Latest results from development of n^+-in-p planar pixel sensors and LGAD devices by KEK/HPK

Y. Unno (KEK)
for ATLAS-Japan Silicon Collaboration
& Hamamatsu Photonics K.K.

Contents

- Two talks combined...

- Latest results from development of n^+-in-p planar pixel sensors
  - 50×50 and 25×100 μm^2 pixels with FE-I4 readout ASIC
  - Non-irradiated, and irradiated with protons
  - Efficiency mapping of various pixel structures

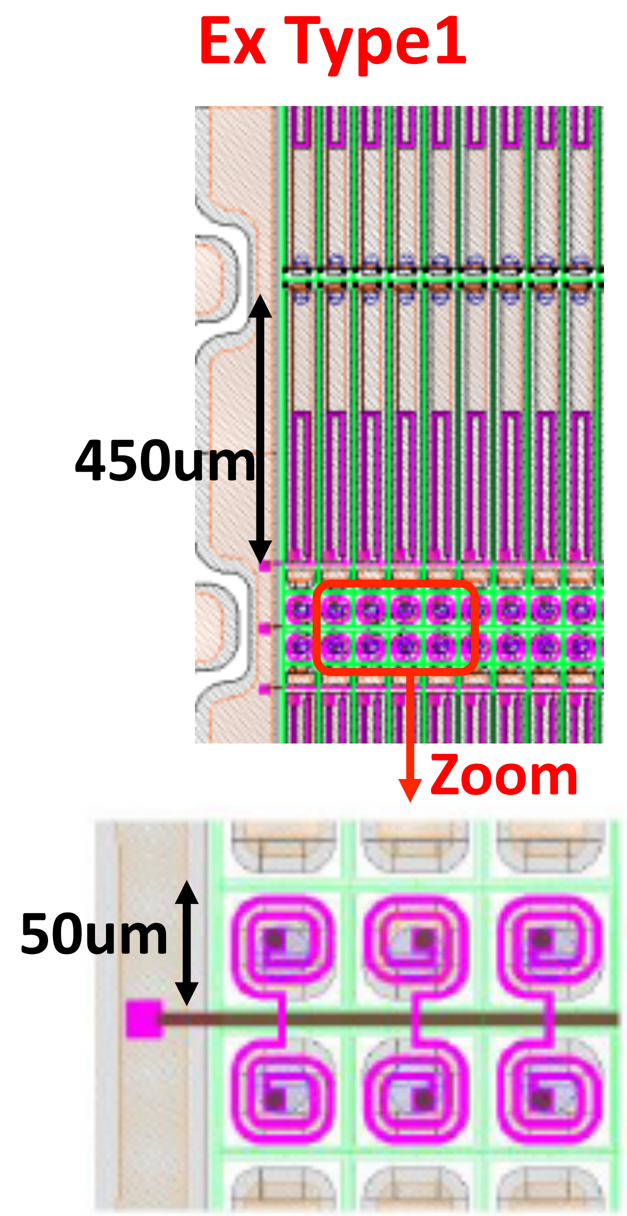
- Latest results from development of LGAD devices
  - Diodes (and strips)
  - Non-irradiated, and
  - Irradiated with gammas or neutrons

50×50 and 25×100 μm^2 pixels with FE-I4 readout ASIC

Main contributor:
Kazuyuki Sato (Uni. Tsukuba)

Motivation

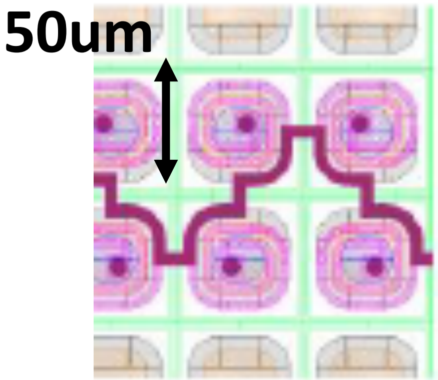
- To design planar pixel sensors with 50×50 μm^2 pixels
  - The pixel size for HL-LHC upgrade
  - ASIC being developed by RD53
- To test the pixel structures with working readout ASIC, FE-I4
  - 2x(50×250) →
  - 50×50/25×100 + 50×450 μm^2
- Evaluation with beams from CERN SPS
  - 120 GeV pions
  - 2016 Aug Testbeam
  - 2016 Nov Testbeam



