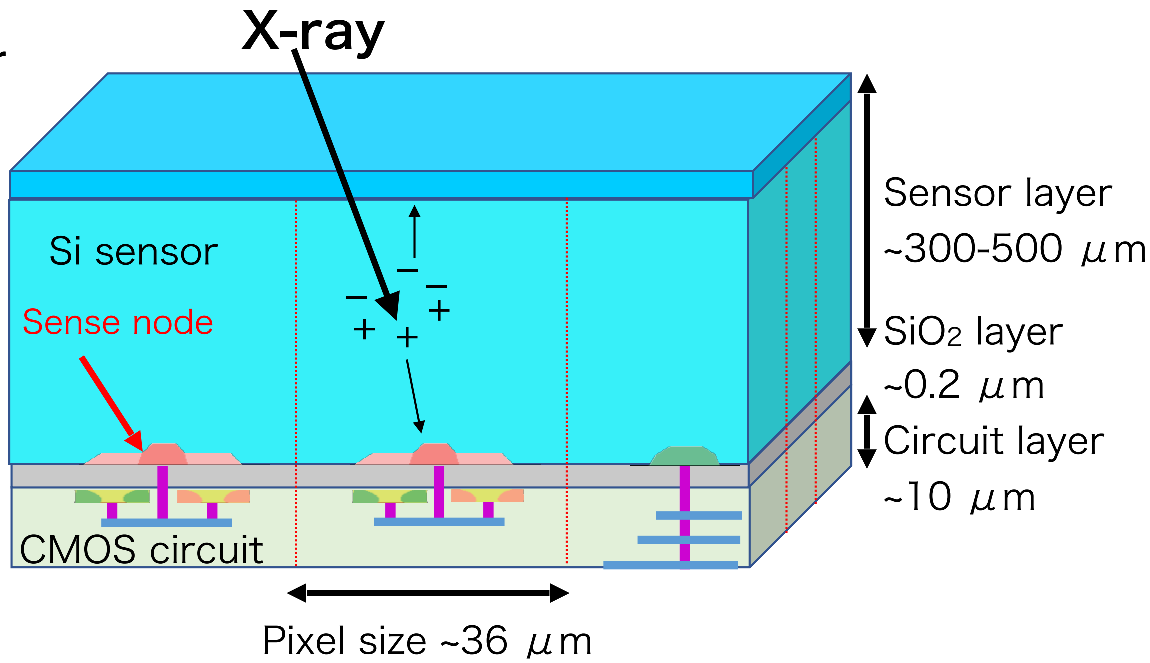


X-ray SOI pixel detector：XRPIX



- XRPIX: Monolithic active pixel sensor composed of
  - high-resistivity Si sensor
  - thin SiO_2 insulator
  - CMOS pixel circuits

  by utilizing the Silicon-On-Insulator (SOI) technology

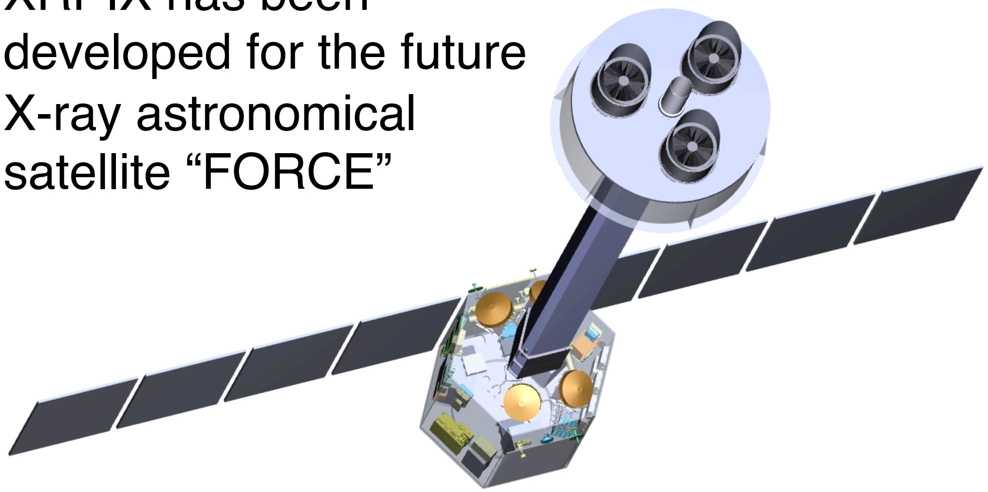


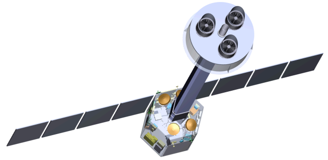
✓ High ρ Si for sensor layer
→ **Thick depletion layer of ~ a few hundreds of micrometers**

✓ Self-trigger function in each pixel circuit
→ **Timing resolution better than ~10 μs**

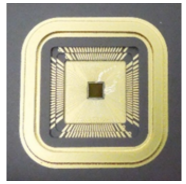
✓ **Energy resolution comparable to X-ray CCDs**

- XRPIX has been developed for the future X-ray astronomical satellite “FORCE”



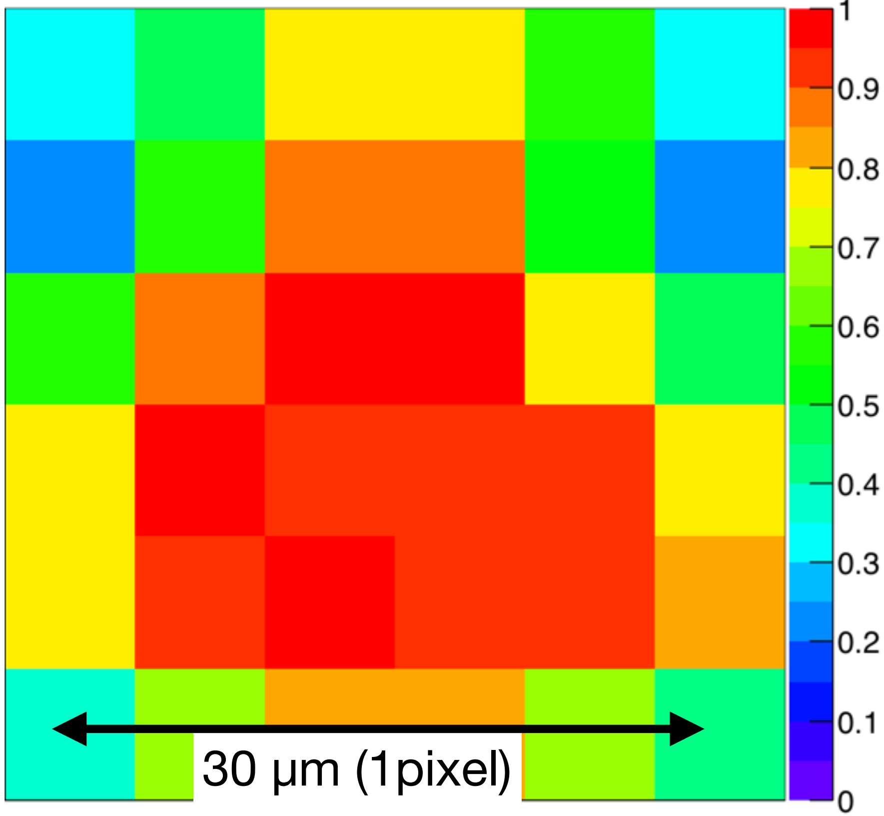


Charge loss issue in XRPIX1b

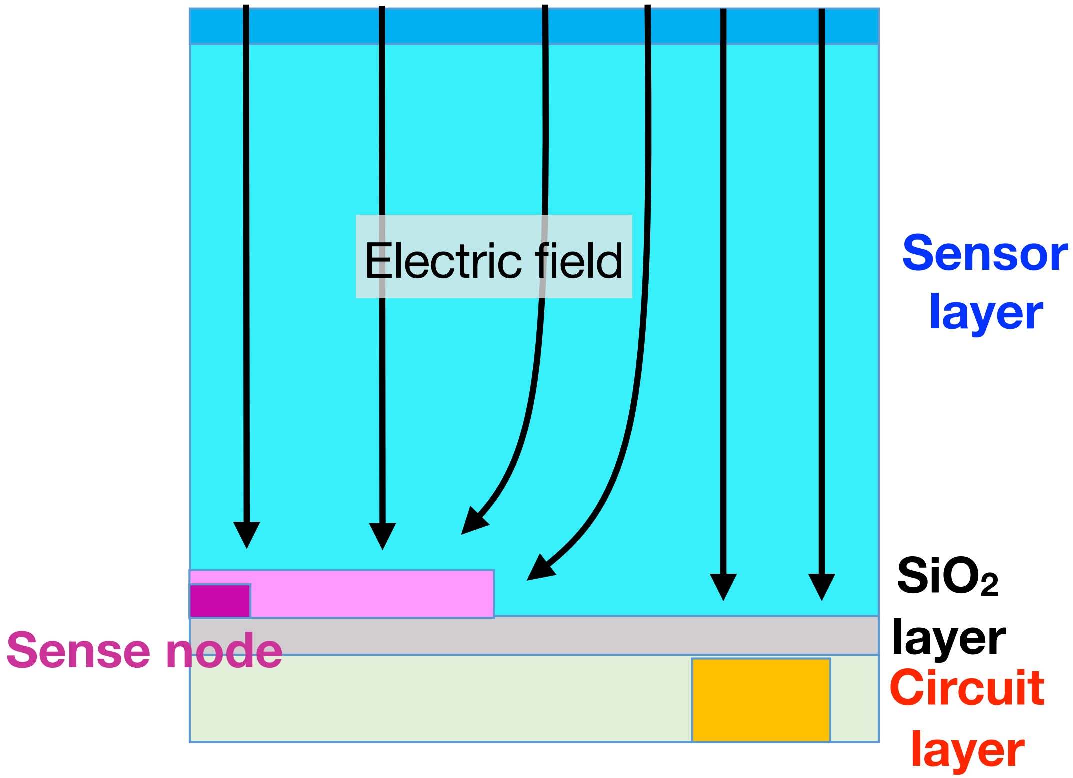


Issue in XRPIX1b: poor X-ray detection efficiency at pixel boundary

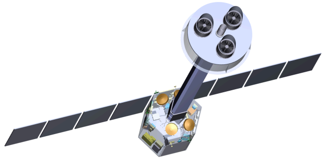
Detected count map of XRPIX1b in sub-pixel scale (=detection eff.)



Before improvement (XRPIX1b)



- In XRPIX3b, we tried to improve the electric field structure in sensor layer by re-arranging pixel circuits under the BPW



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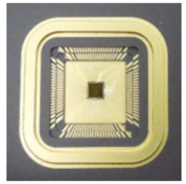

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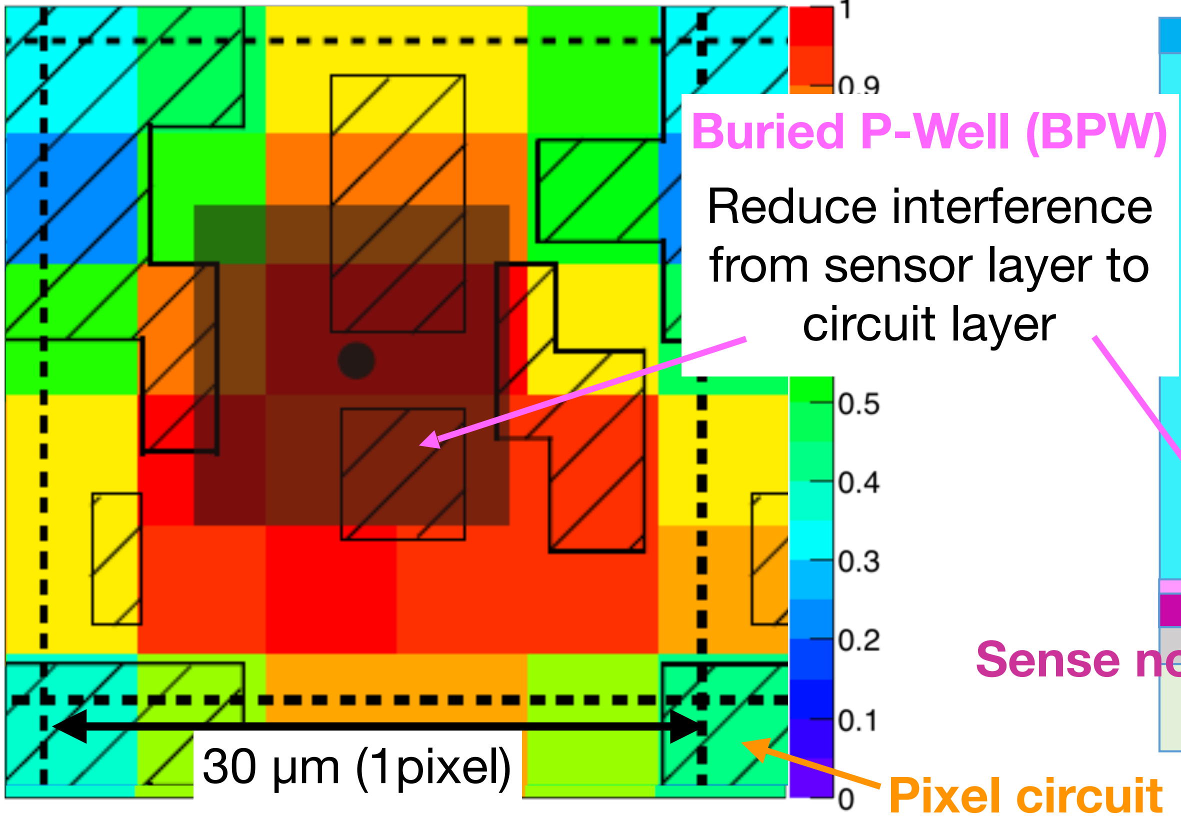

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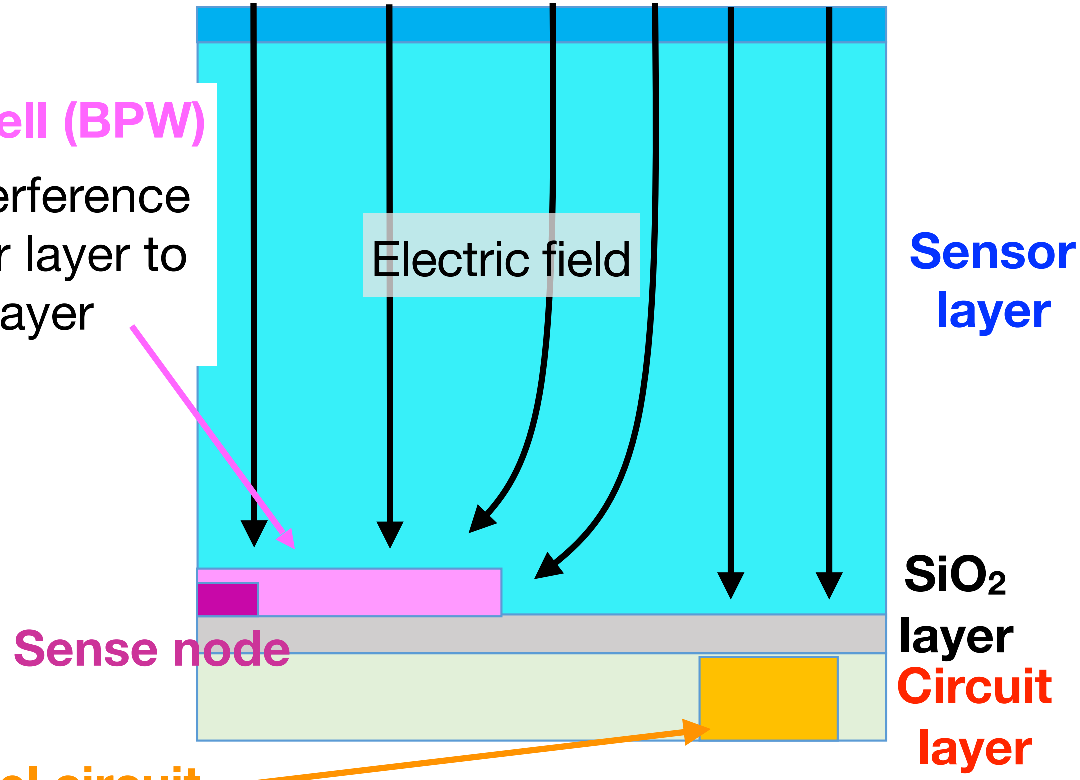

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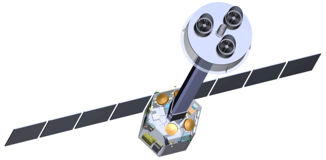

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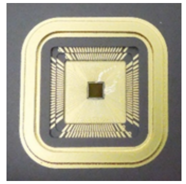

