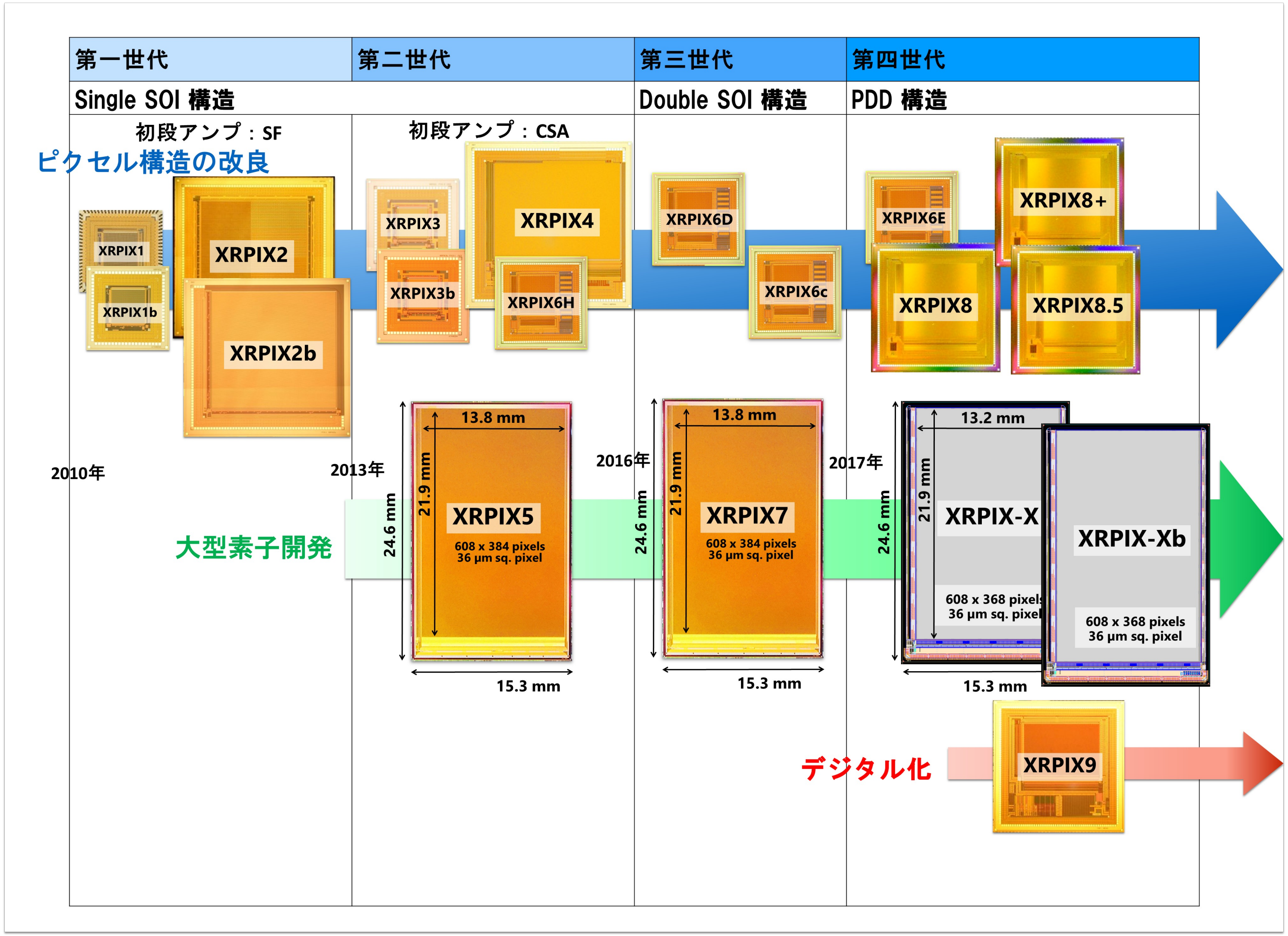
高比抵抗ウェハを用いた
Ｘ線SOI-CMOS検出器の試作

X-ray SOI pixel detector made with high-resistivity substrate

2025-12-01

森 浩二 (宮崎大学)、the XRPIX collaboration

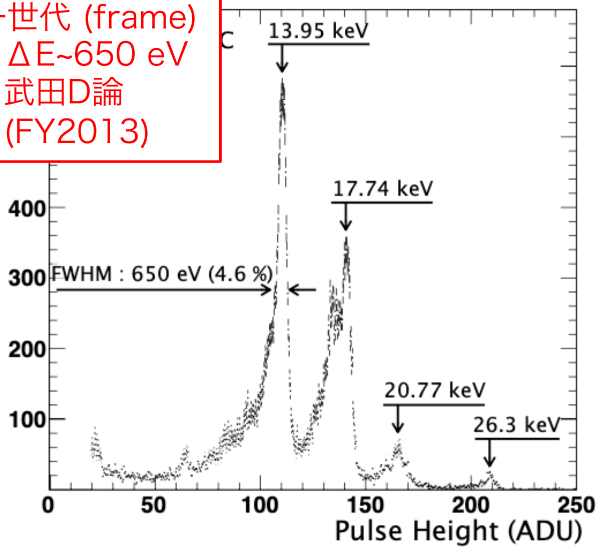
History of XRPIX development



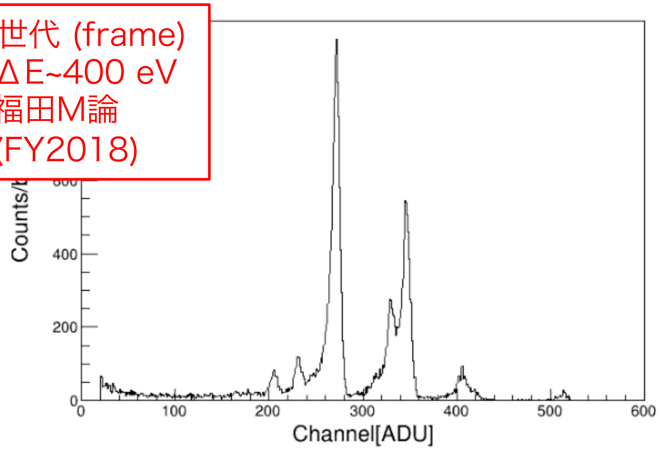
- The history of XRPIX is almost a history of its spectroscopic performance
  - Enlargement and Digitization do not make sense without spectroscopic performance