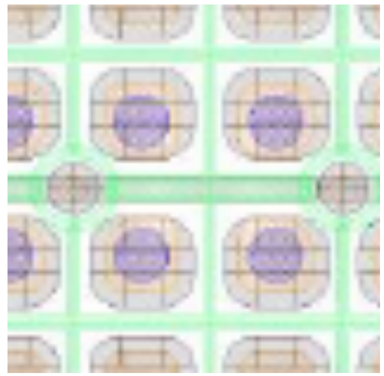
Pixel Structures

Non Irrad

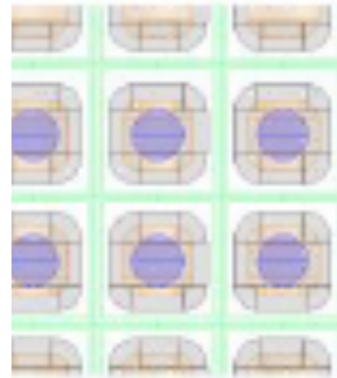
Type2 Small Offset



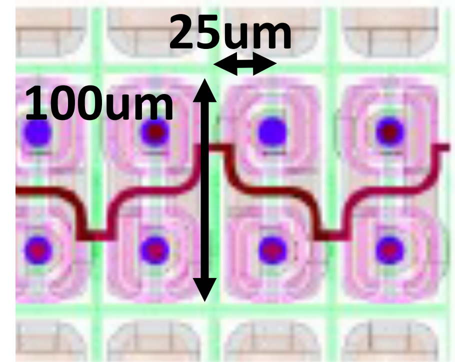
Type3 PT



Type5 No Bias

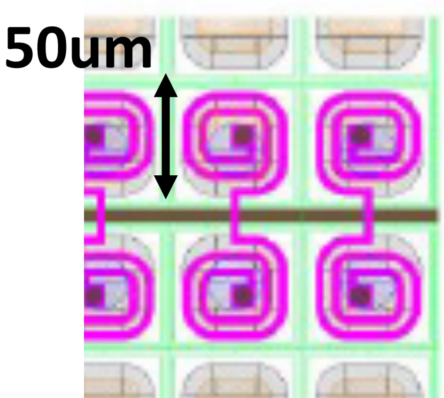


Type6 25um x100um Small Offset

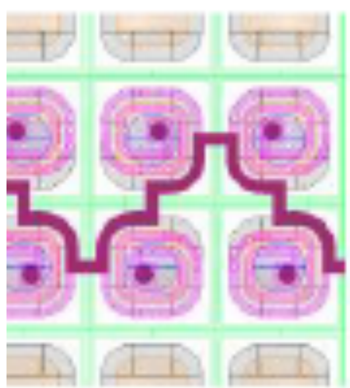


Proton Irrad $3x10^{15}$ 1MeV n_{eq}/cm^2

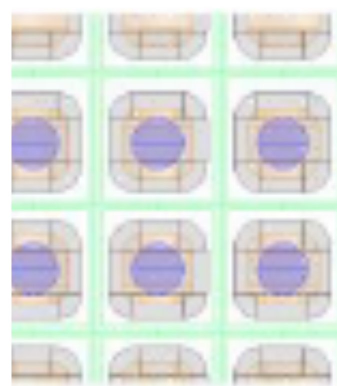
Type1 No Offset



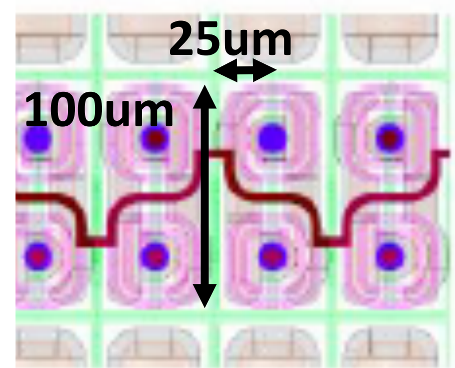
Type2 Small Offset



Type5 No Bias



Type6 25um x100um Small Offset

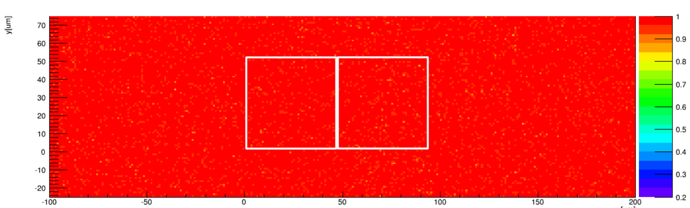


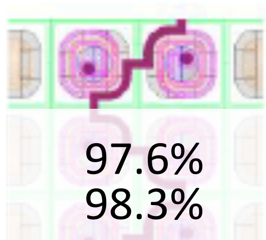
Efficiency Map in Pixel – Non irrad.