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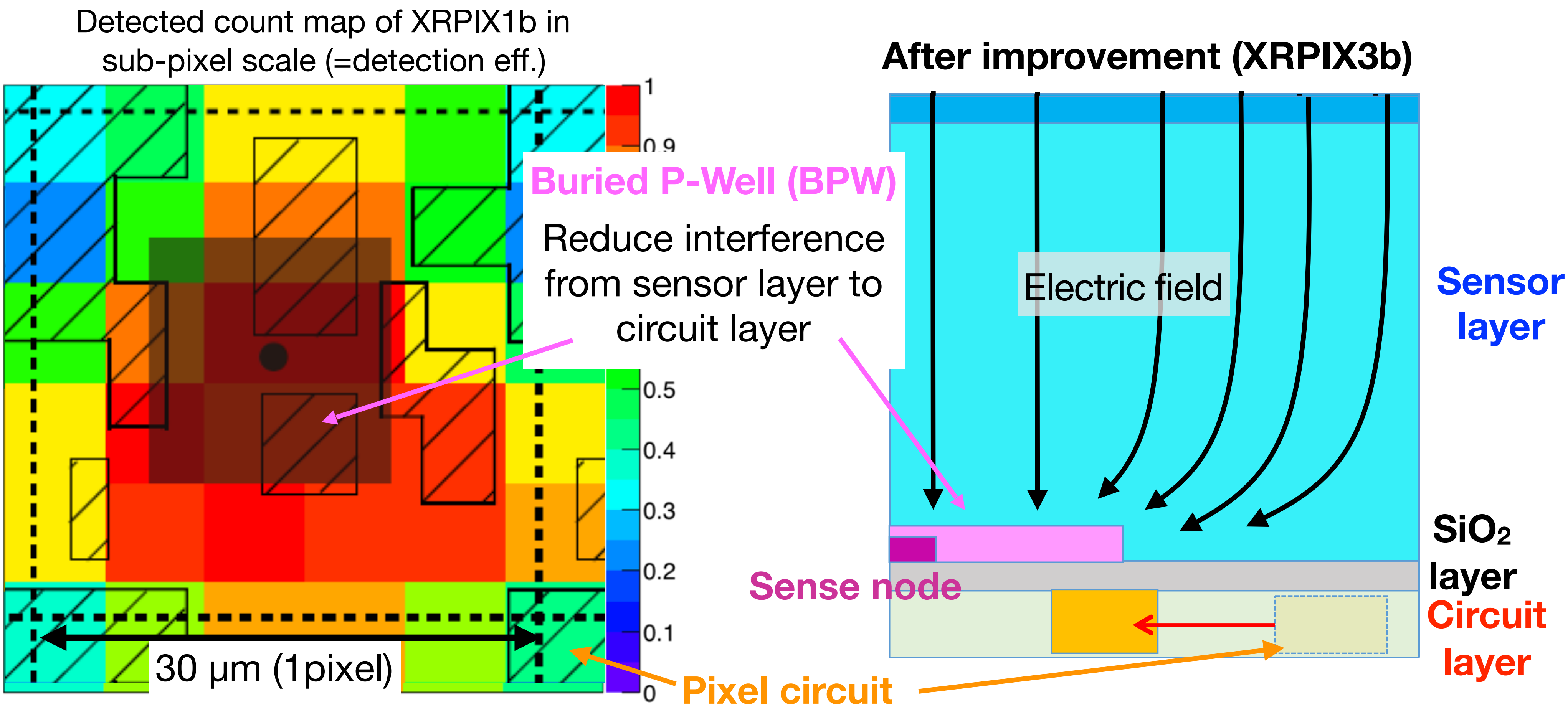

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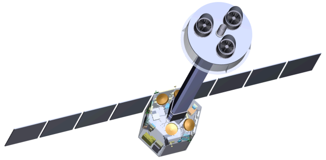
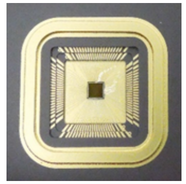
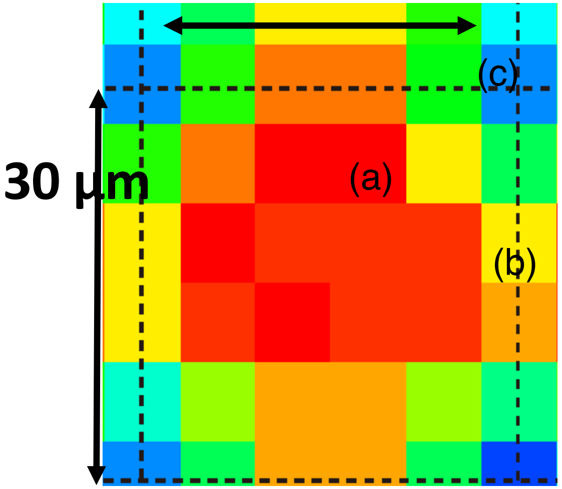


Improvement in XRPIX3b



- We evaluated X-ray response of XRPIX3b (pixel circuit was re-arranged) in sub-pixel scale.

Matsumura+ 2015, Negishi+ 2018



XRPIX1b@8.0 keV

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XRPIX3b@2.1 keV

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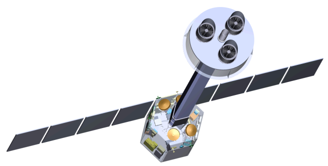

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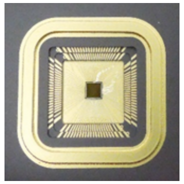

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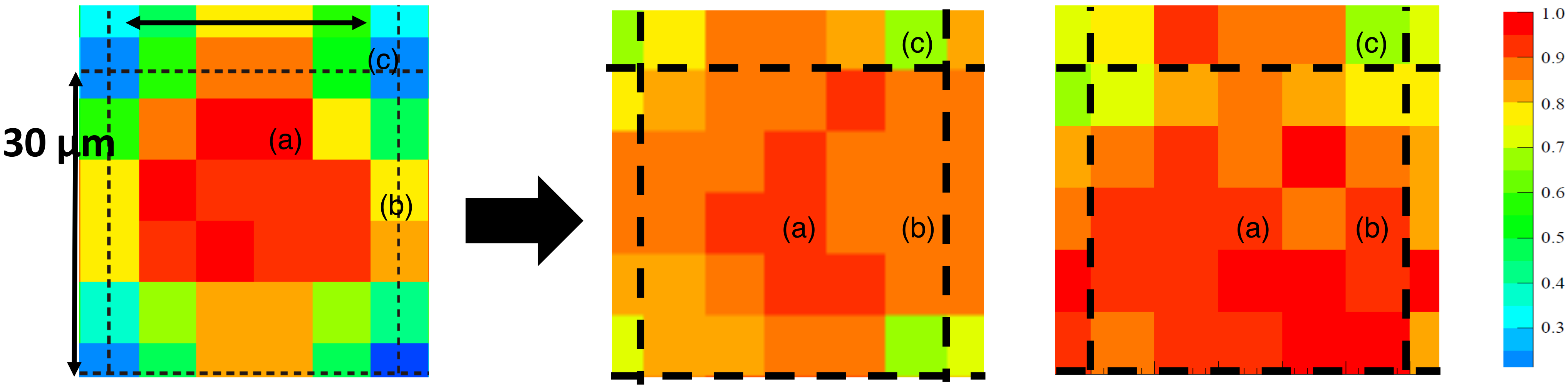

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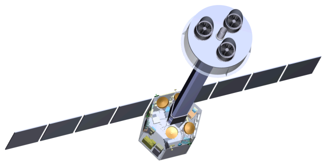

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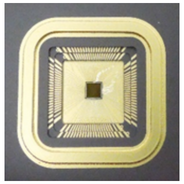

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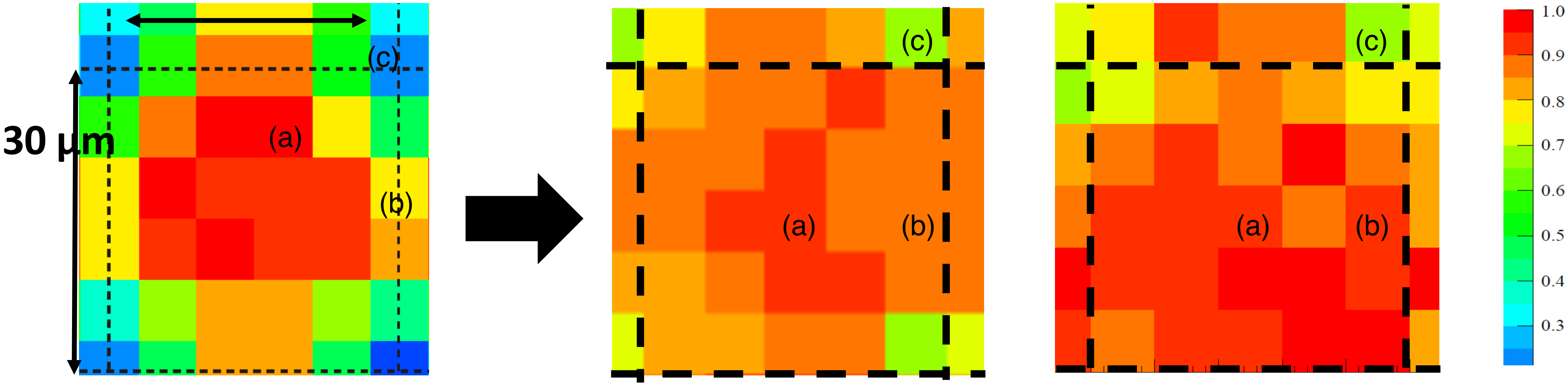

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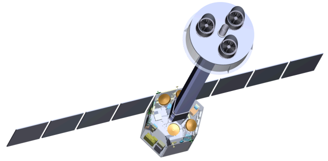

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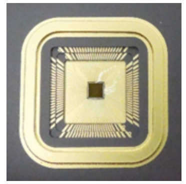

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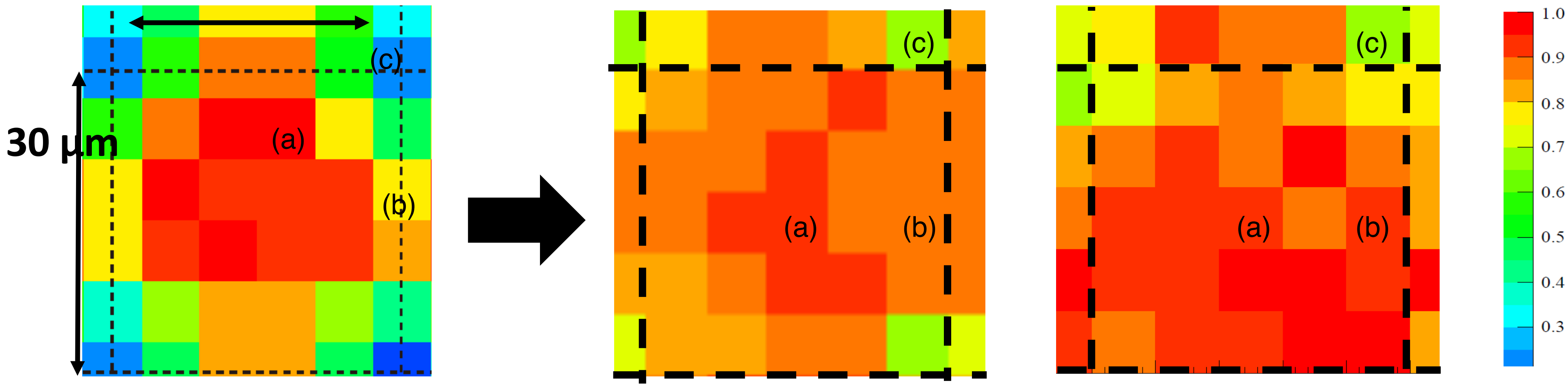

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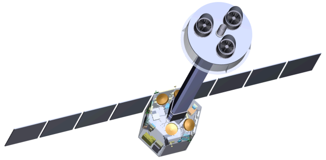
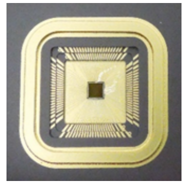
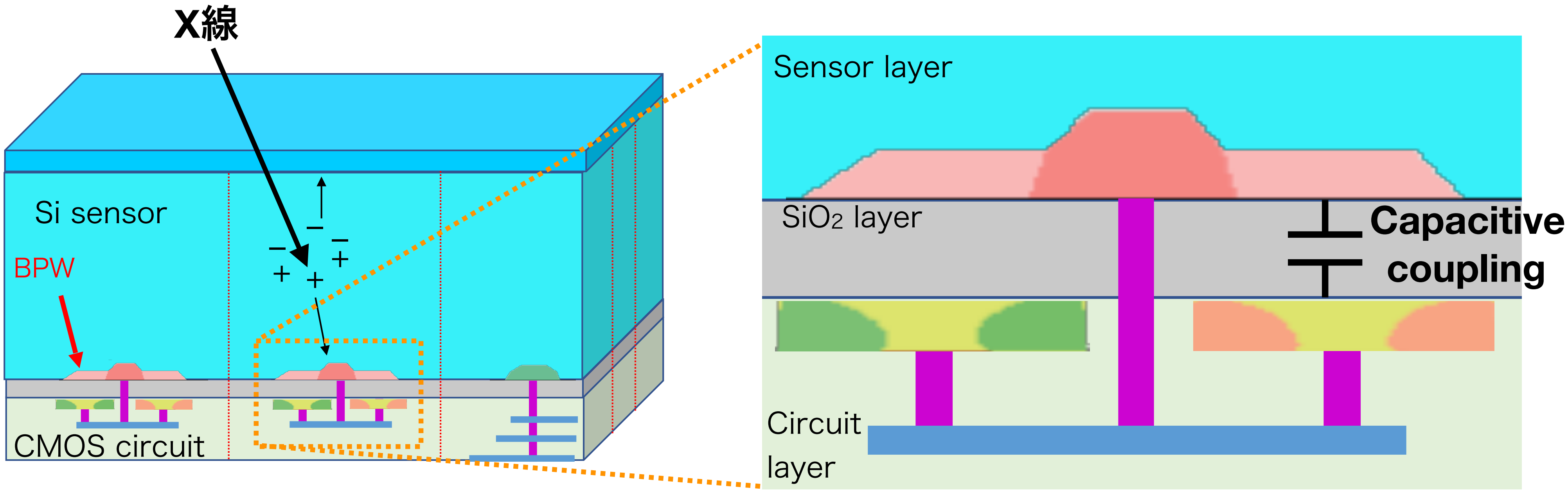
- Flatness of the detection efficiency was improved
- At 4 pix. boundary, efficiency is 70–80% of those at pixel center



Double SOI structure



- A thin Si layer (middle Si) was added in SiO_2 layer
- The middle Si layer works as an electrostatic shield, and reduce the electric interference between sensor layer and circuit layer



※XRPIX6bD is composed of
p-type bulk + n-type sense node

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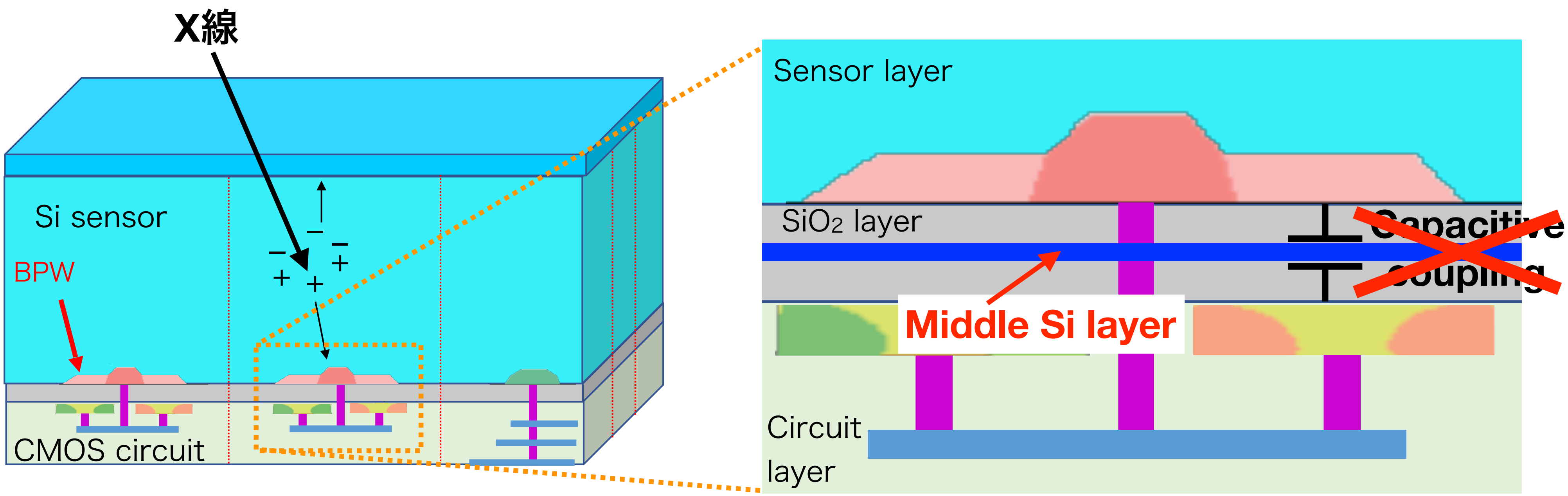