History of XRPIX development

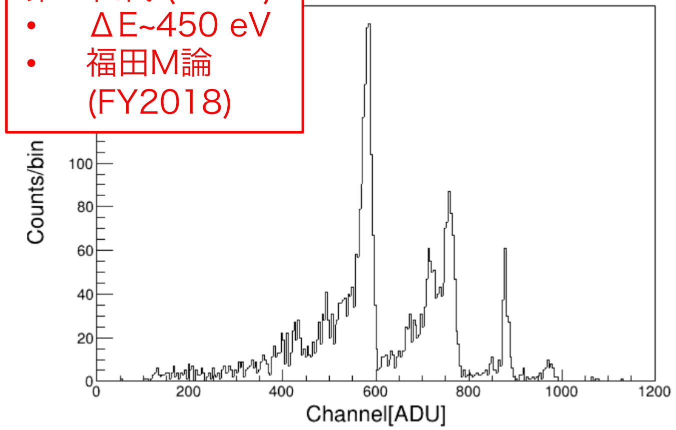
第一世代 (frame)
- ΔE~650 eV
- 武田D論 (FY2013)



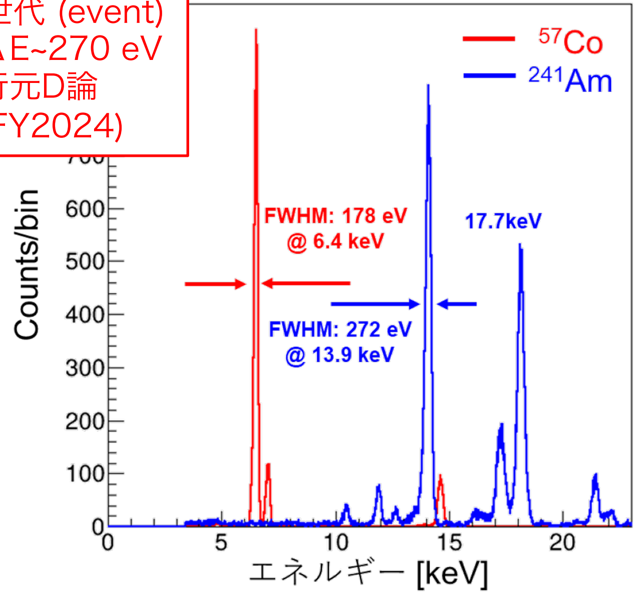
第二世代 (frame)
- ΔE~400 eV
- 福田M論 (FY2018)



第三世代 (event)
- ΔE~450 eV
- 福田M論 (FY2018)

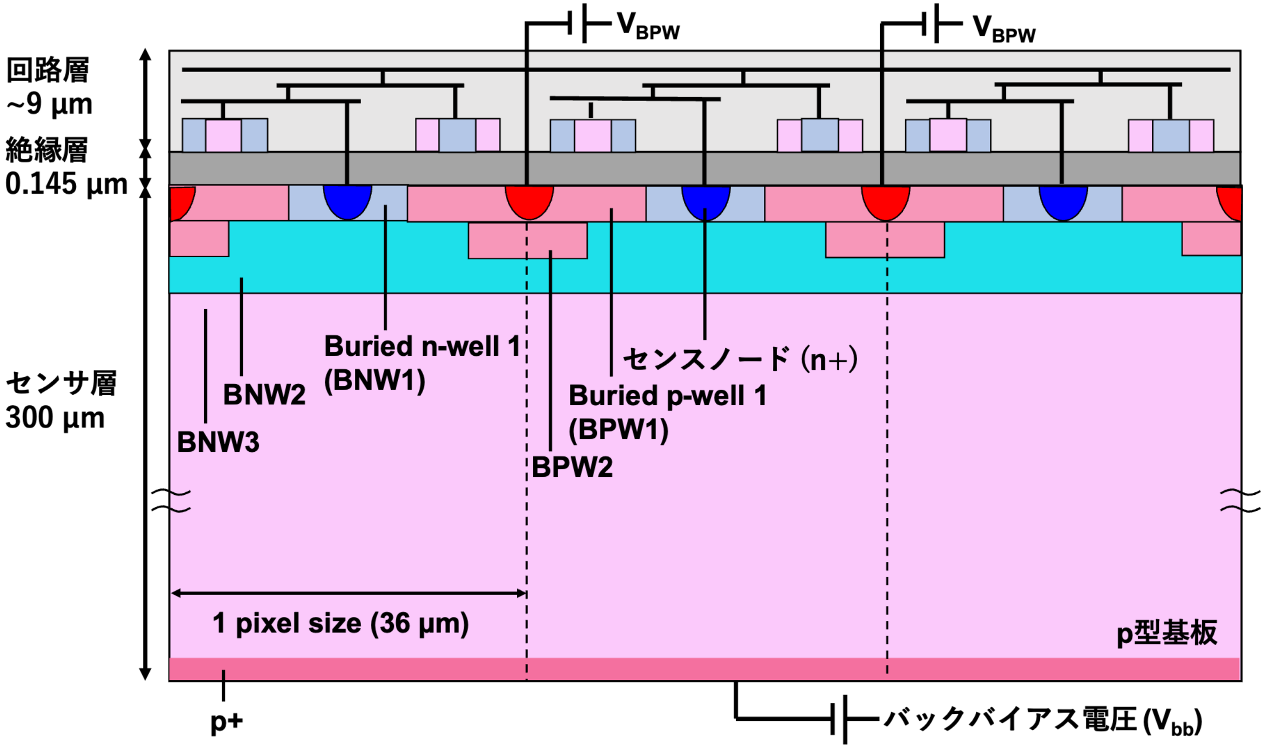


第四世代 (event)
- ΔE~270 eV
- 行元D論 (FY2024)



- The history of XRPIX is almost a history of its spectroscopic performance
  - Enlargement and Digitization do not make sense without spectroscopic performance
  - XRPIX has the frame and event-driven readout modes, and the spectroscopic performance of the latter is more important
  - The PDD structure developed in the 4th generation is a milestone in this history, and CCD-comparable-performance has been achieved