- Little efficiency loss in non-irrad. devices with PolySi bias network.
- Efficiency loss observed with the PT structure.
  - PT dot (n^+) is "visible" to the drifting charges. Then,
  - charges are induced to the PT dot and lost (from the readout pixels).

Eff.:
Overall
Central

Type2 (PolySi) 200V

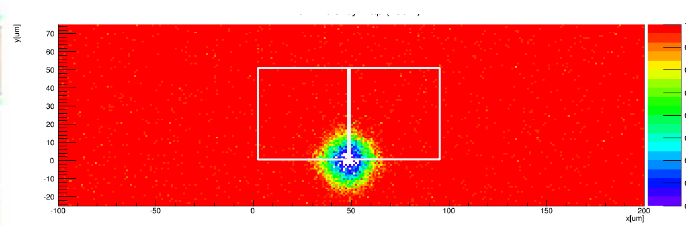


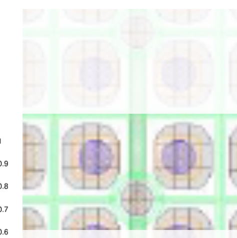


97.6%
98.3%

Systematics → (98.5% 50×450 μm^2)

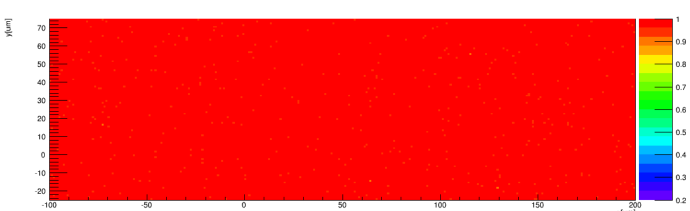
Type3 (PT dot) 200V

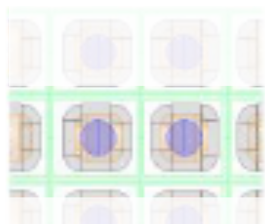




94.8%
99.1%

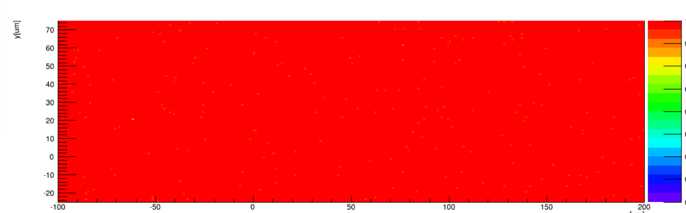
Type5 (No bias) 200V

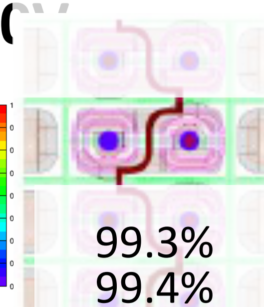




99.2%
99.3%

Type6 (25×100, PolySi) 20





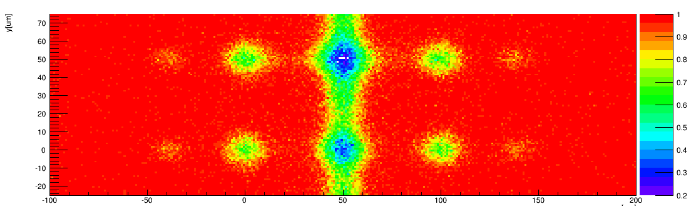
99.3%
99.4%

Efficiency Map in Pixel – Irrad.