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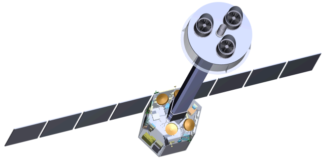
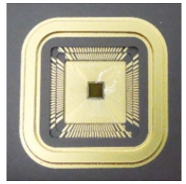
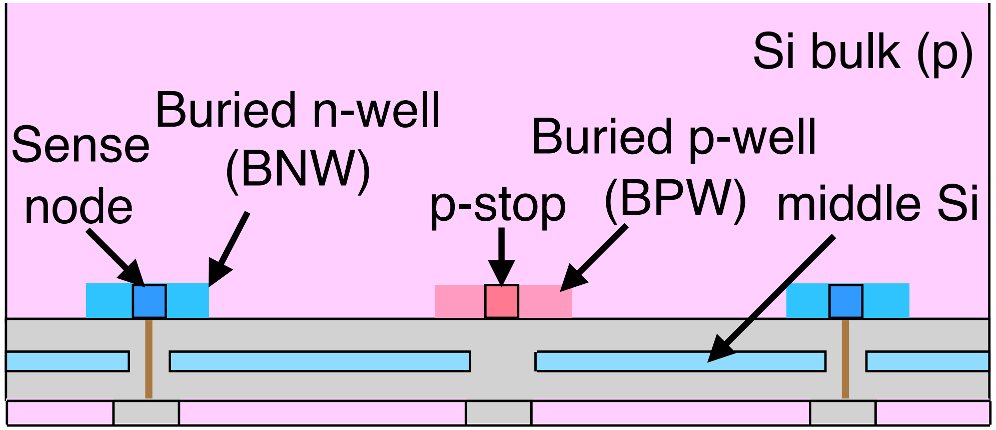
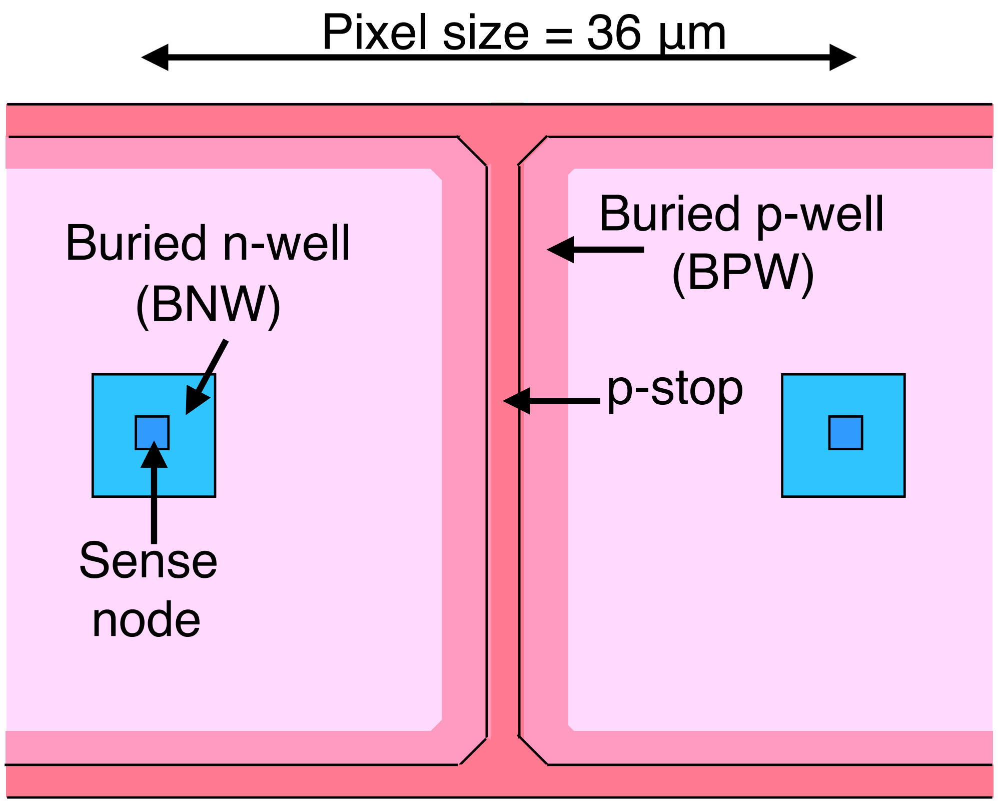


Double-SOI XRPIX: XRPIX6bD







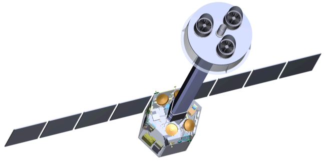
Parameter	Value
Depletion layer	66 µm
Pixel size	36×36 μm^2
Number of pixels	48×48

✓ Double-SOI structure (middle Si in SiO_2 layer)

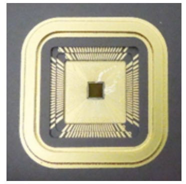
➡ Reduce the interference between sensor layer and circuit layer

✓ Introduction of p-stop and BPW at pixel boundary

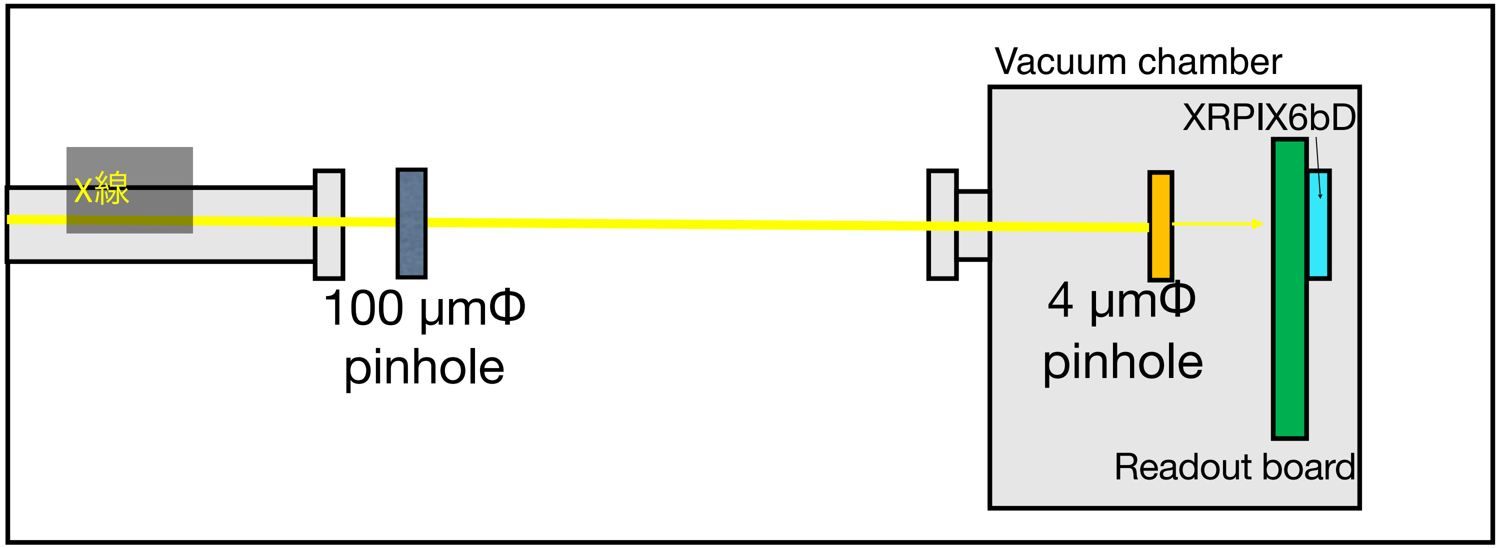
➡ Efficiently collect charge into sense node

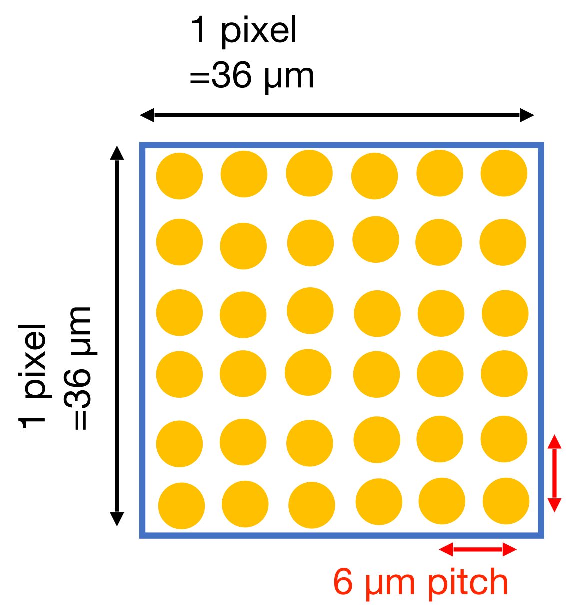


X-ray beam scan in subpixel scale

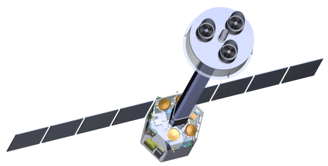


- 6.0 keV X-ray beam collimated with 4 μmϕ pinhole (Au ~90 μmt) was irradiated to XRPIX6bD (Double SOI) at a synchrotron radiation facility Photon Factory of KEK in Japan

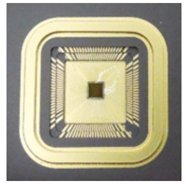


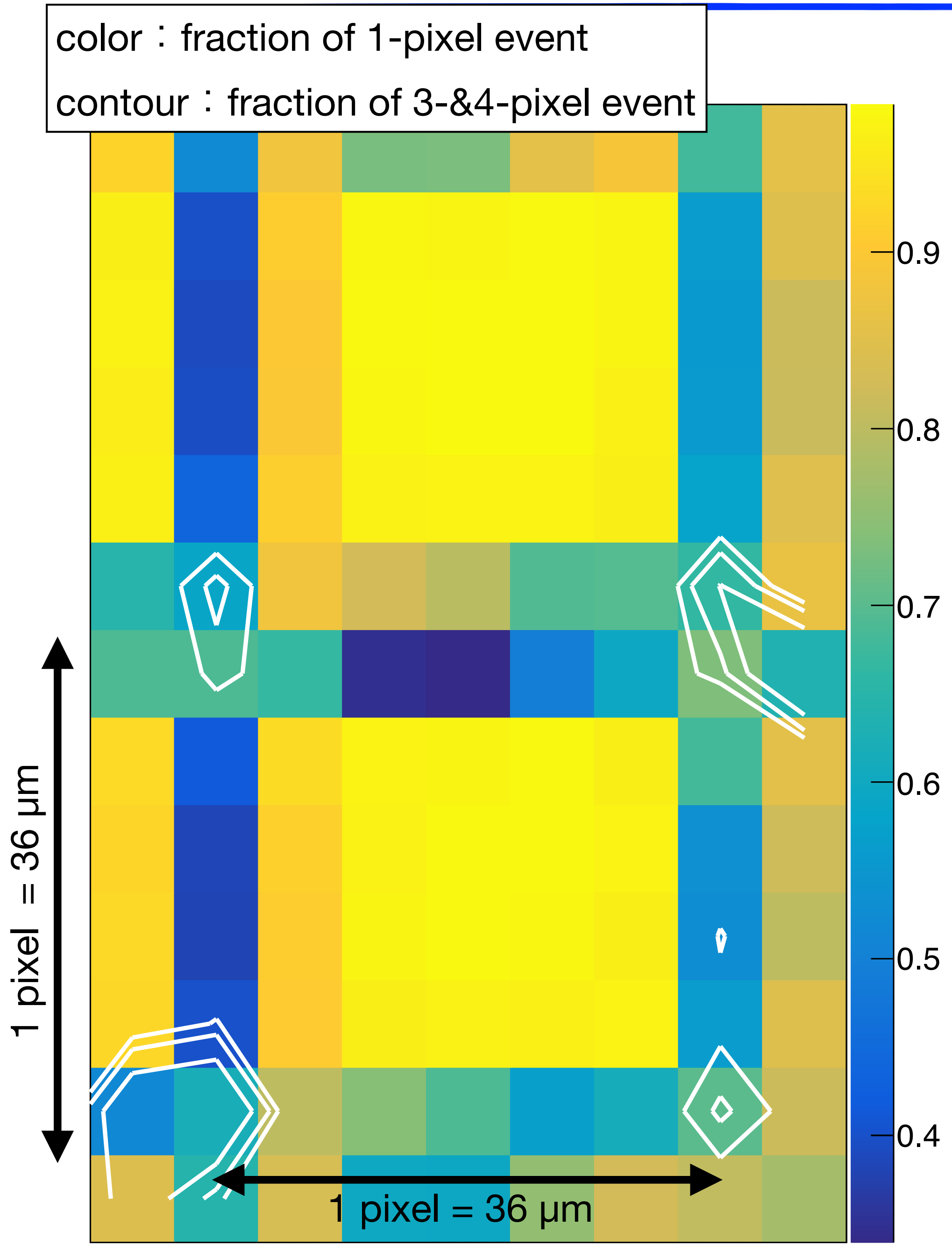


- Scanned with 6 μm pitch (1/6 of pixel size) by moving the detector with X-Z stage
- To correct variability of beam intensity, X-ray was periodically irradiated at a certain position as a reference



Estimation of pixel boundary





- We estimated the pixel boundary, by plotting fraction of 1-pixel/3&4-pixel events for each irradiation spots

- **We successfully obtained X-ray response of XRPIX6bD in sub-pixel (a few μm) scale**

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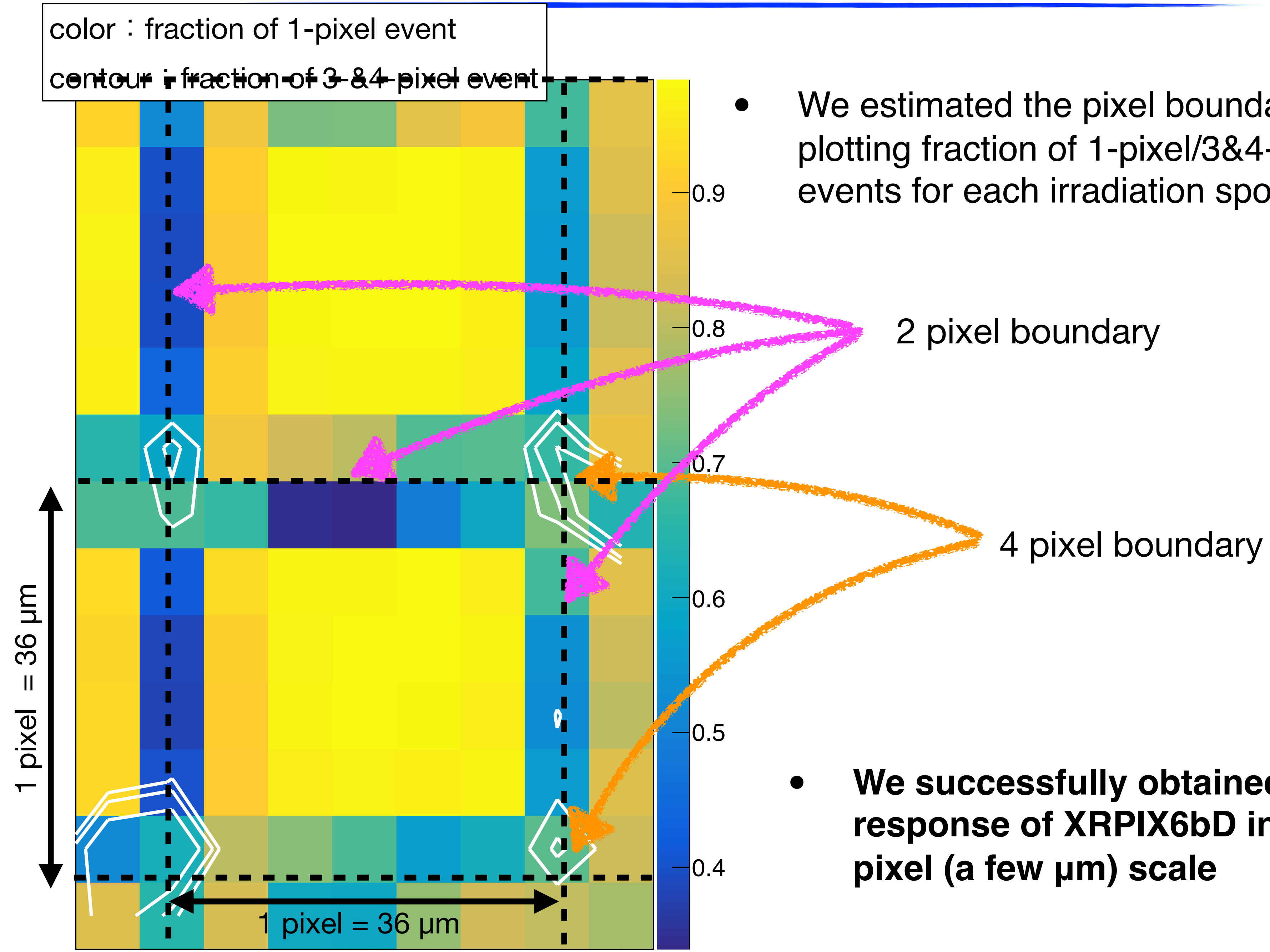

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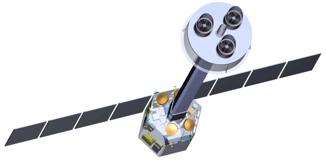
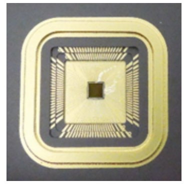
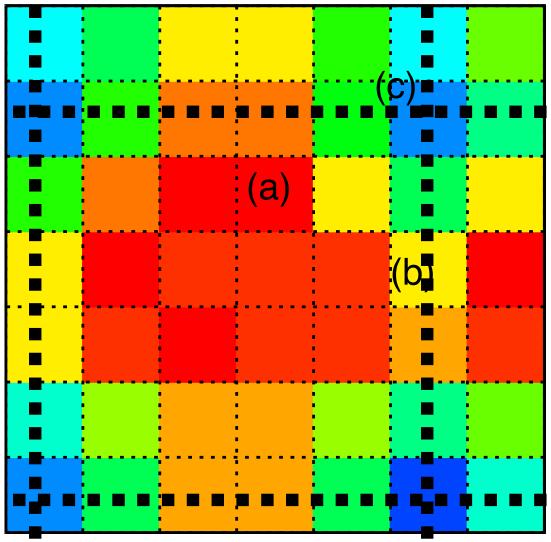


2D map of detection efficiency

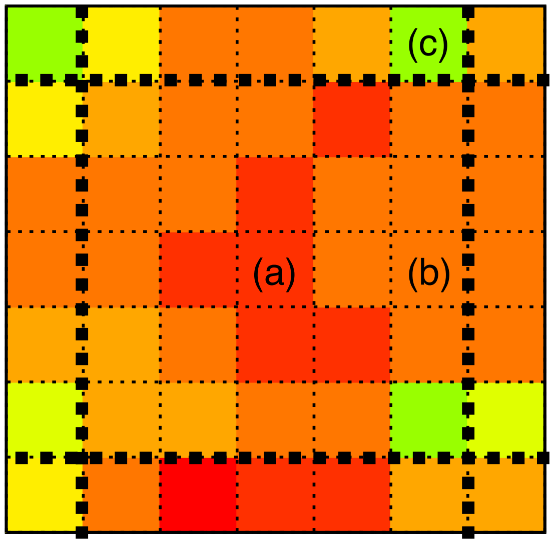


- We compared the 2D map of detected counts ($\propto$ detection efficiency) of XRPIX6bD with XRPIX1b and XRPIX3b

XRPIX1b

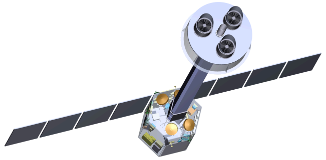


XRPIX3b
(improved circuit)



	XRPIX1b @ 8.0 keV	XRPIX3b @ 5.0 keV	XRPIX6bD @ 6.0 keV
2 pix. boundary	81.1 ± 2.8%	95.7 ± 2.2%	**96.1 ± 2.4%**
4 pix. boundary	22.4 ± 1.2%	76.3 ± 1.9%	**86.8 ± 2.1%**