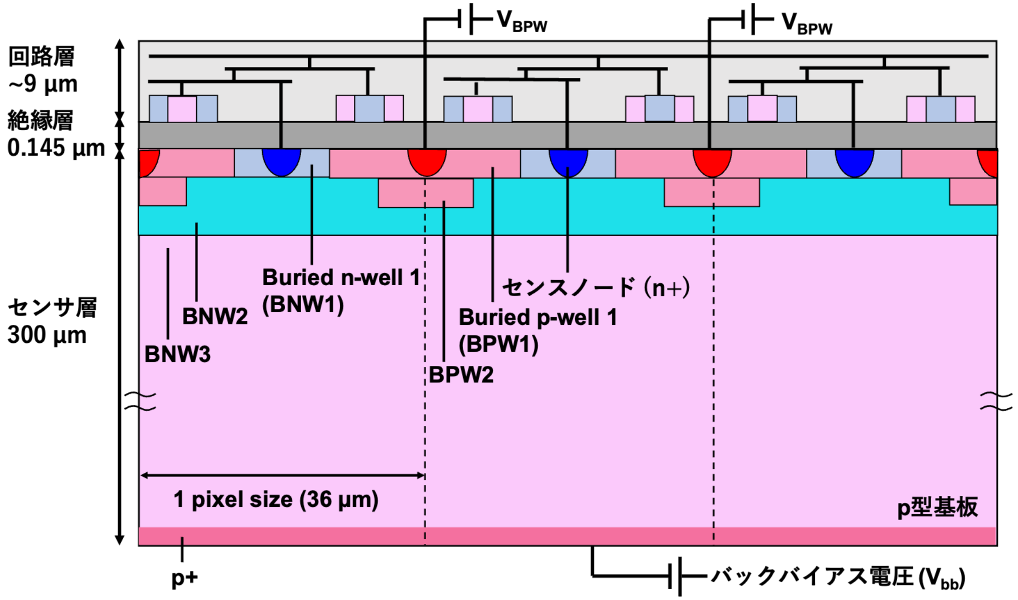
Pinned-Depleted-Diode (PDD) structure

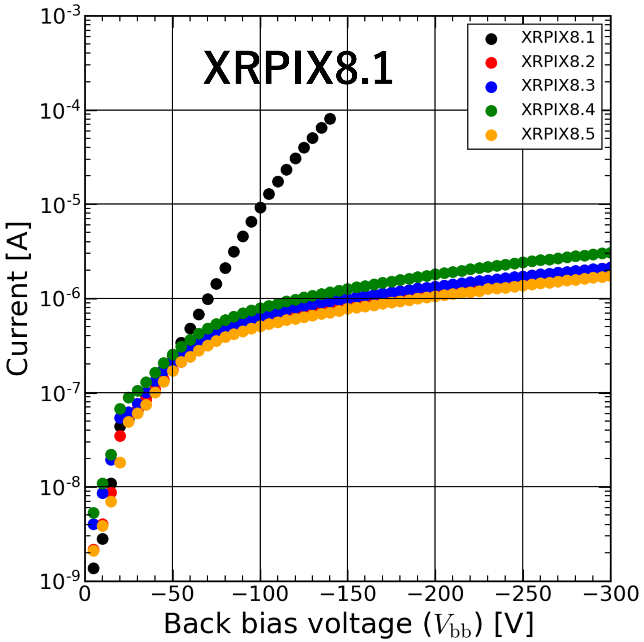


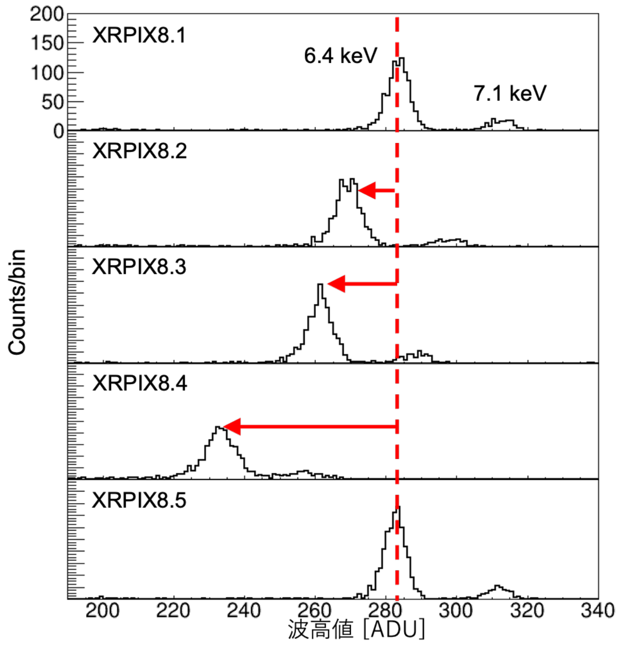
Cross-section of the PDD structure

- The PDD structure is quite efficient, but a little bit complex
  - The pinned BPW suppresses the back-gate effect and the dark current generation at the interface between the BOX and sensor layers
  - The BNW2 suppresses the punch-through between the BPW and the p-type substrate, and also forms a lateral electric field to gather carriers generated in the sensor layer into the sense node