- Proton Irrad. 3×10^{15} 1MeV n_{eq}/cm^2
- Efficiency loss under the bias rail (in Type1 (wide p-stop))
- Efficiency loss at the four corner of four pixels due to charge sharing and high threshold (3000 e) (e.g. in Type5 (No bias))
  - was improved with lowered threshold
  - In future, 500 e (?) with the new RD53 ASIC.
- In Type6, efficiency loss at the four and the three corners of 2×25 – 50 μm

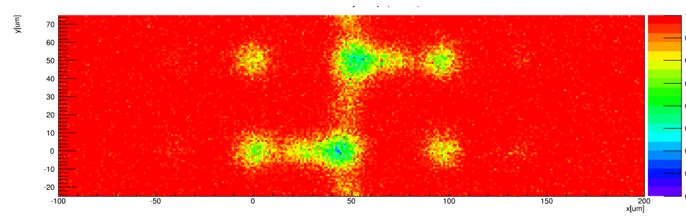
Eff.:
Overall
Central

Type1(No offset) 1000V



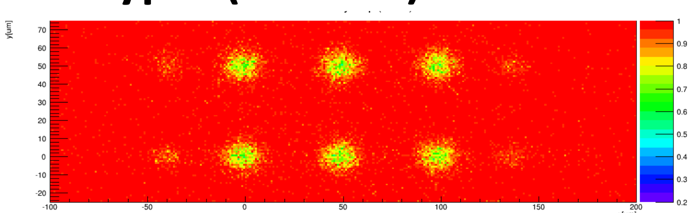
89.3%
99.0%

Type2(Large offset) 1000V



93.9%
99.2%

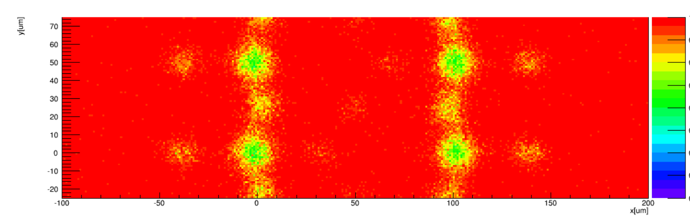
Type5(No bias) 1000V

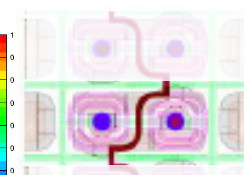


97.1%
99.3%

(to-be improved with lower threshold)