- **Compared with XRPIX1b/3b, detection efficiency is very uniform in XRPIX6bD**



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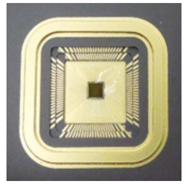

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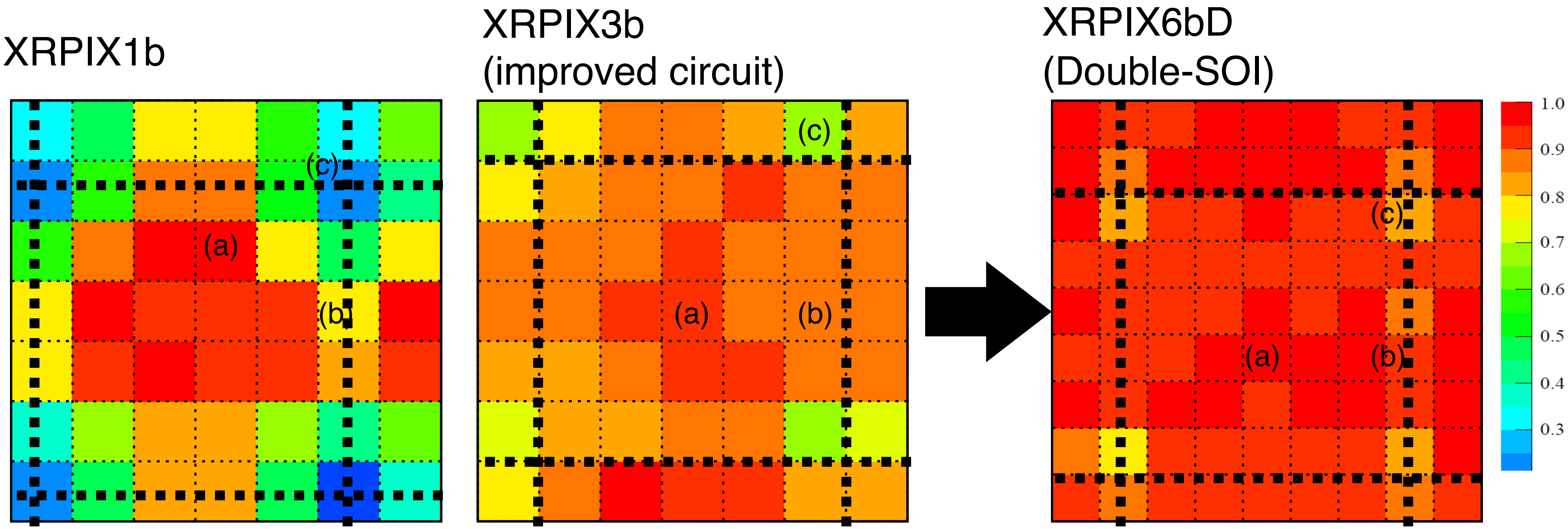

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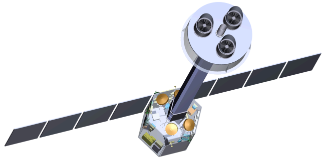

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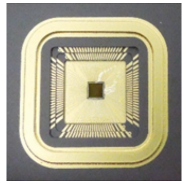

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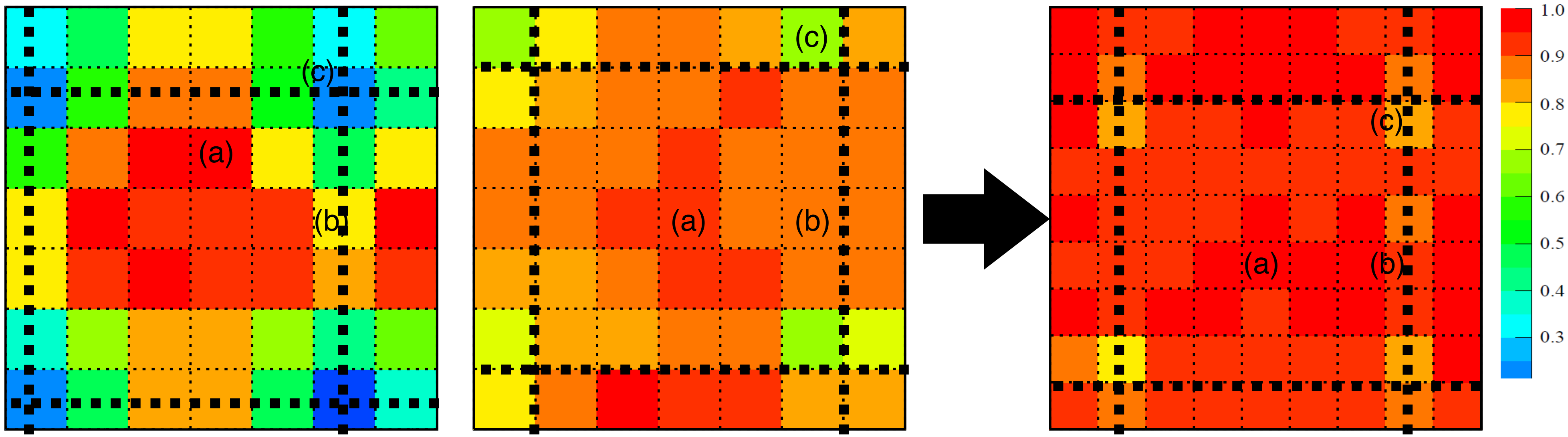
XRPIX1b

XRPIX3b
(improved circuit)

XRPIX6bD
(Double-SOI)



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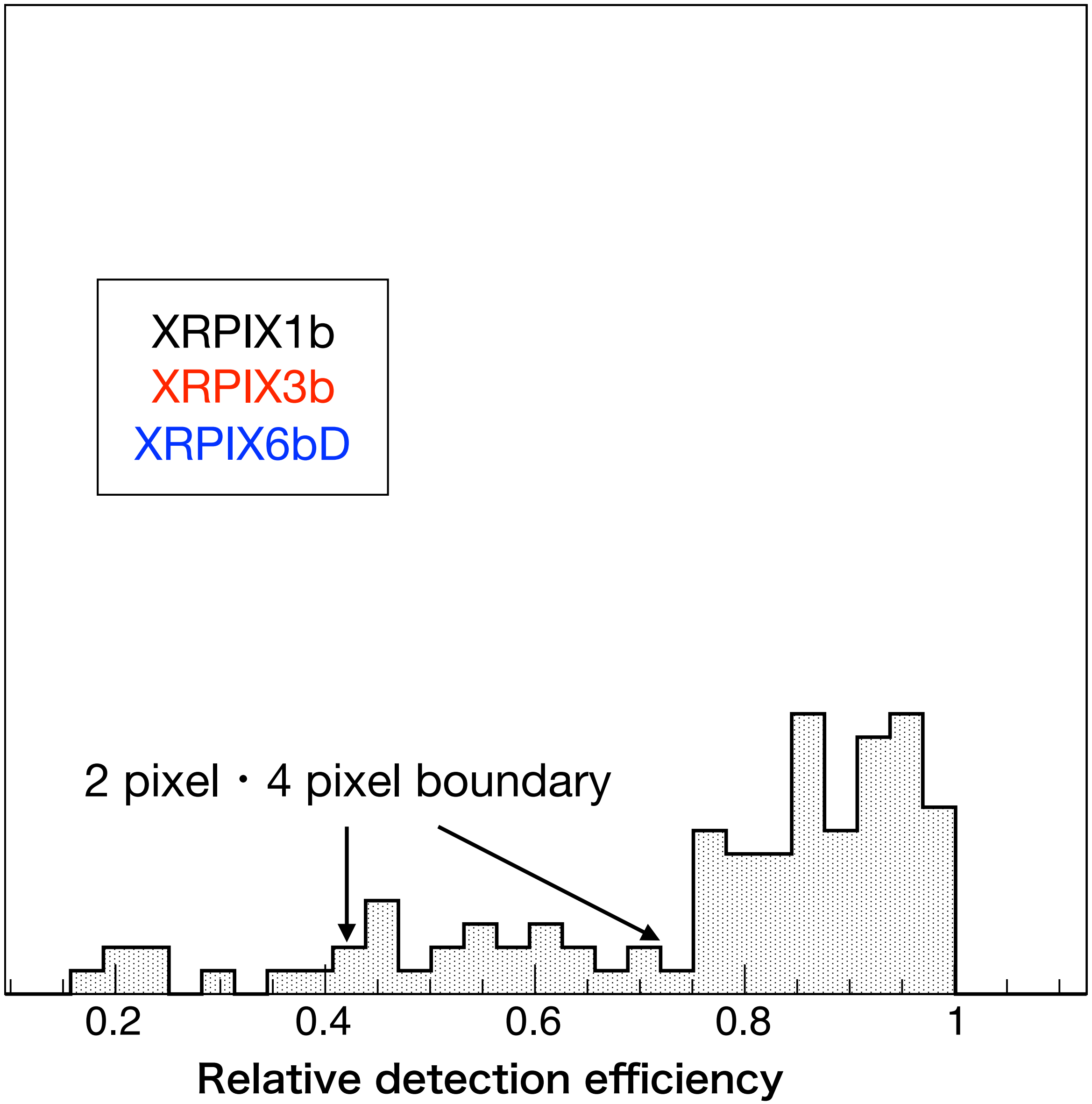
Uniformity of detection efficiency



- In order to evaluate the uniformity in the whole pixel, we plotted 1D histogram of detection efficiency for each irradiation spot
- **In XRPIX6bD, relative detection efficiency in sub-pixel scale is uniform with σ=2.7%**
- **Variation of detection efficiency (σ=2.7%) is in similar level to statistical uncertainty (σ~2%)**

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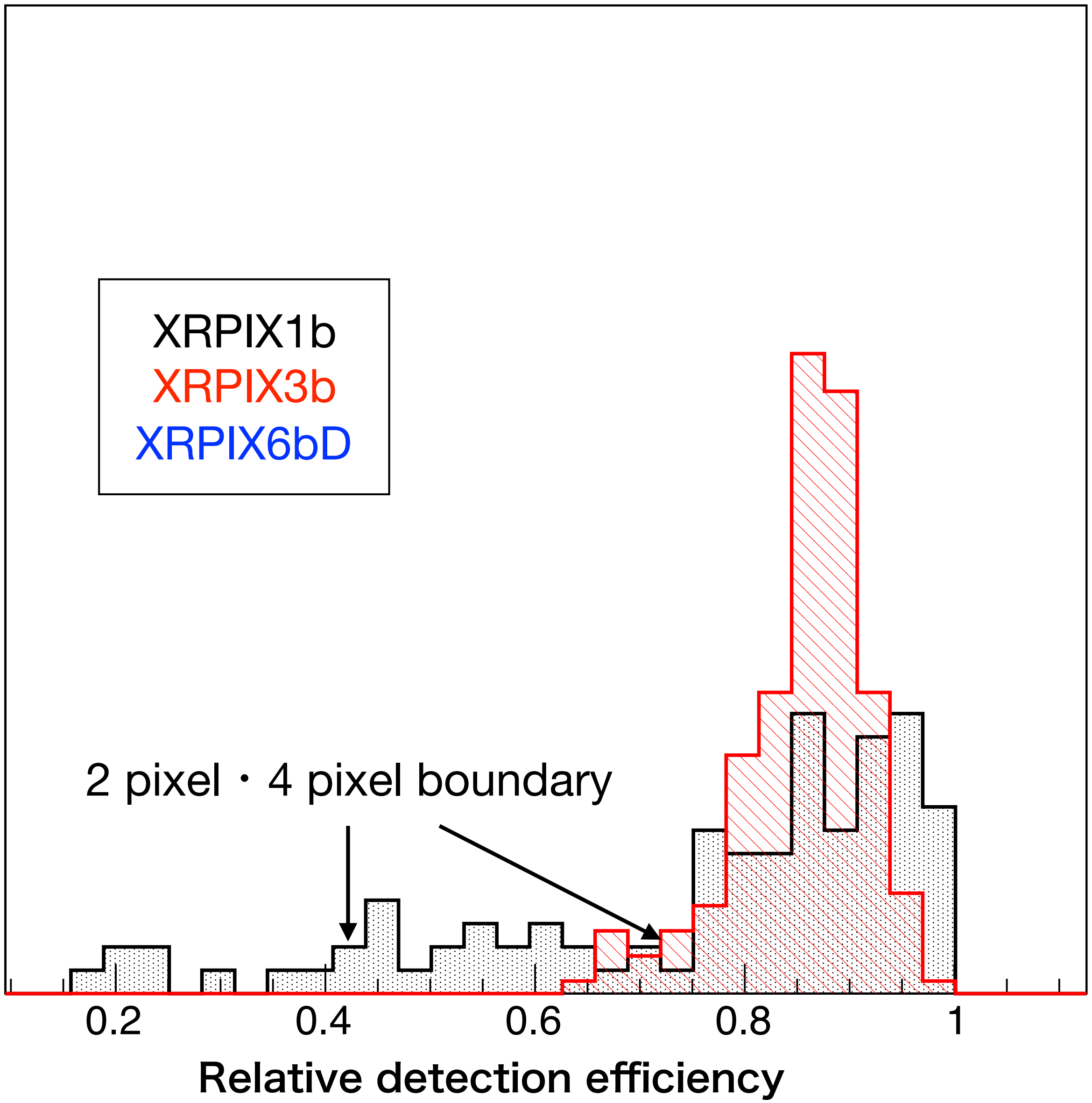

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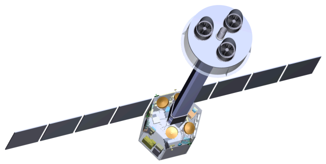

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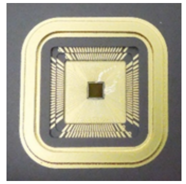

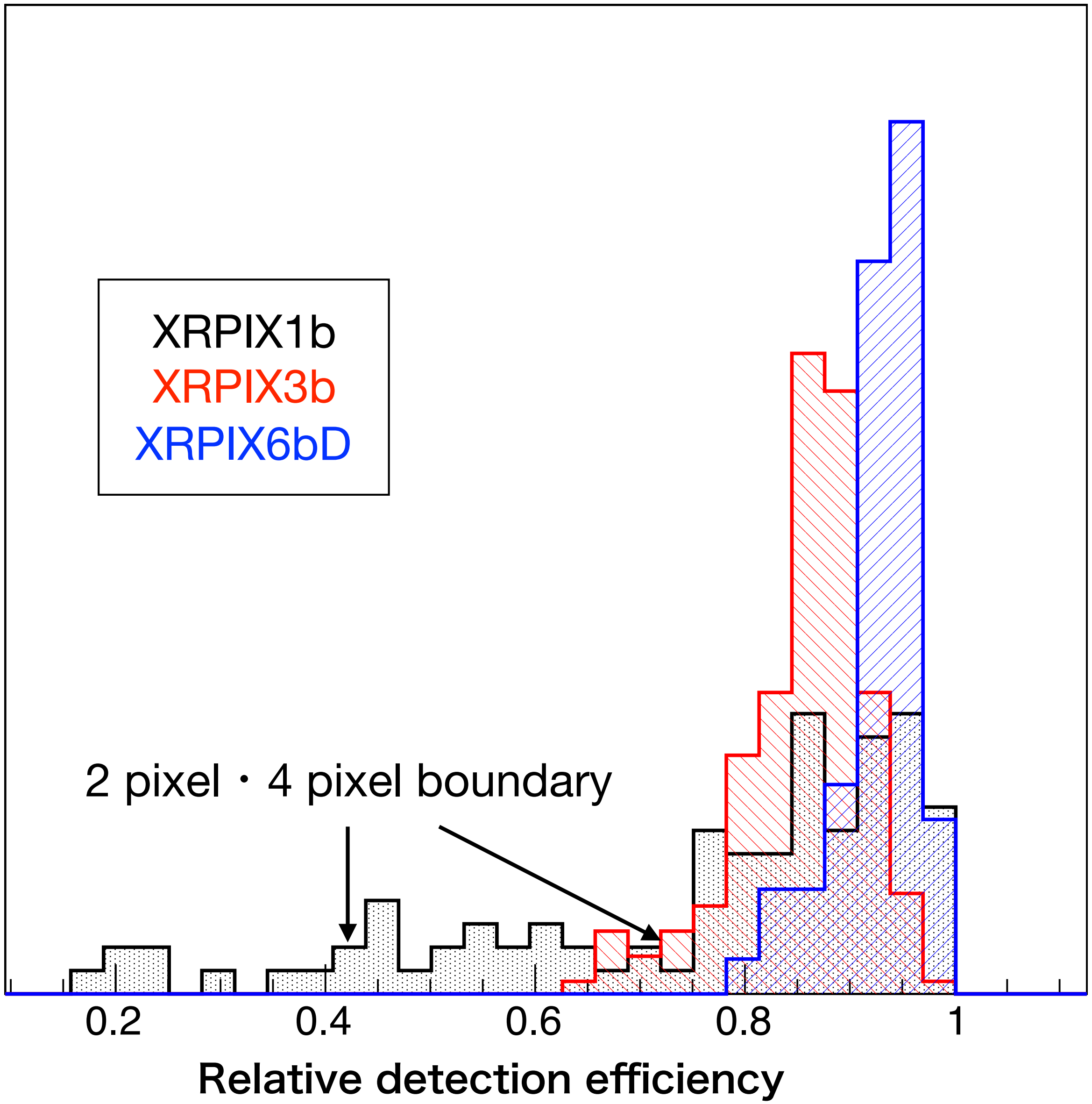

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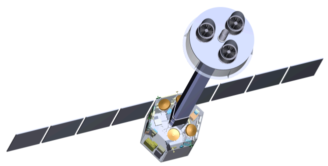

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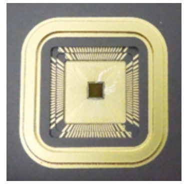