Optimization of BNW2 concentration

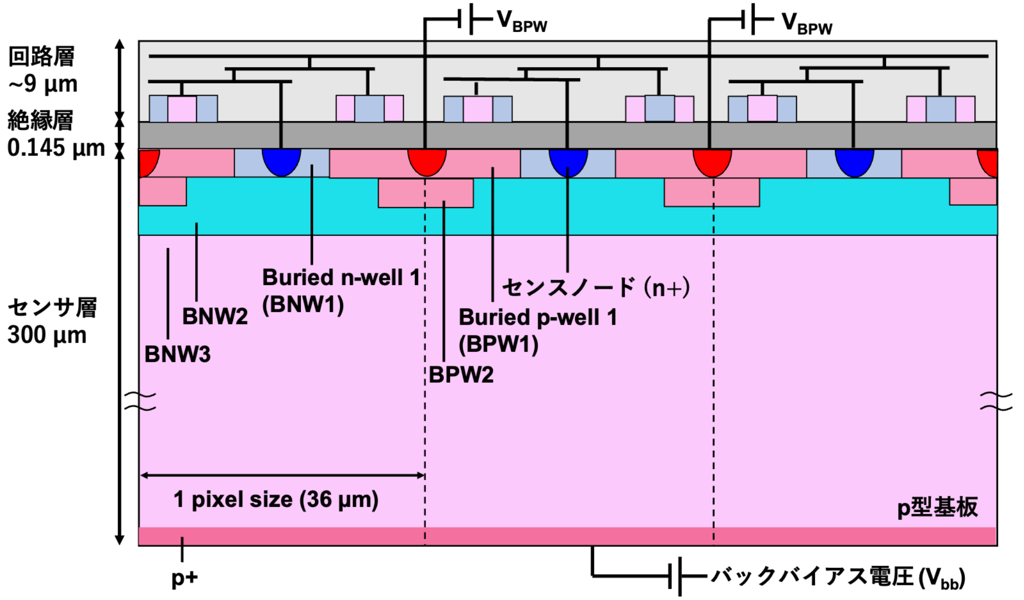


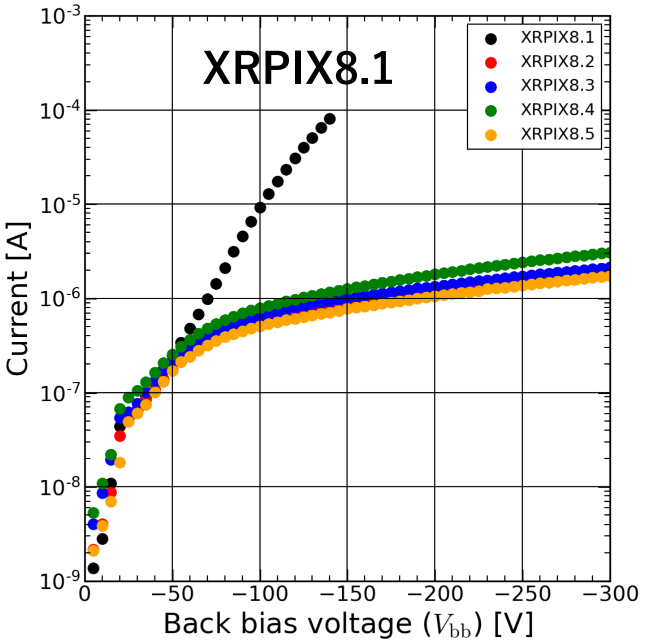


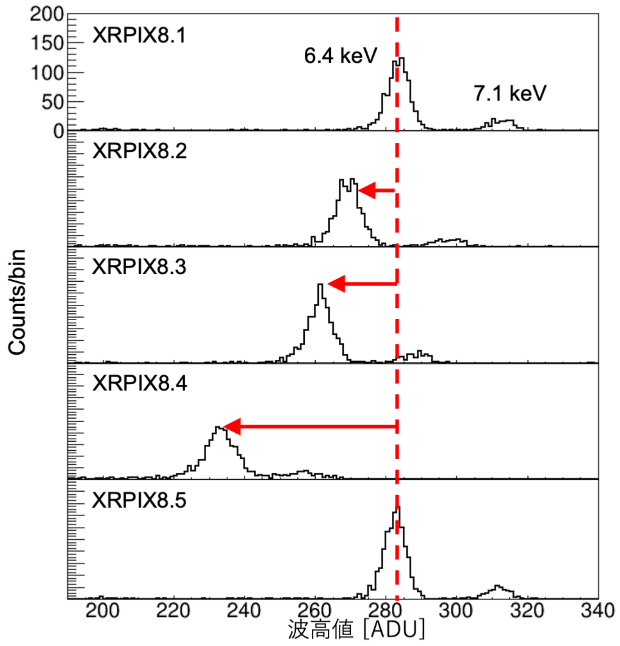


- An optimization study on the BNW concentration is necessary because a higher dopant concentration could result in a higher potential barrier but also in a larger sense-node capacitance leading to a lower spectroscopic performance
- We successfully found the best value, which suppressed a large leakage current and showed satisfactory X-ray spectroscopic performance.

Resistivity of substrate





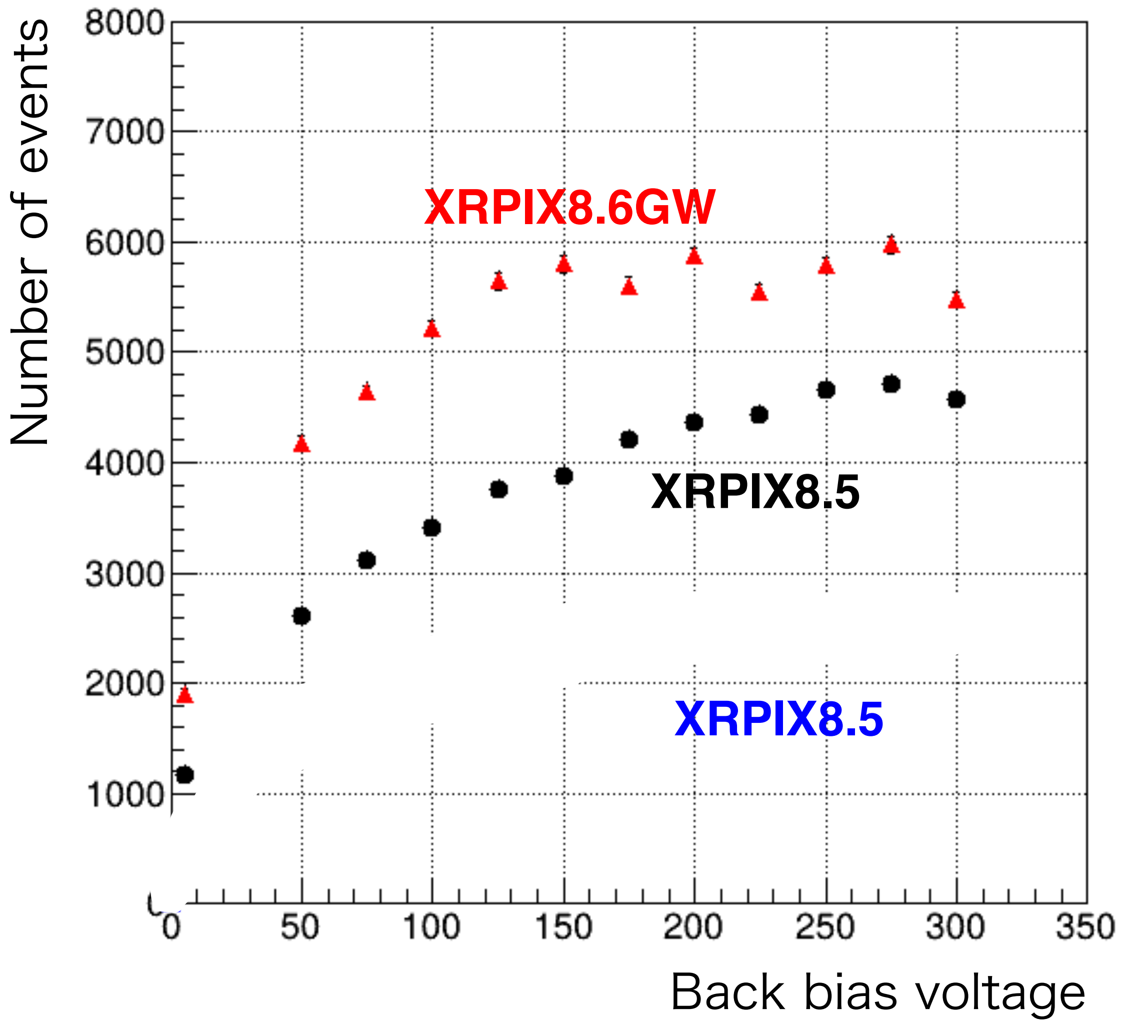


- The best condition practically depends on the resistivity of substrate. Higher resistivity substrates allows
  - lower back-bias voltage for full depletion,
  - lower BNW2 concentration for punch-through suppression,
  - lower sense-node capacitance, and
  - higher node gain, lower power consumption, and lower heat generation