Type6(25×100) 1000V

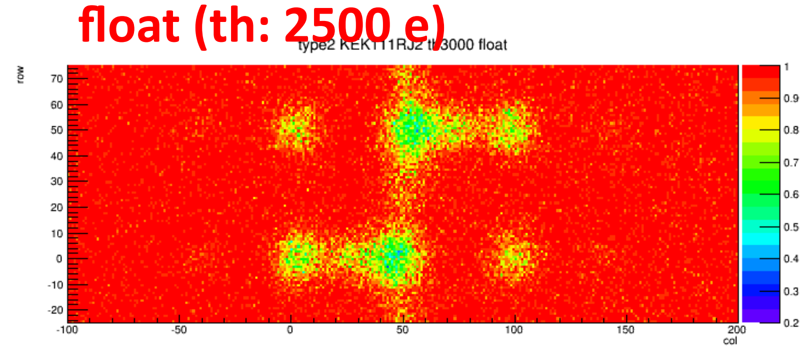


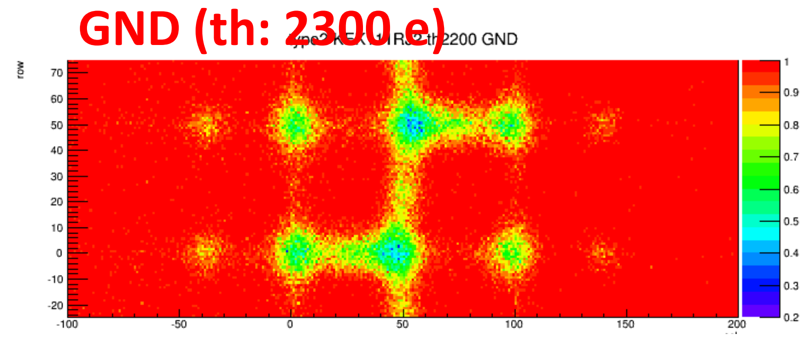


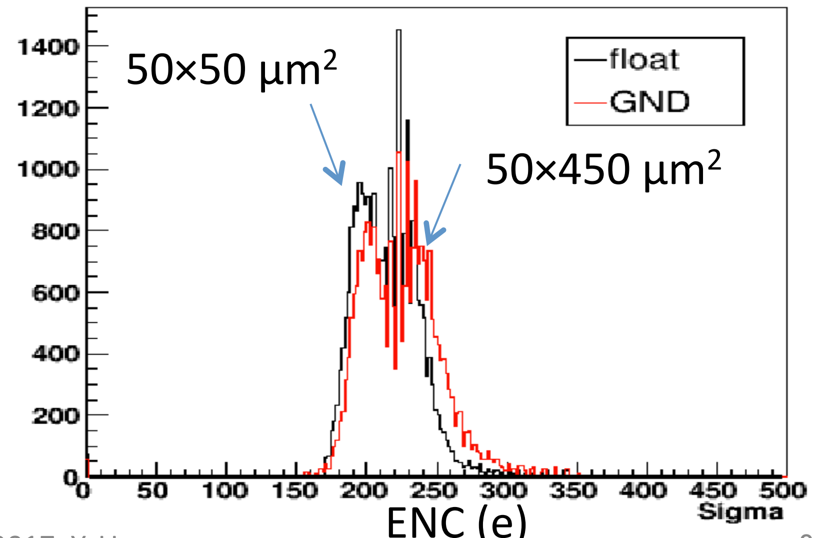
96.9%
99.2%

Biasing network, floating or GNDing

- Bias rail connection:
  - Default: float
  - Trial: GND
- Efficiency loss:
  - In an irradiated device
  - GND > float
  - Charges are induced to the electrodes with a fixed potential.
    - The more fixed, the more induced charges (?)
- Noise (ENC):
  - Two peaks because of two pixel sizes (50×50, 50×450 µm^2)
  - GND ≥ float