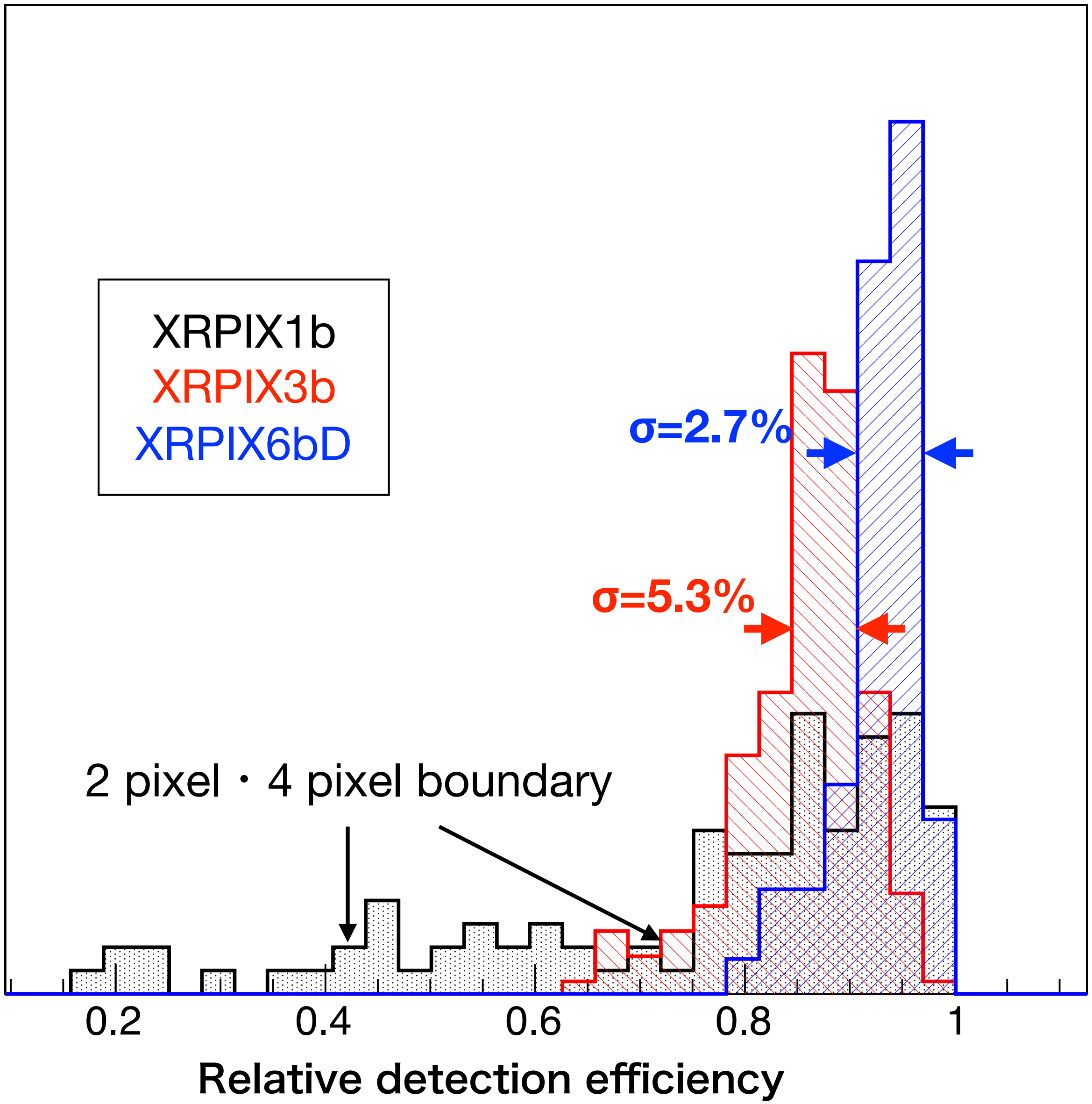

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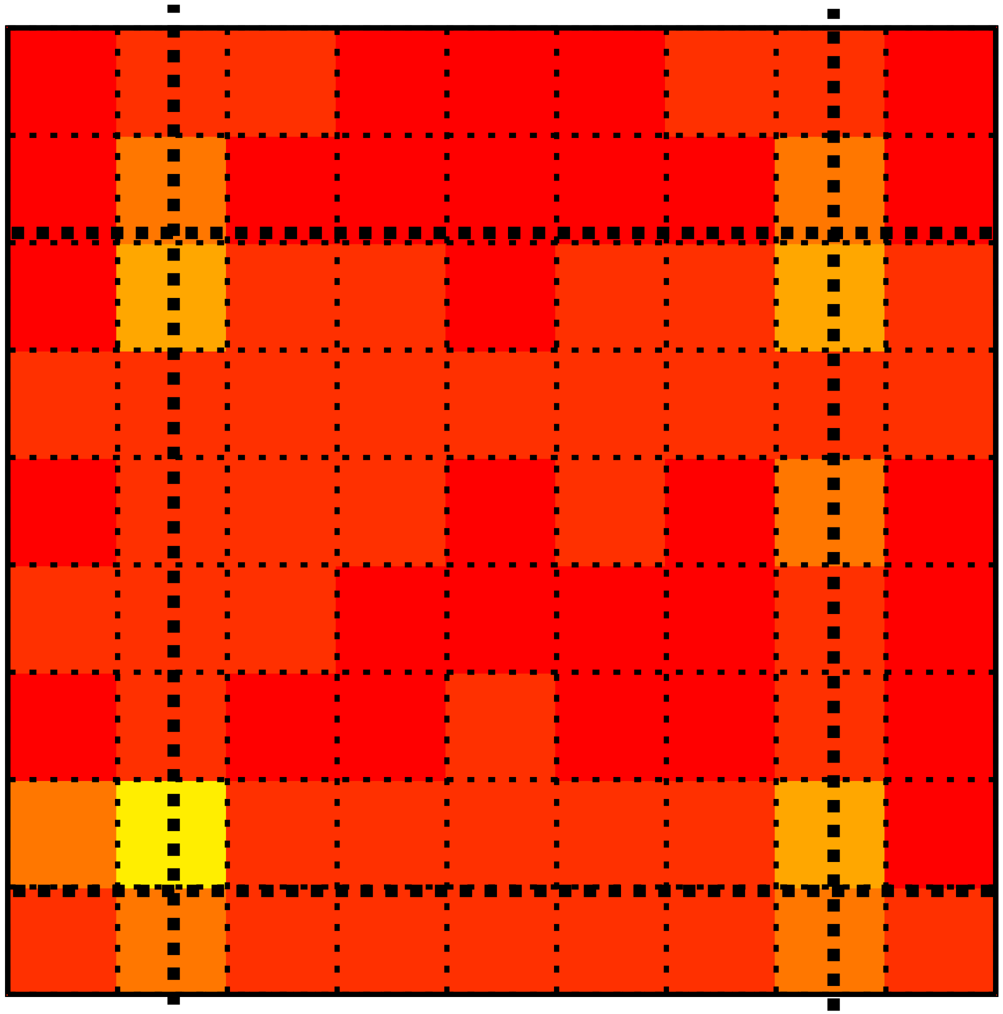
Remaining issue in spectral shape



- **At 3×3 spots (~12 μm × 12 μm) in pixel center, no charge loss is seen (sharp peak & no tail), while at pixel boundary ~50% of charge is lost**

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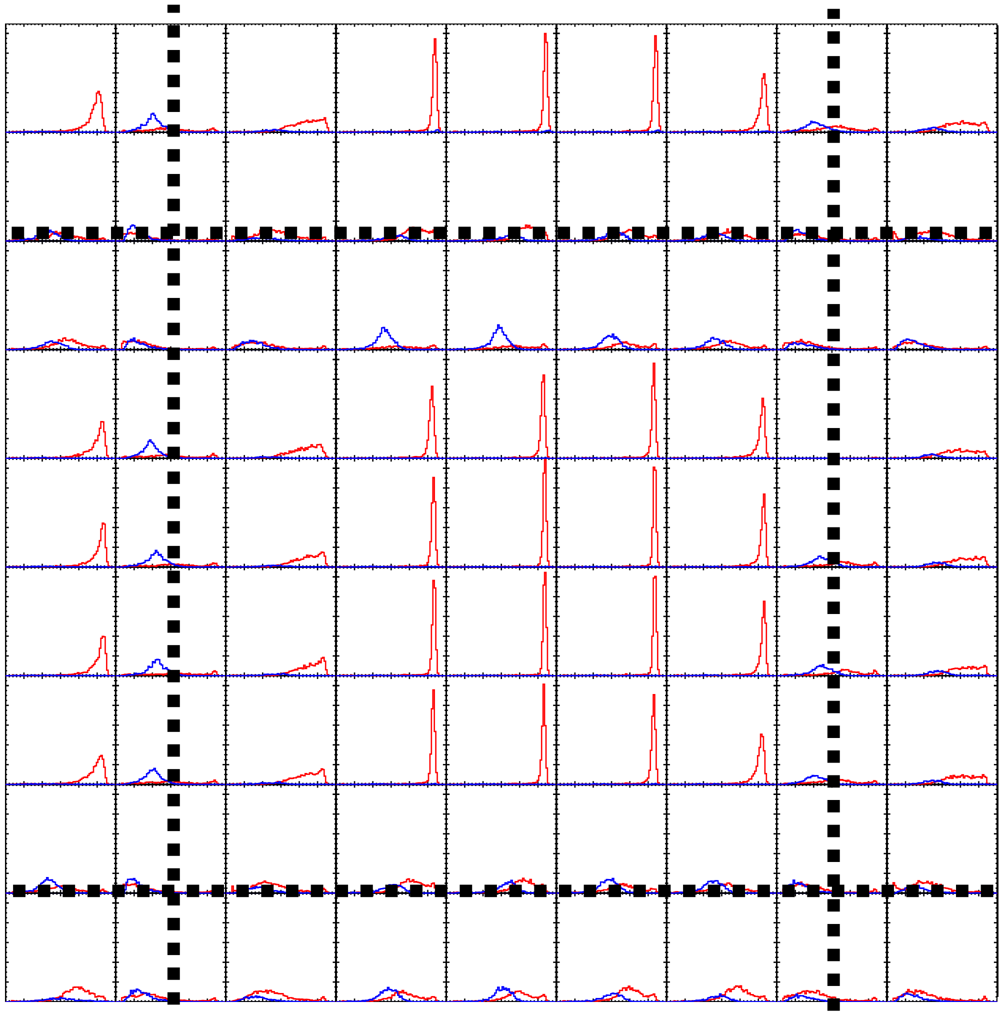

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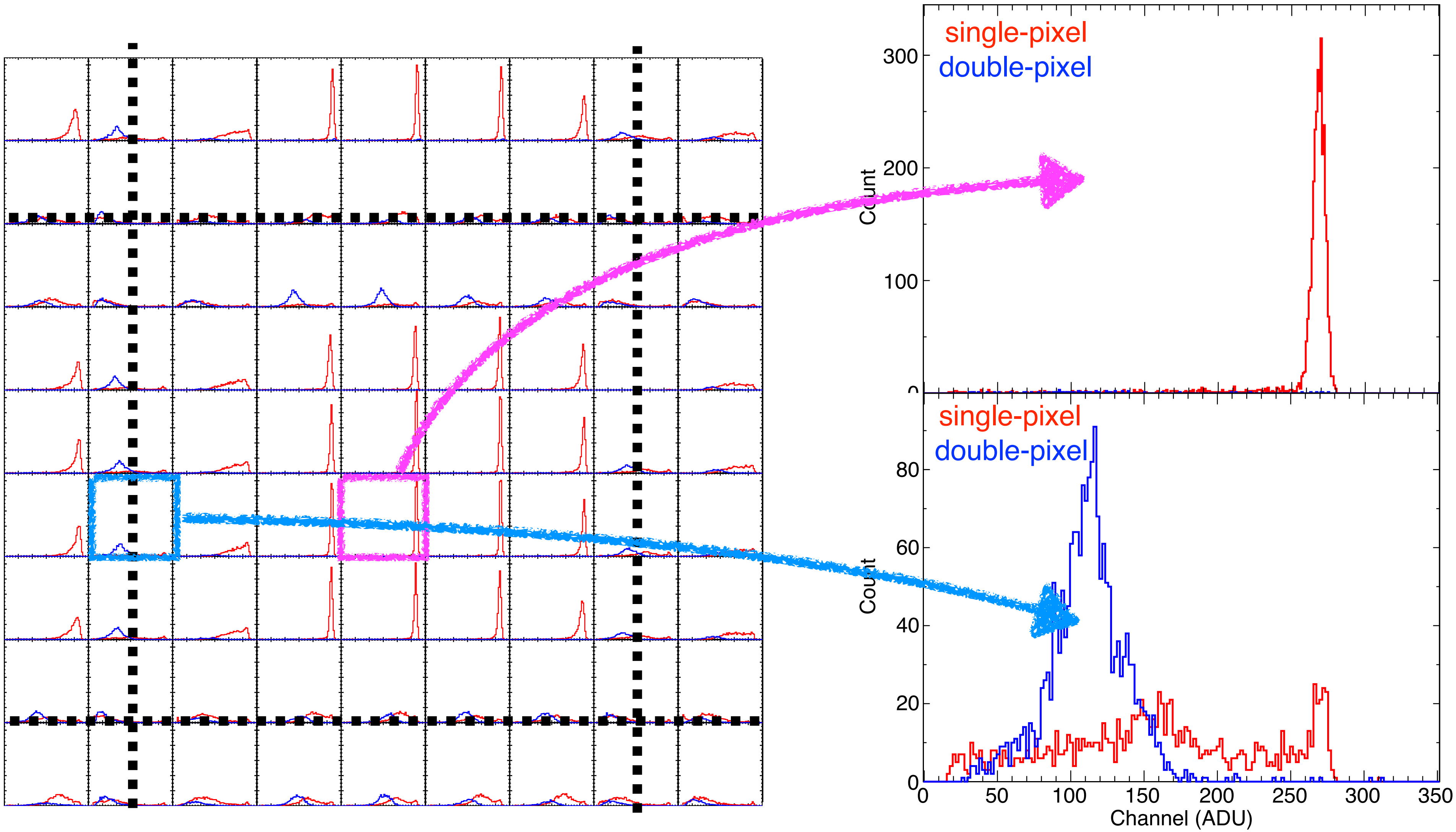

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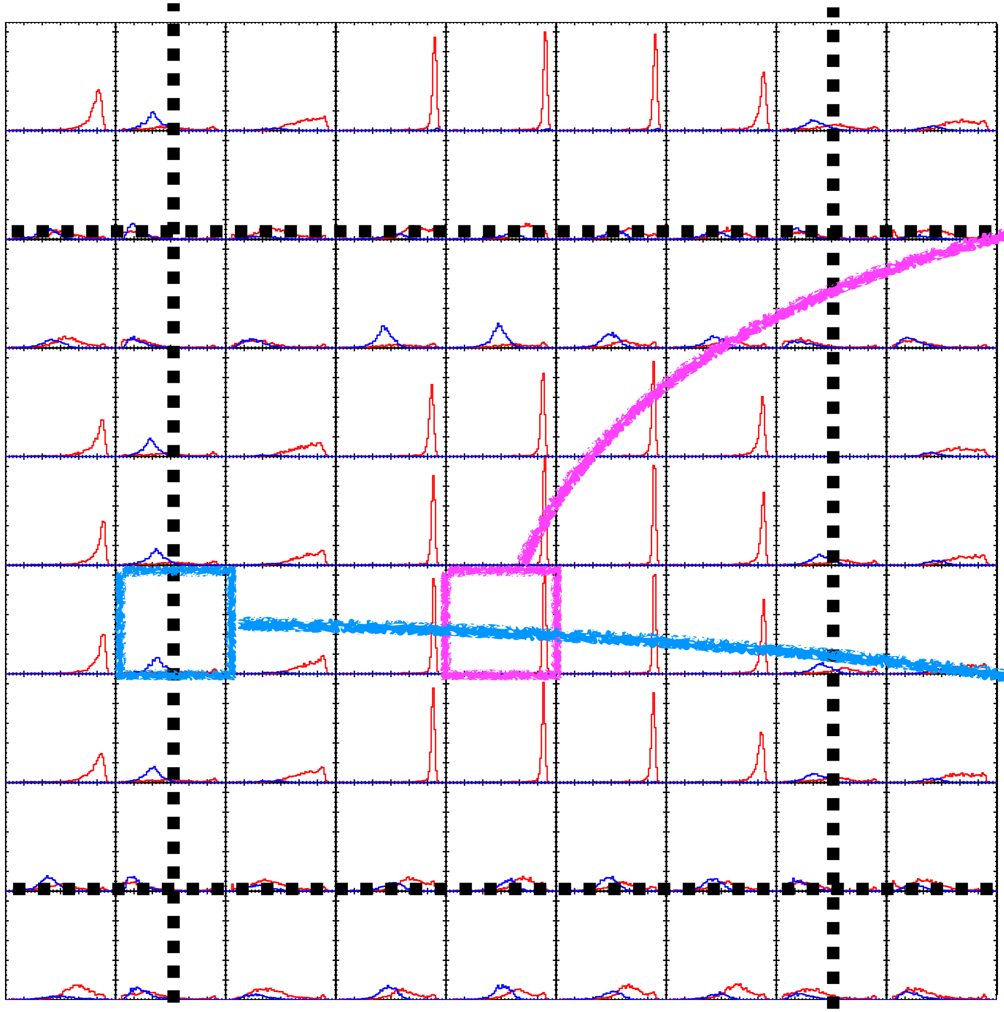