XRPIX8.6GW with high-resistivity substrate

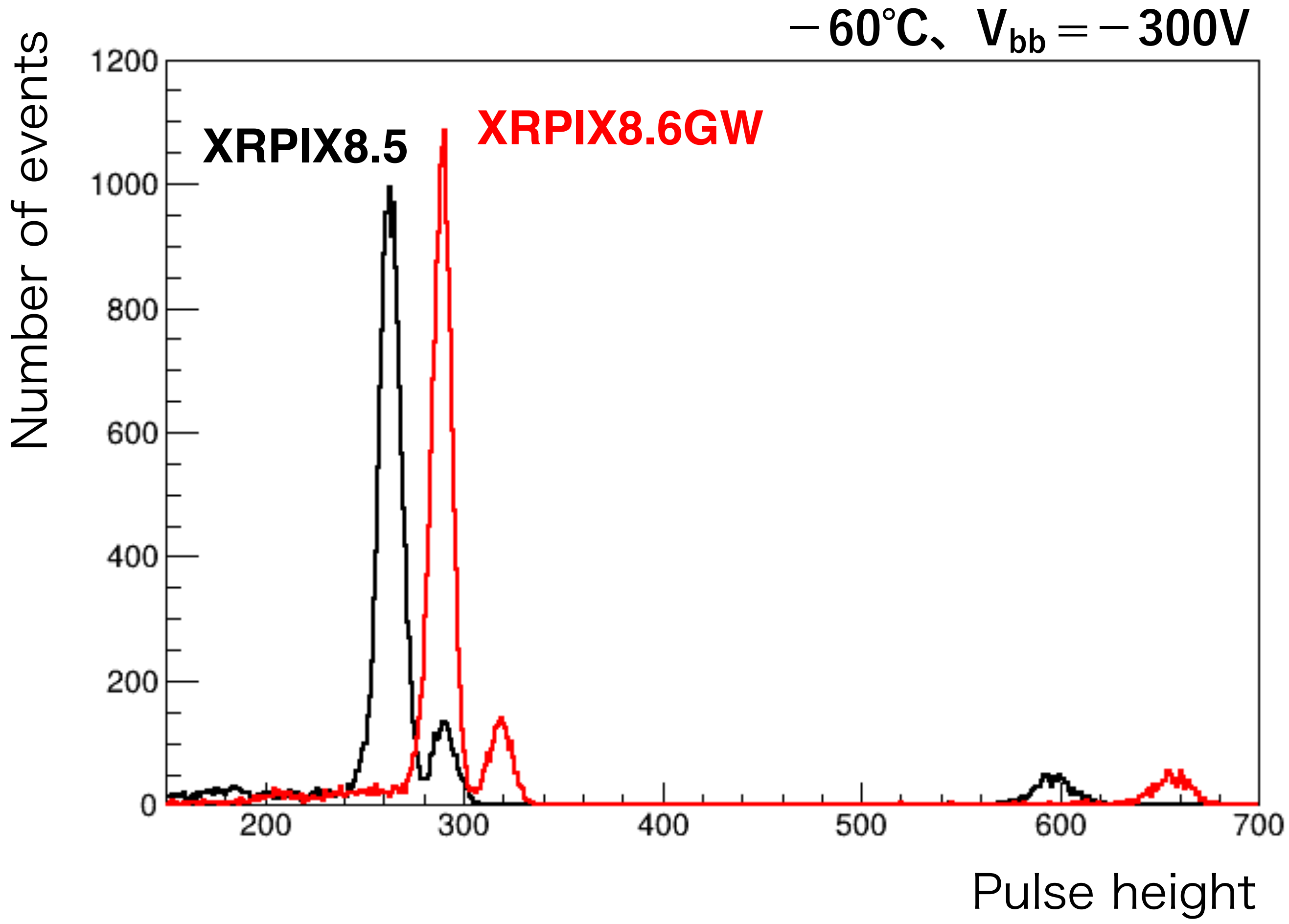
- XRPIX8.5 is the best optimized chip with the PDD structure in terms of dopant concentration
- XRPIX8.6GW has the same PDD structure but fabricated with about three-times higher resistivity substrate

Full depletion voltage



- Number of events, N, as a function of Vbb
  - As the applied voltage increases, the depletion layer thickness grows, and N increases
  - N saturates once the full depletion voltage, Vfull, is reached
- Vfull of XRPIX8.6GW and XRPIX8.5 is about 150 V and 300 V, respectively
  - 8.6GW clearly has the lower Vfull
  - The difference is not quite three times, but rather about two times
  - That of XRPIX11 is about 200 V