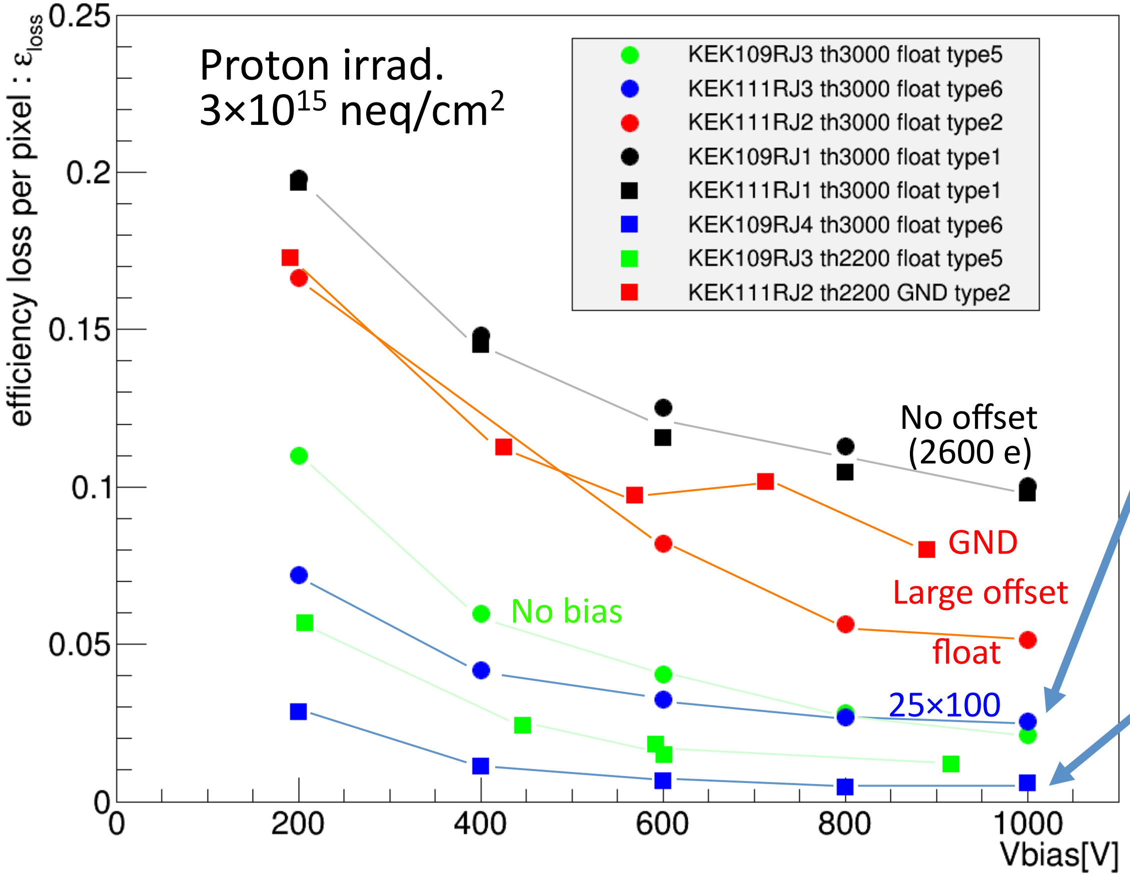




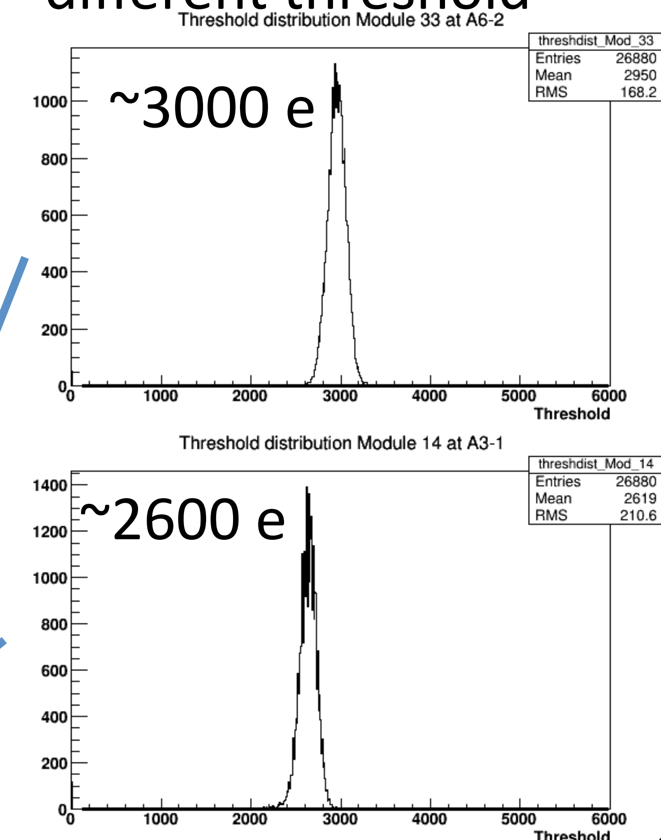


Efficiency Loss per Pixel – Irrad.

- Type5 (no bias) < type2 (small offset) < type1 (no offset)
- Type5 threshold : 2600 e < 3000 e
- Bias rail connection: float < GND