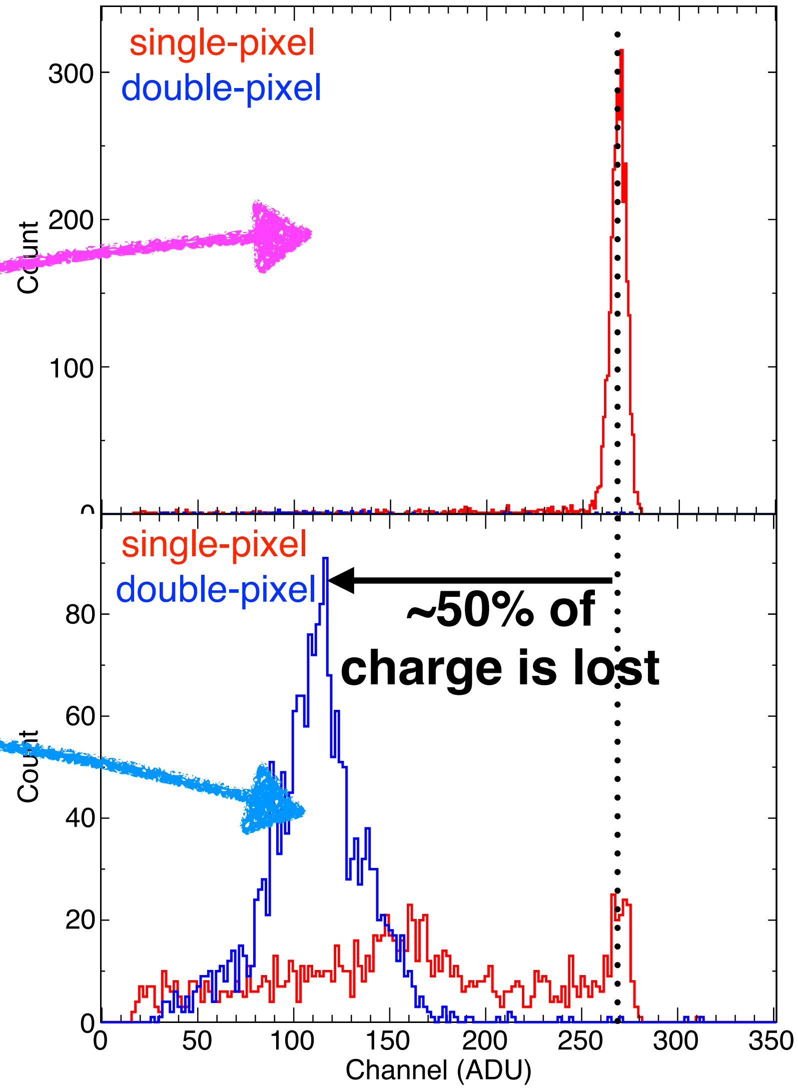

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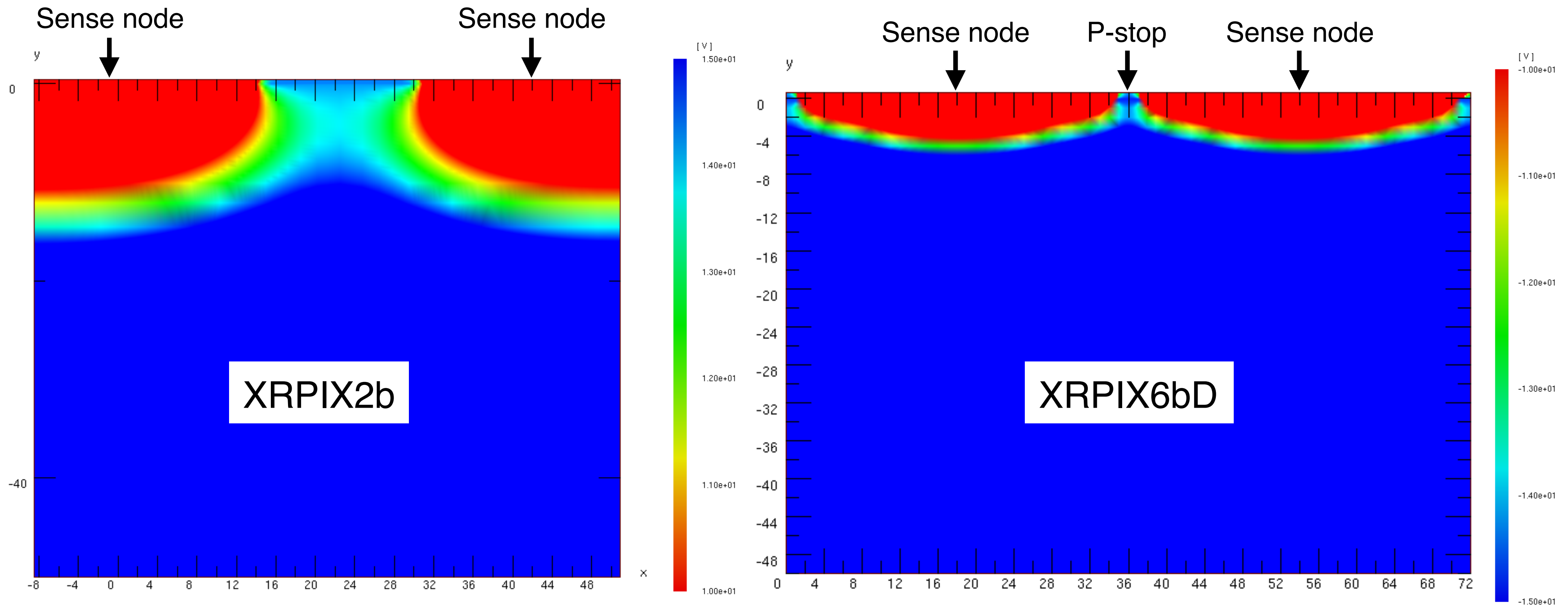
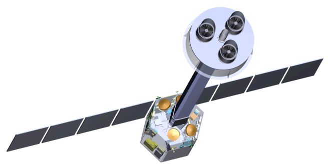
Charge loss due to electric field structure?

- We calculated the electrostatic potential in sensor layer of XRPIX6bD with TCAD device simulator “HyENEXSS”



- Potential local minimum is not seen at pixel boundary in XRPIX6bD
- According to this TCAD simulation, **charge loss seems to be NOT due to the electric field structure in XRPIX6bD.**



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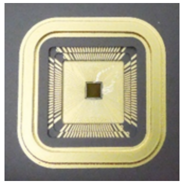

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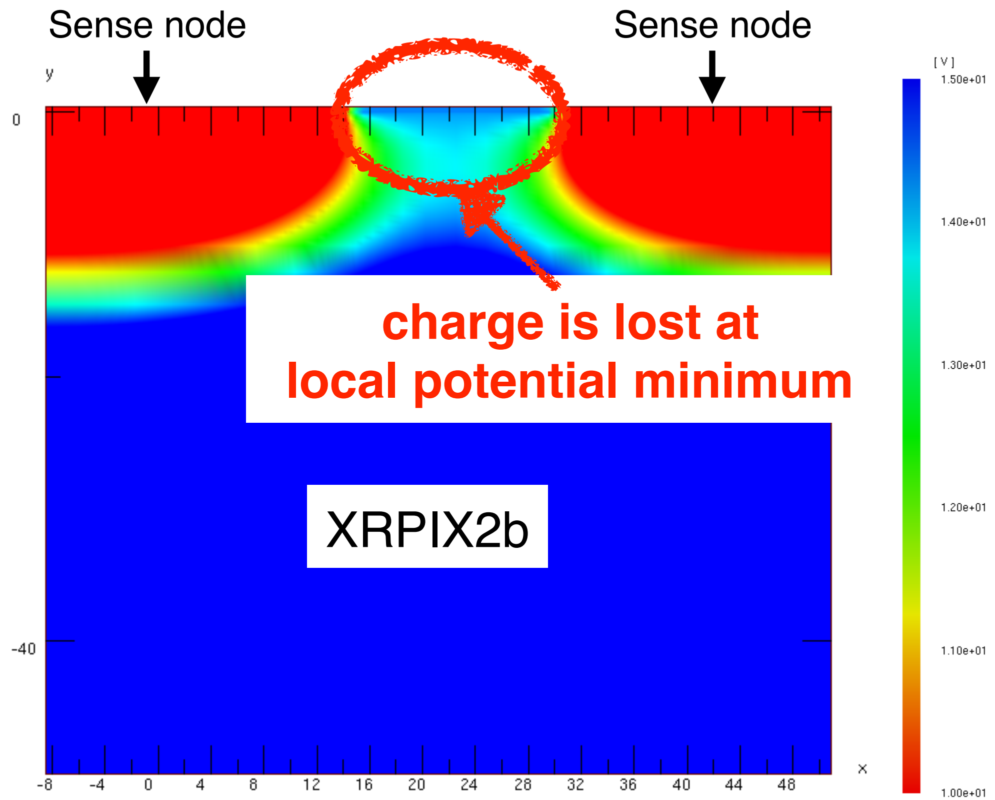

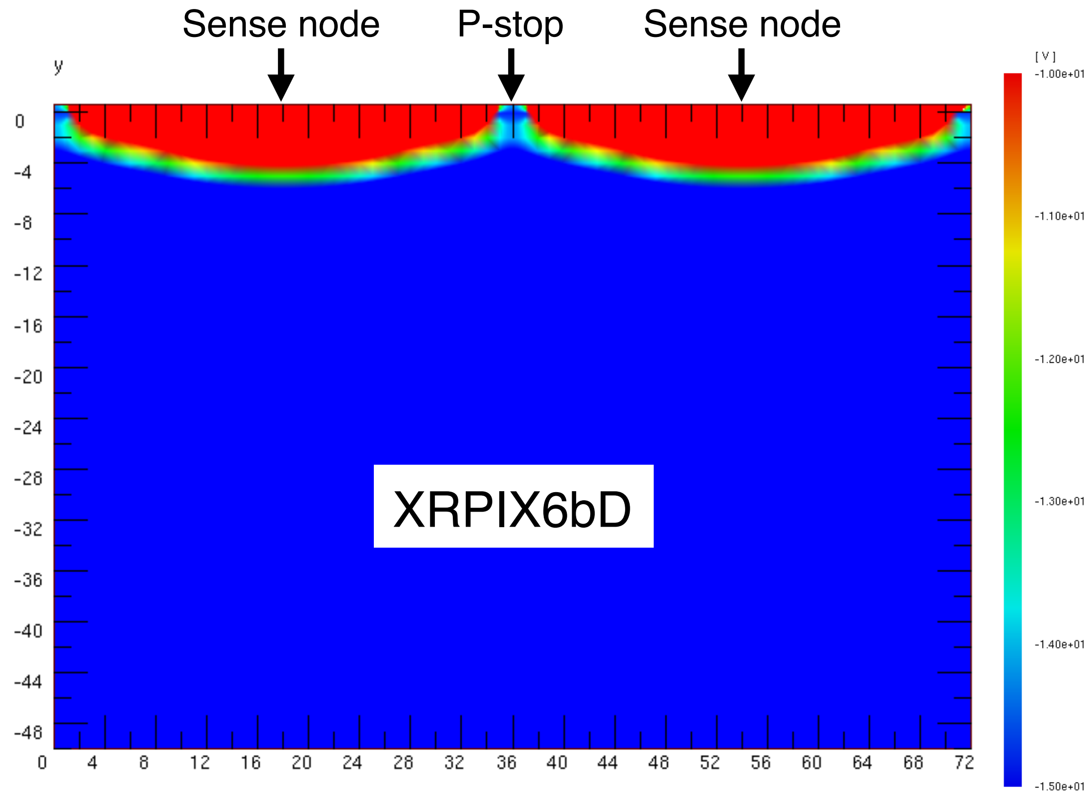

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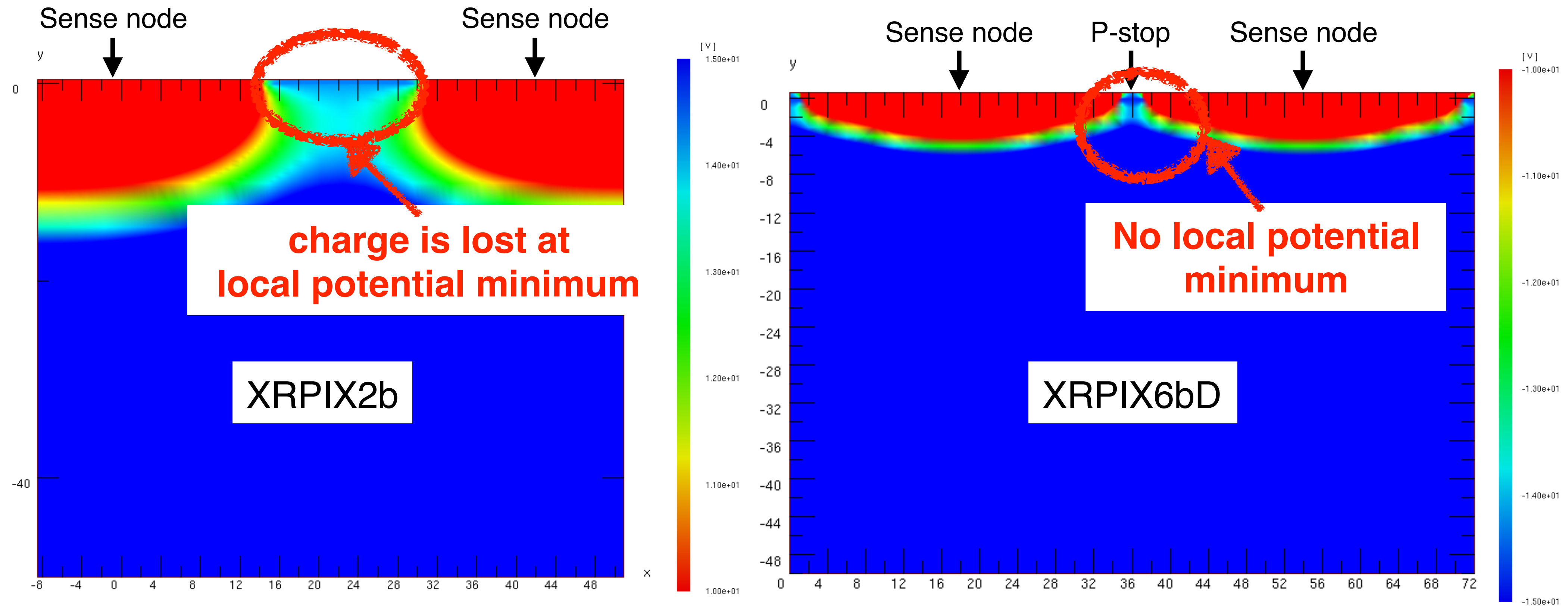

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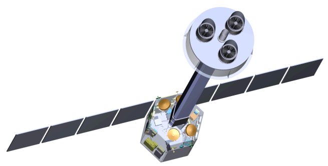
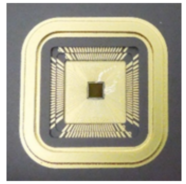
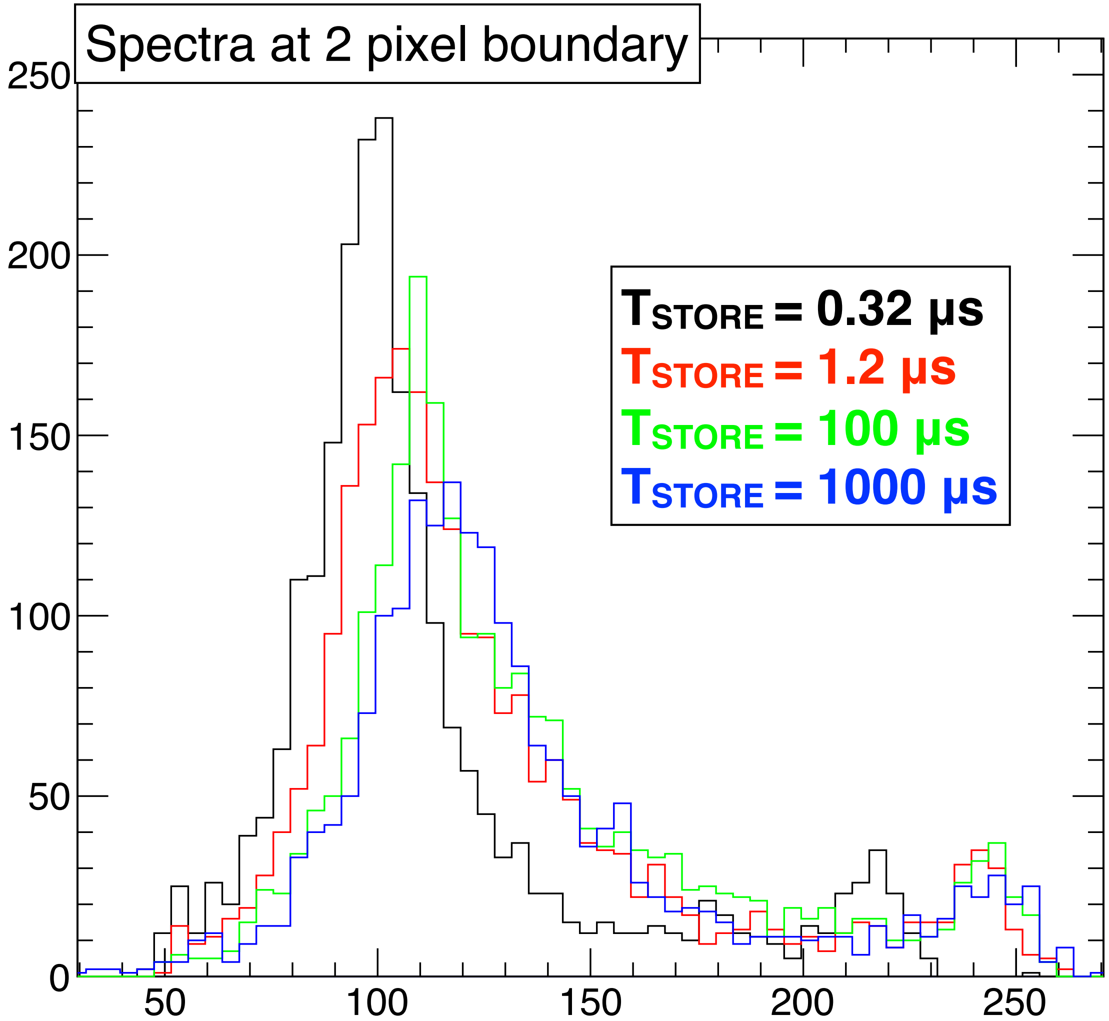