X-ray spectrum @ –60°C

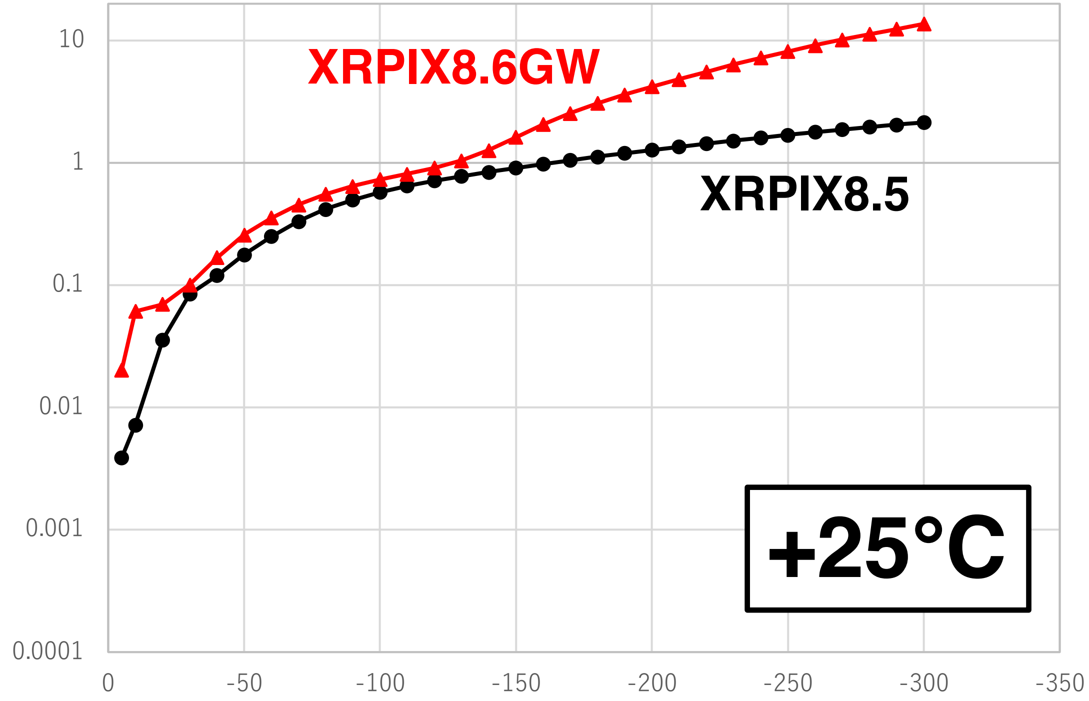


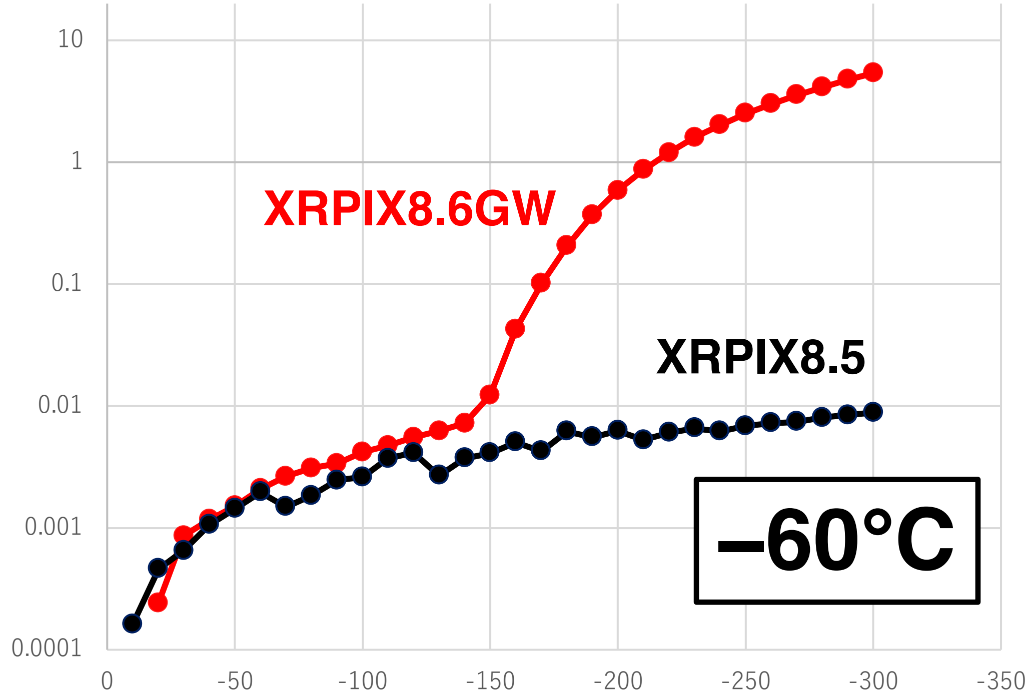
- Co-57 spectrum taken at −60℃ with Vbb of −300V and the frame readout mode
- XRPIX8.6GW shows comparable or better performance compared to XRPIX8.5 in the gain and energy resolution

XRPIX8.5FZE
ES は 41.2±0.100
FWHM@6.4keV は 306±2.94[eV]
Gainは 36.7±0.0889 [μV/e⁻]

XRPIX8.6GW_AI250501_27
ES は 45.6±0.114
FWHM@6.4keV は 262±2.80[eV]
Gainは 40.6±0.101 [μV/e⁻]