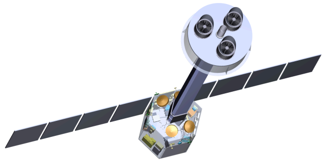
Long charge collection time





※T_{STORE} : exposure time after trigger generation

- XRPIX6bD shows dependence on the charge integration time in very long time scale of **~100 µs** or more
- Too long to be explained by weak electric field because ~100 µs requires E = v/µ ~ 0.1 V/cm



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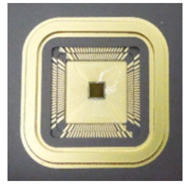

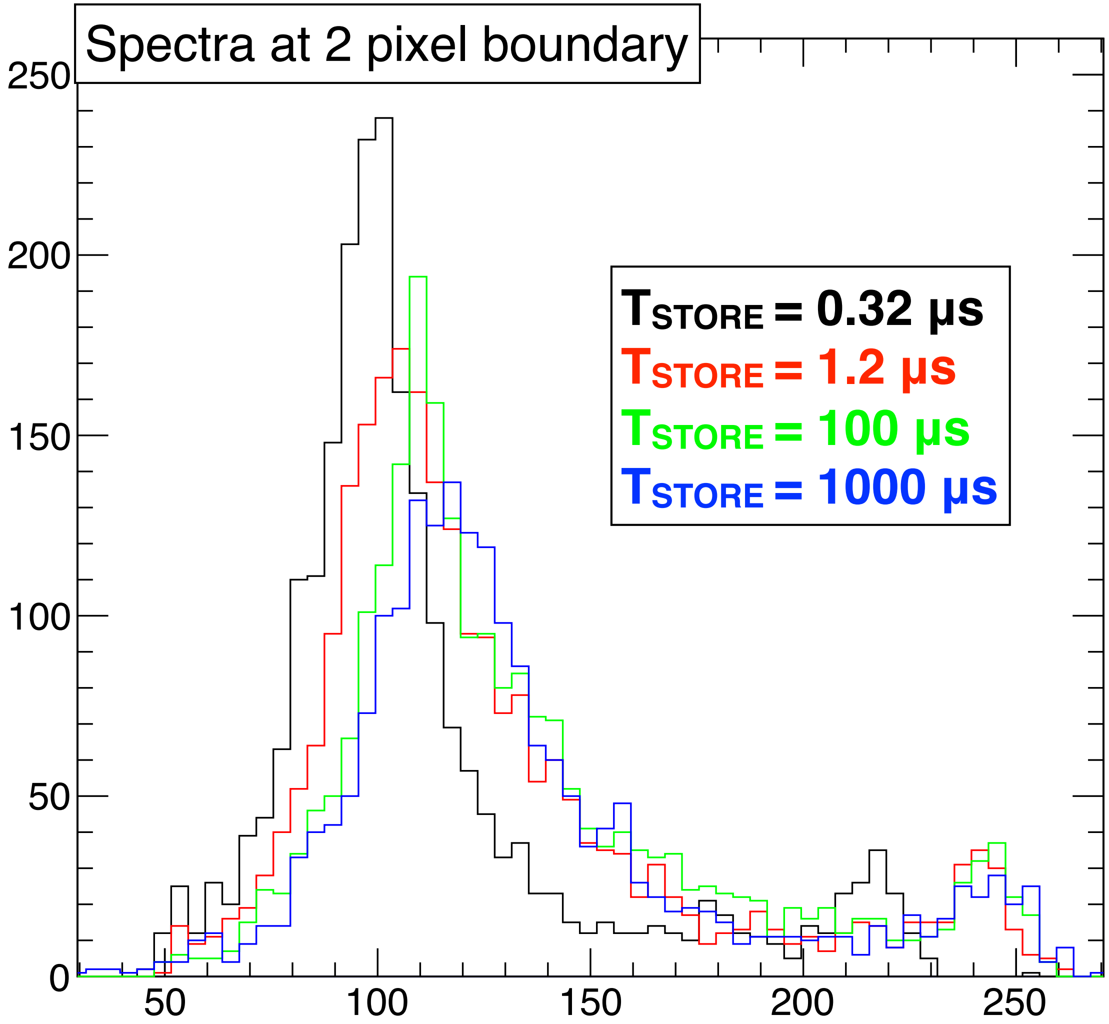

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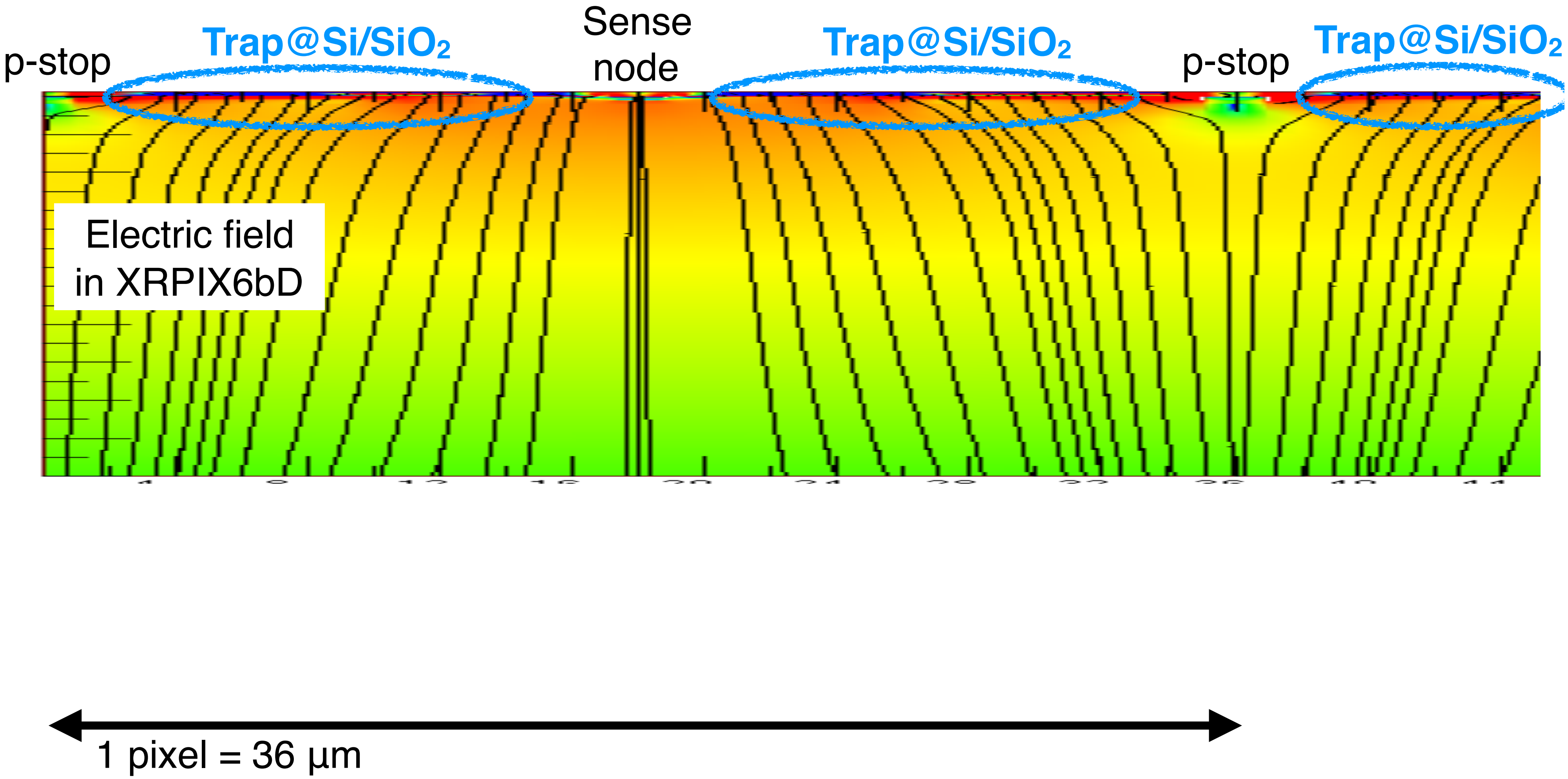
➡ **The other effect than electric field structure must be one of the causes of charge loss issue**

Charge trapping at Si/SiO_2 interface?

- We speculate that the charge loss seen in the spectral shape is due to charge trapping (with τ~100 μs?) at Si/SiO_2 interface



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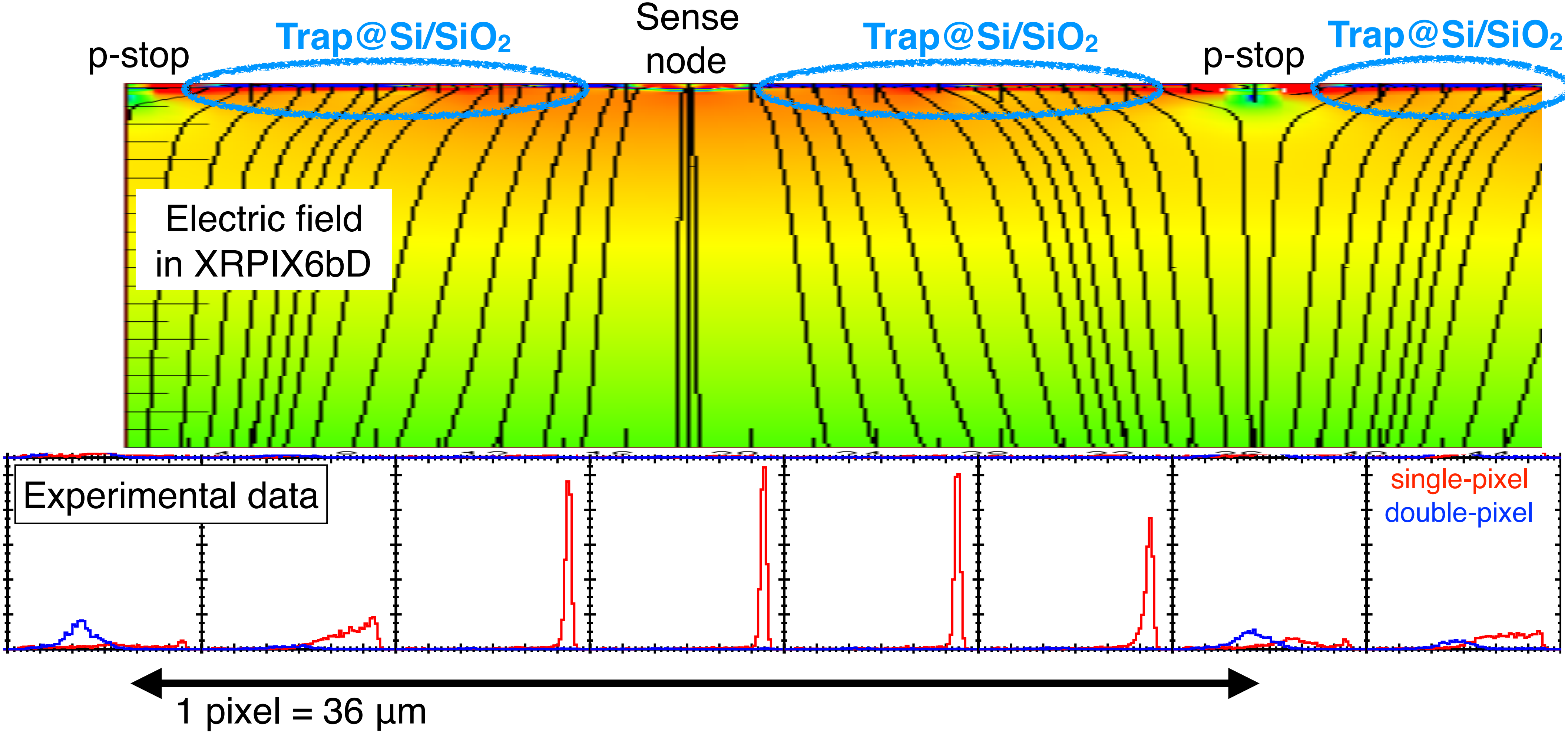

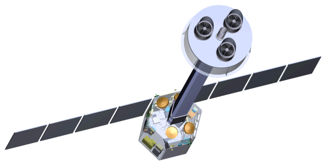

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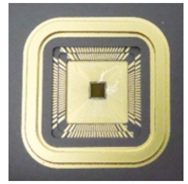

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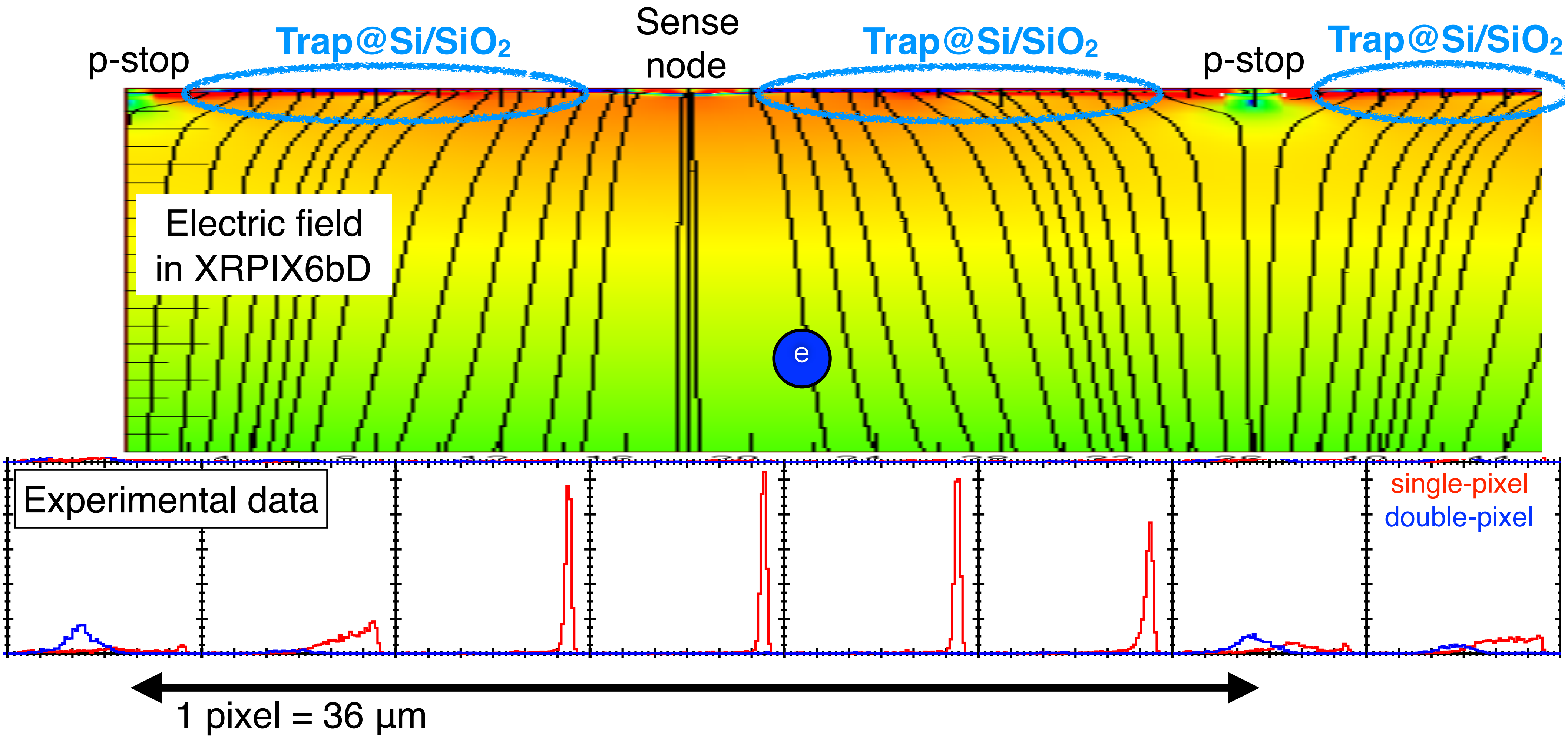

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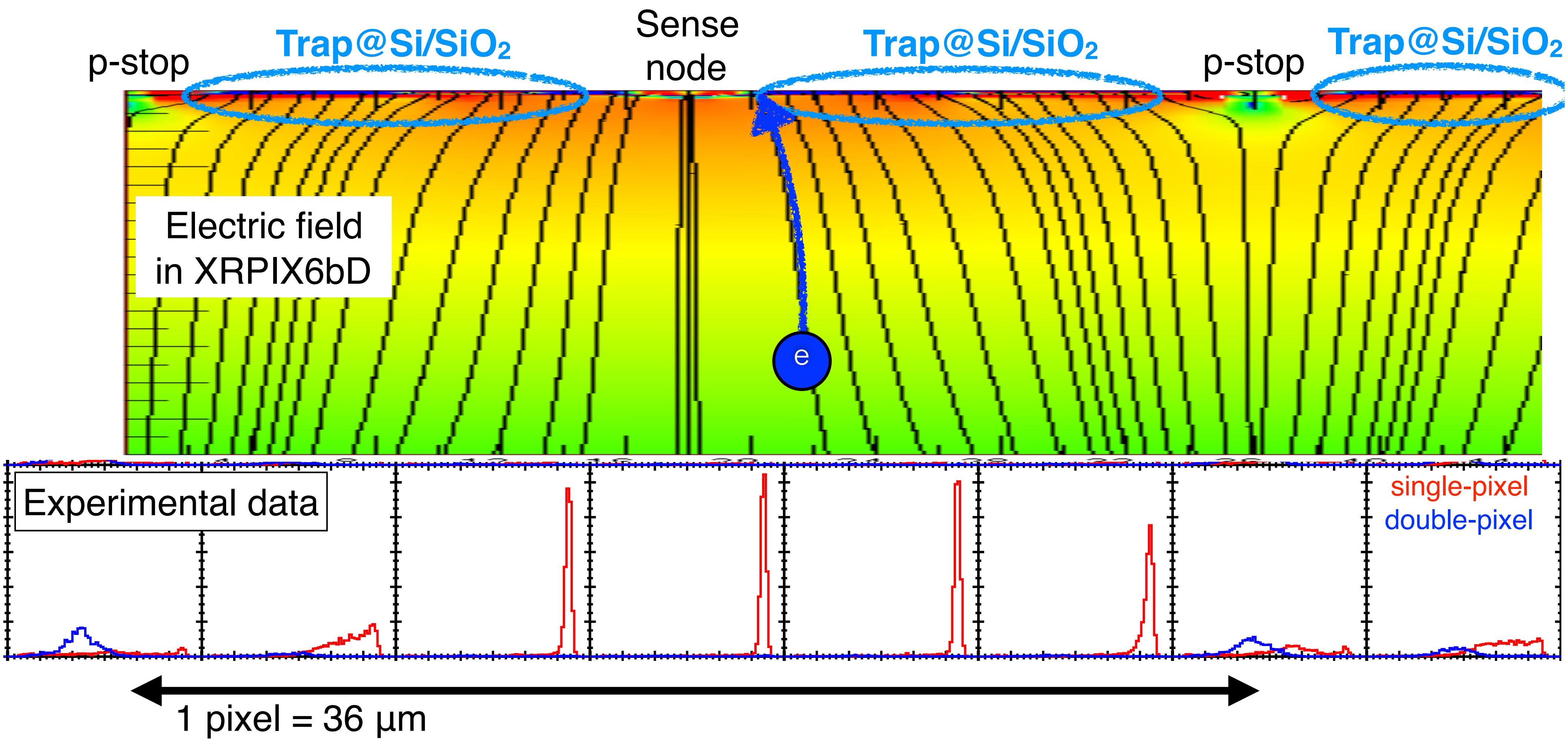