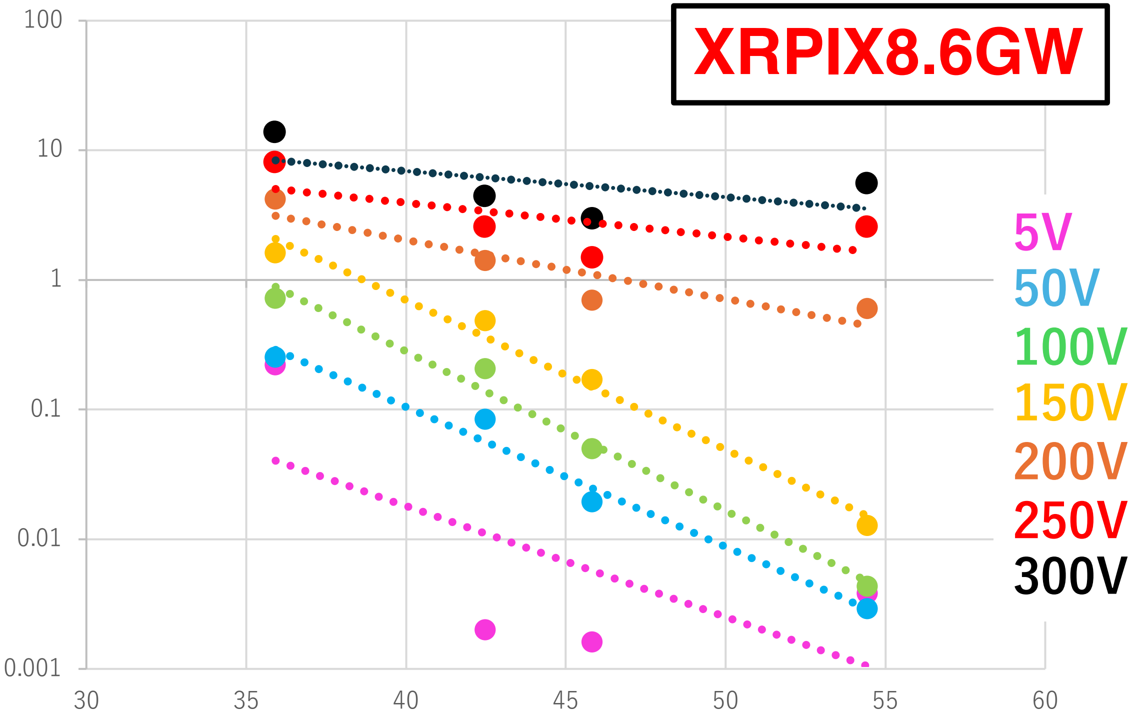
Current-Voltage curve

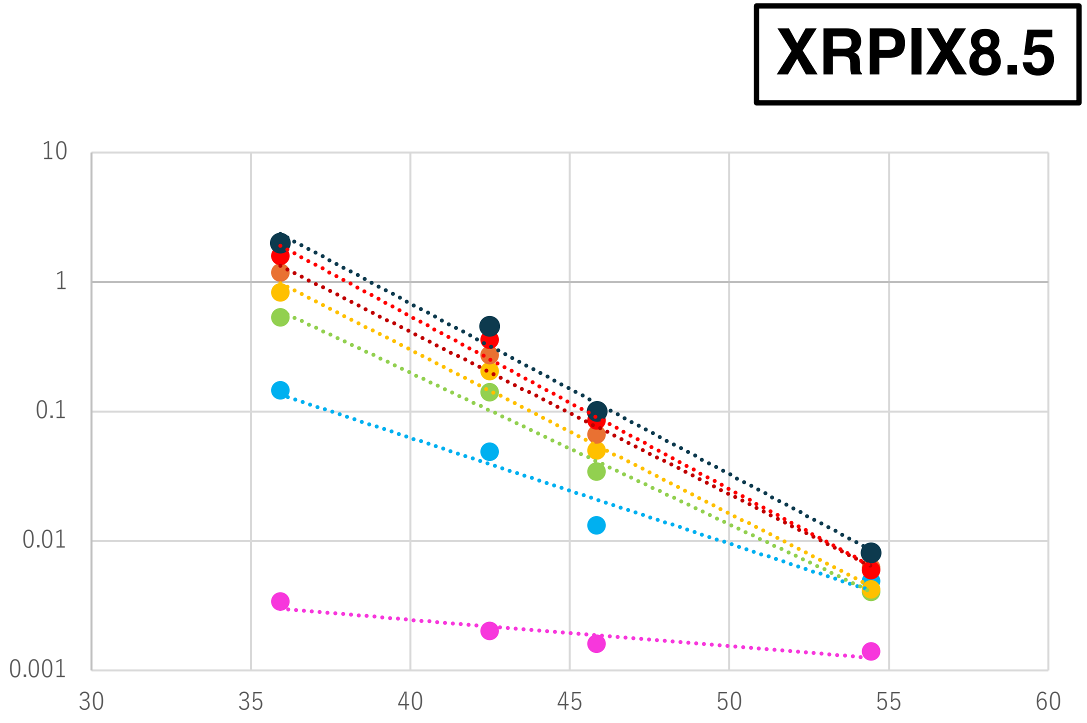




- The I-V curve of XRPIX8.6GW closely follows that of XRPIX8.5 up to approximately 150V, its full depletion voltage, but deviates upward beyond that point
- The former fact indicates that the interface state density between BOX and sensor layers of XRPIX8.6GW is similar to that of XRPIX8.5, but the latter fact indicates that something unexpected is happening at the back side of the sensor layer