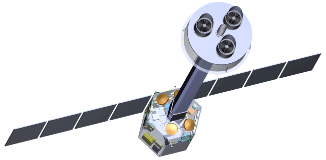

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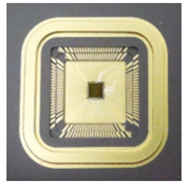

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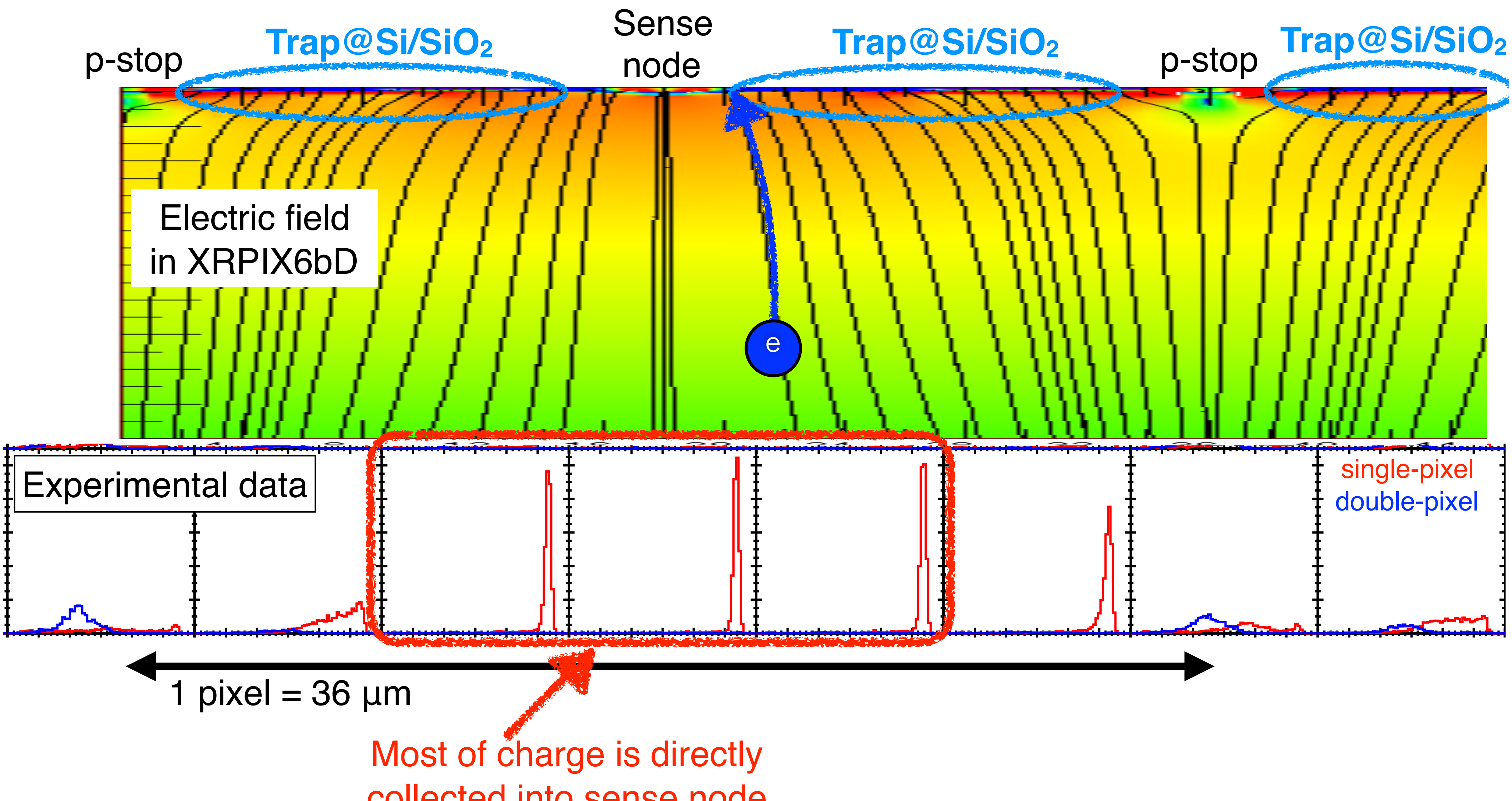

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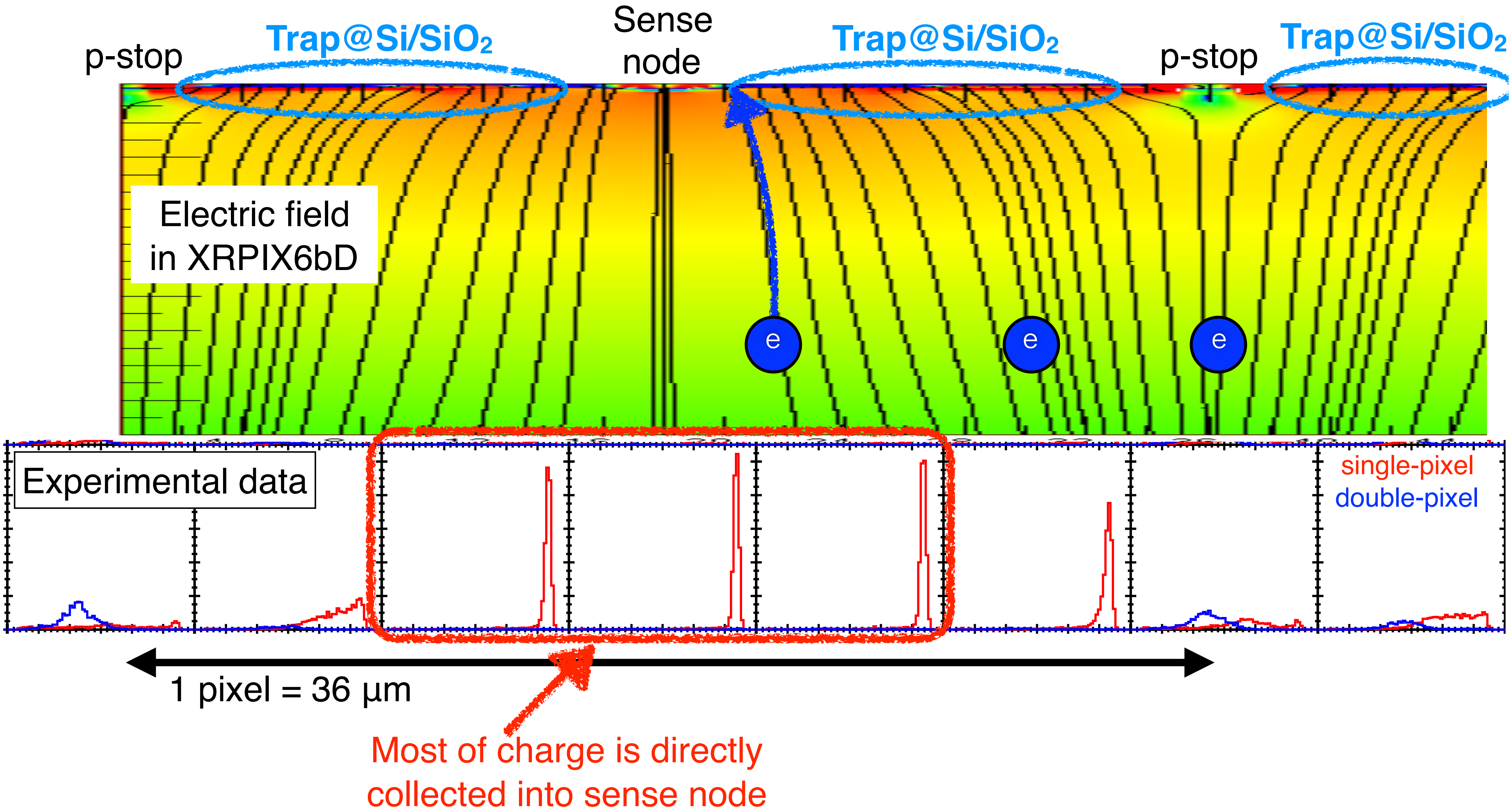

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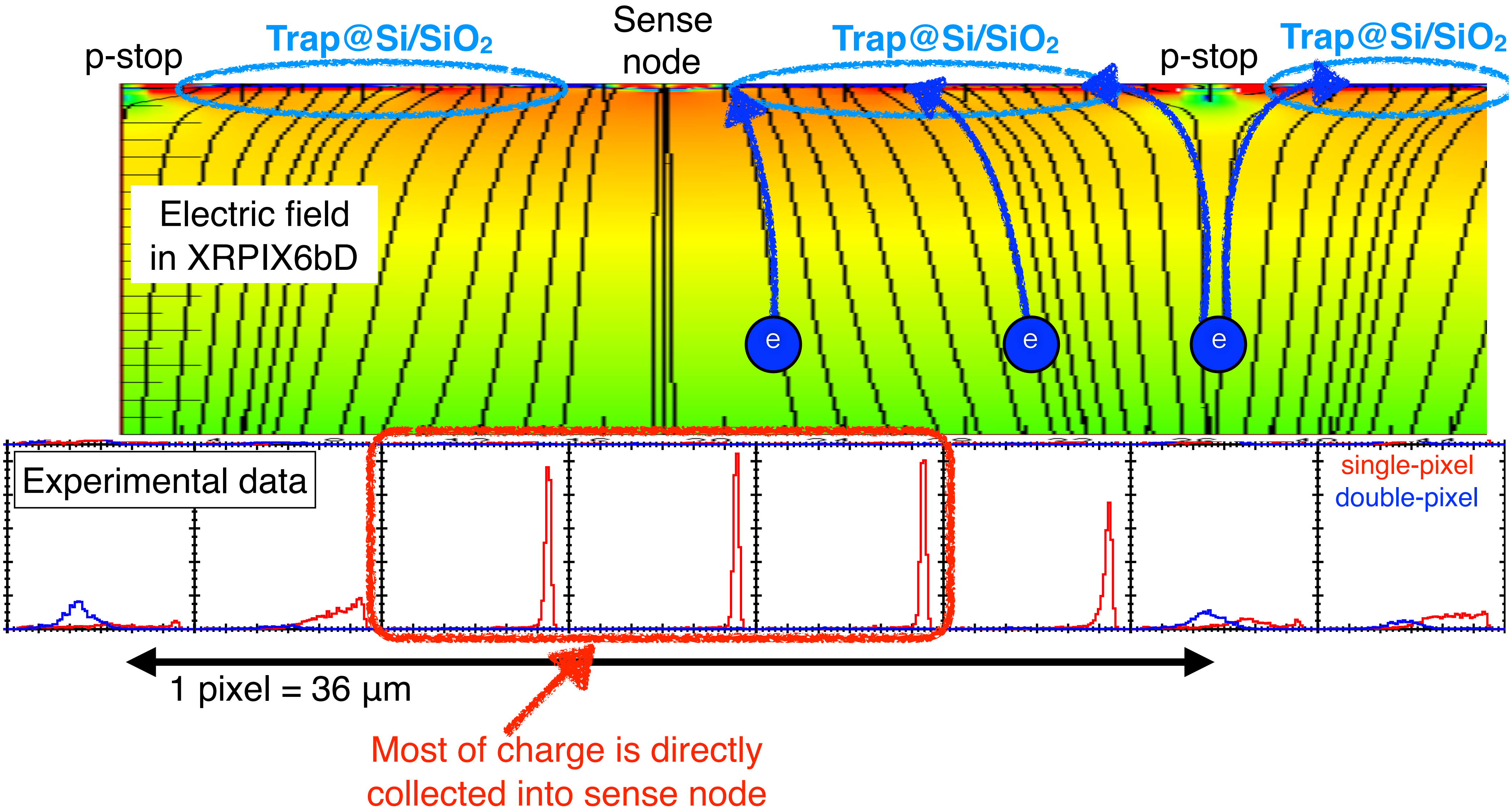

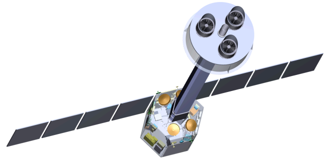

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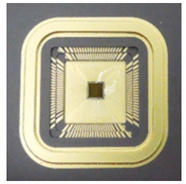

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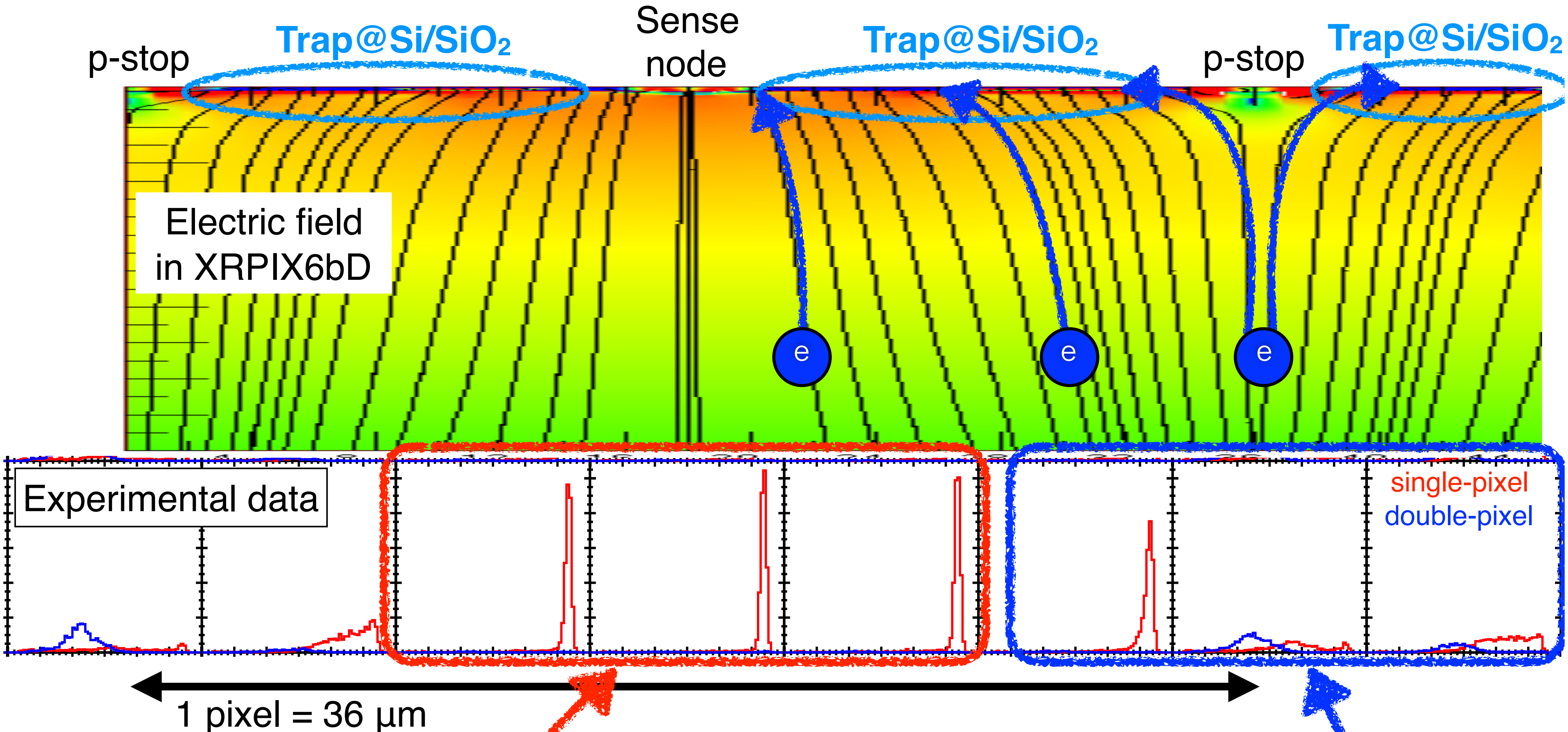
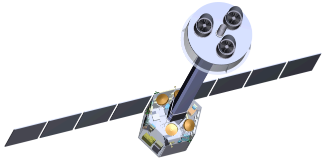
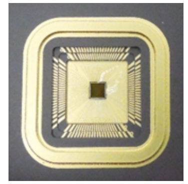


Most of charge is directly collected into sense node

Charge is trapped at Si/SiO$_2$ interface, and not fully collected into sense node



Summary



- We have evaluated X-ray response in subpixel scale of double-SOI type X-ray detector “XRPIX6bD” at at a synchrotron radiation facility Photon Factory of KEK in Japan.
- Detection efficiency at 4 pixel boundary was improved from 76% in XRPIX3b to 88% in XRPIX6bD
- We found an issue in spectra in which ~50% of charge was lost at pixel boundary
- Based on TCAD device simulation, charge loss is not explained by only the electric field structure
- We speculate that the charge loss issue is caused by charge trapping at Si/SiO_2 interface