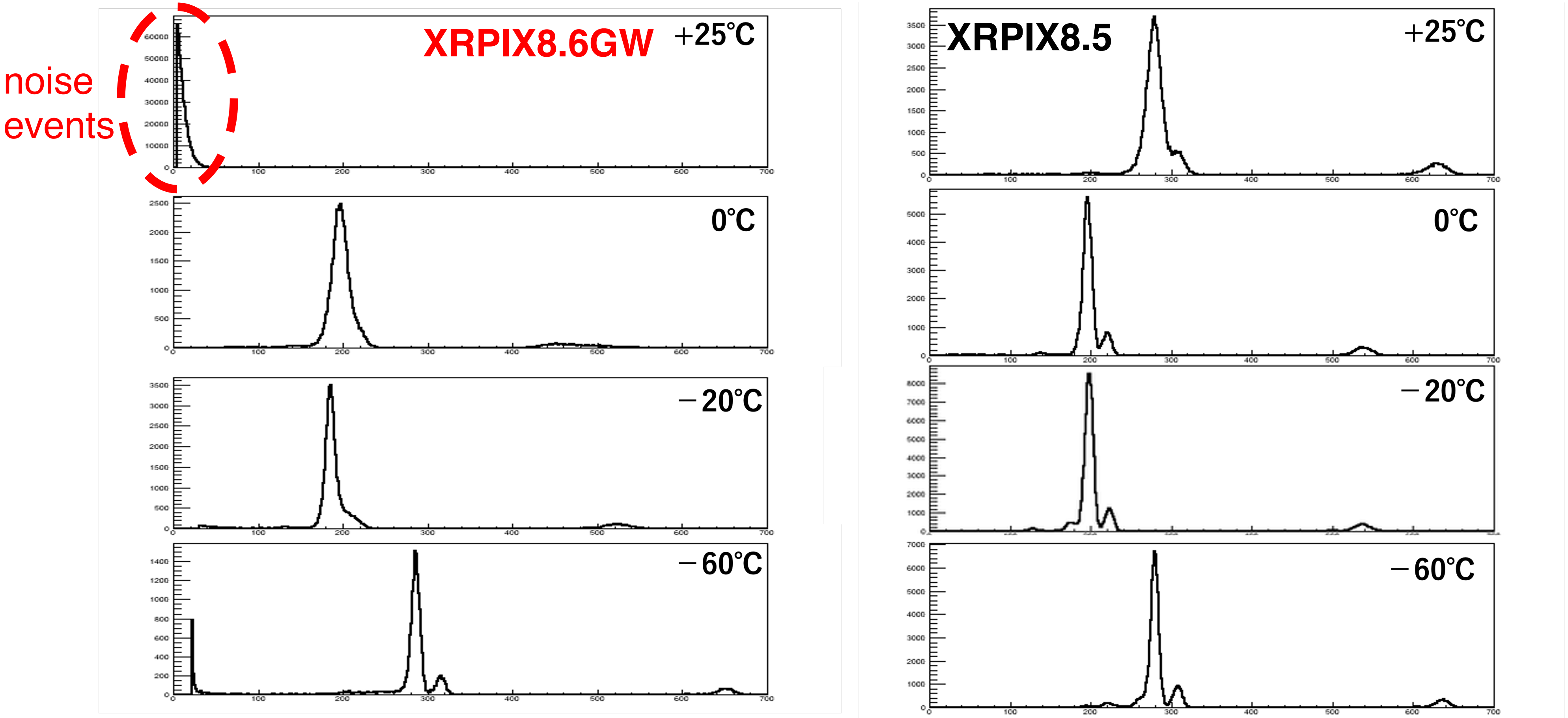
Arrhenius plot





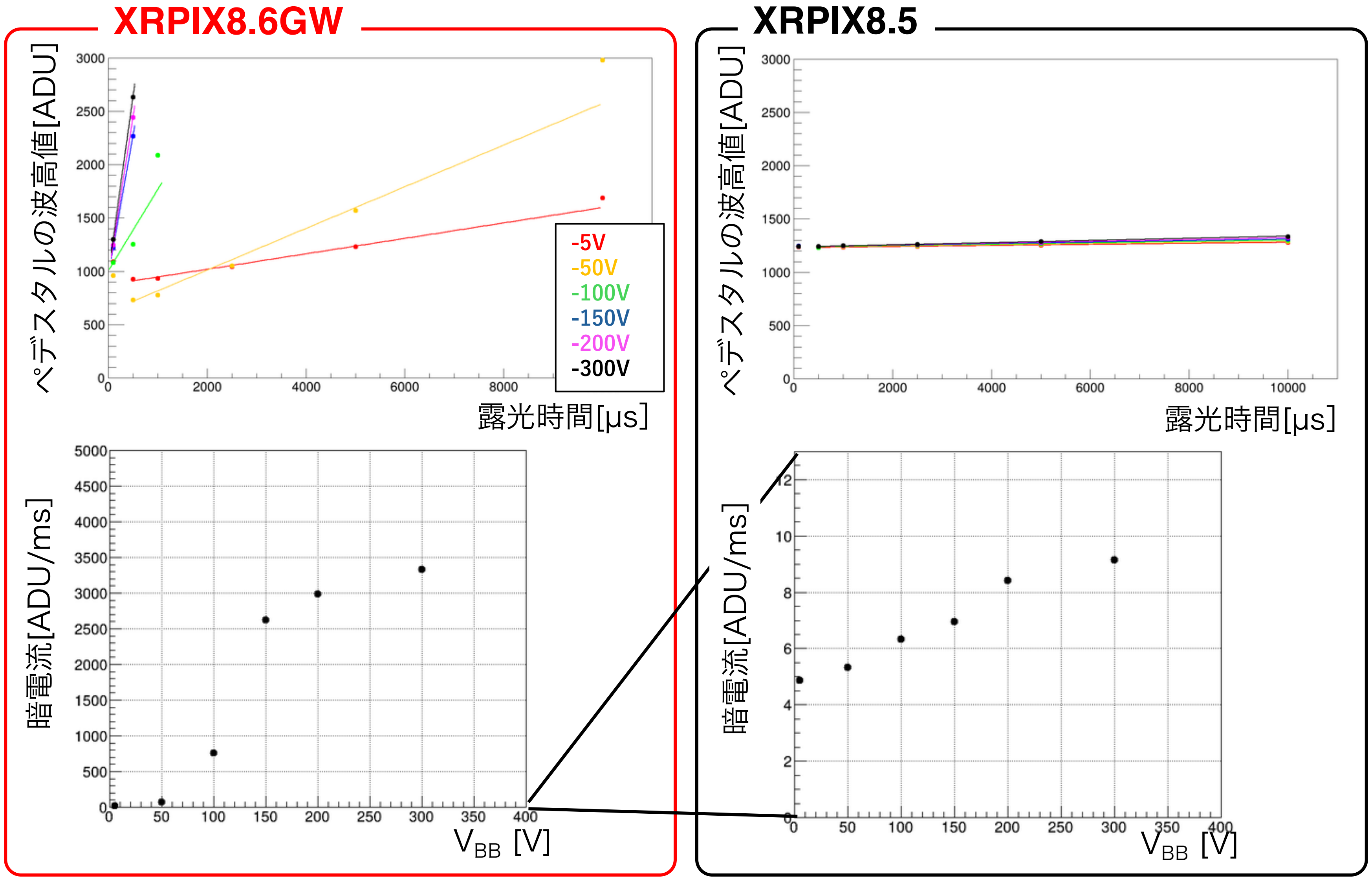
- Beyond the full depletion voltage (>150V), the temperature dependency of the leak current becomes weaker in the case of XRPIX8.6GW
- Non-thermal activation processes, e.g., quantum tunneling effect due to increased interface state density, may in operation at the back side of the sensor layer

X-ray spectrum @ higher temperatures



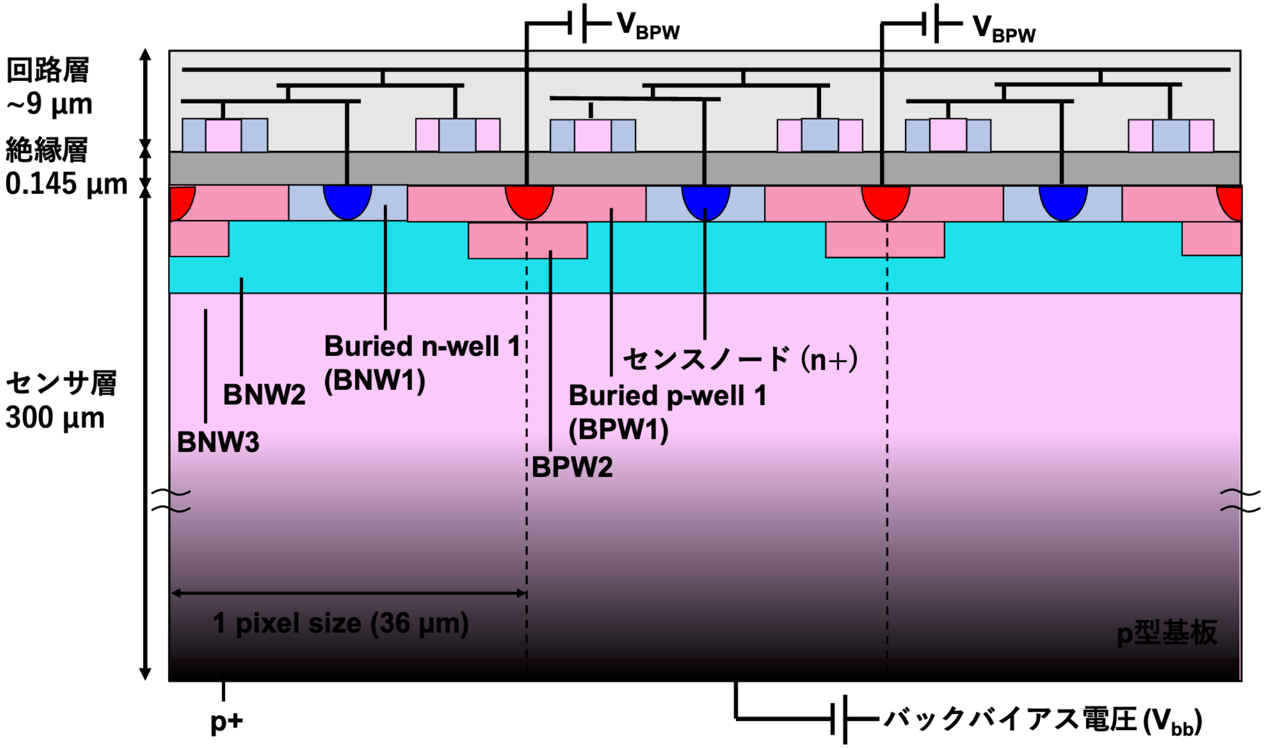
- The spectral degradation in higher temperatures is more significant in XRPIX8.6GW and no X-ray events are detected in the case of +25℃

Dark current @ 25°C



- At room temperature, the dark current of XRPIX8.6GW is about 300 times larger than that of XRPIX8.5
- XRPIX8.6GW has a strong Vbb dependence compared to XRPIX8.5

What's going on…



- The back side process might have not been well controlled
  - Sudden increase in the leak current at the full depletion voltage is likely due to increased interface state density
  - Strong Vbb dependence of the dark current may be explained by the metal contamination and diffusion from the back side, which make bulk GR current larger as the depletion layer grows

Summary

- We fabricate XRPIX with a high-resistivity substrate
- The full depletion voltage is nearly as expected, and the X-ray spectrum at −60℃ is satisfactory
- The leak current suddenly increases at the full depletion voltage, and the dark current gradually increases as the back-bias voltage increases
- We expect that such unfavorable behaviors would be gone by improving back-side process