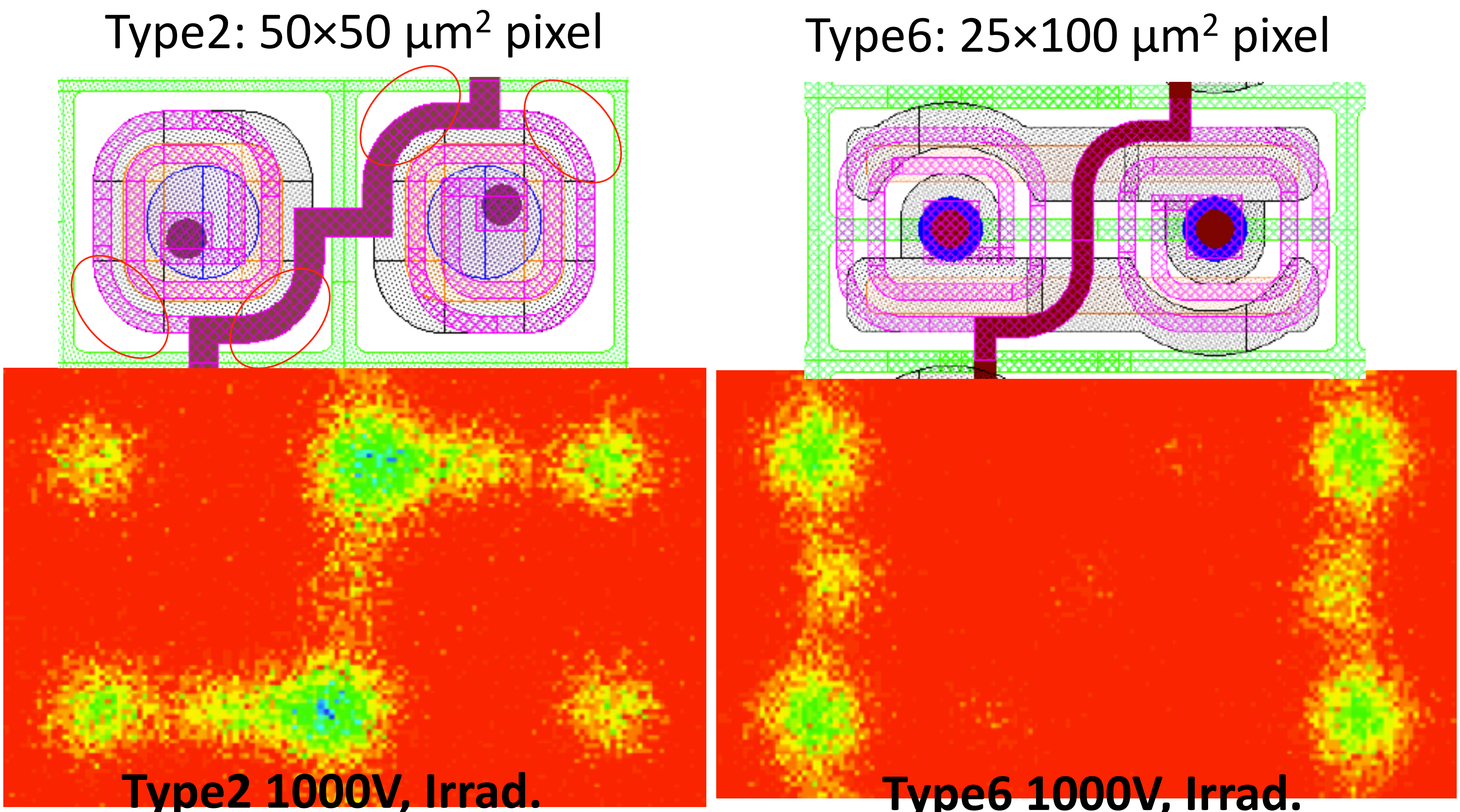


Different ε_{loss} in the same structure ← different threshold



Can Type 2 be Improved?

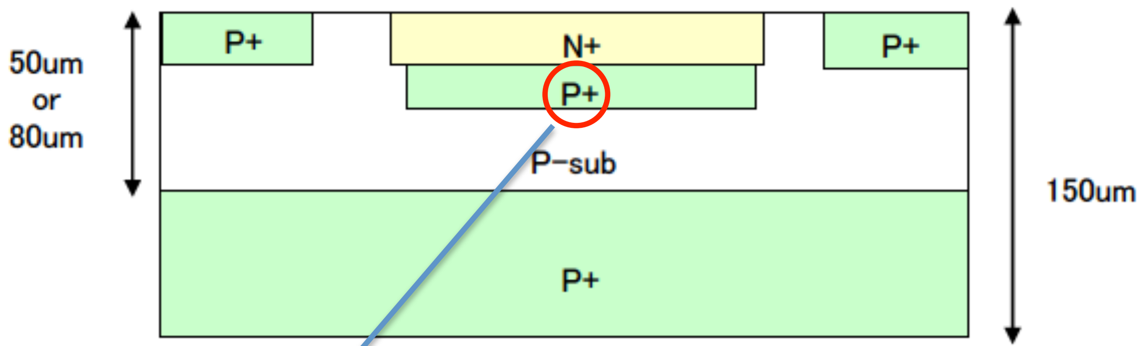
- Yes. We have now understood which structures have caused the efficiency loss...

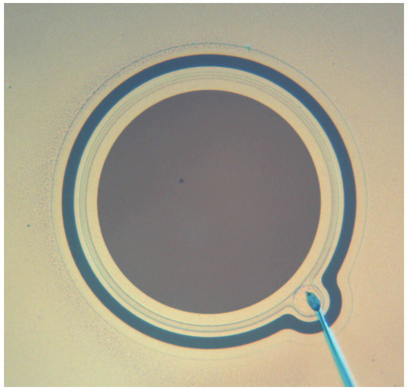


LGAD Devices (Diode, Strip) before and after gamma/neutron irradiation

Main contributor:
Sayaka Wada (Uni. Tsukuba)

Diode Samples

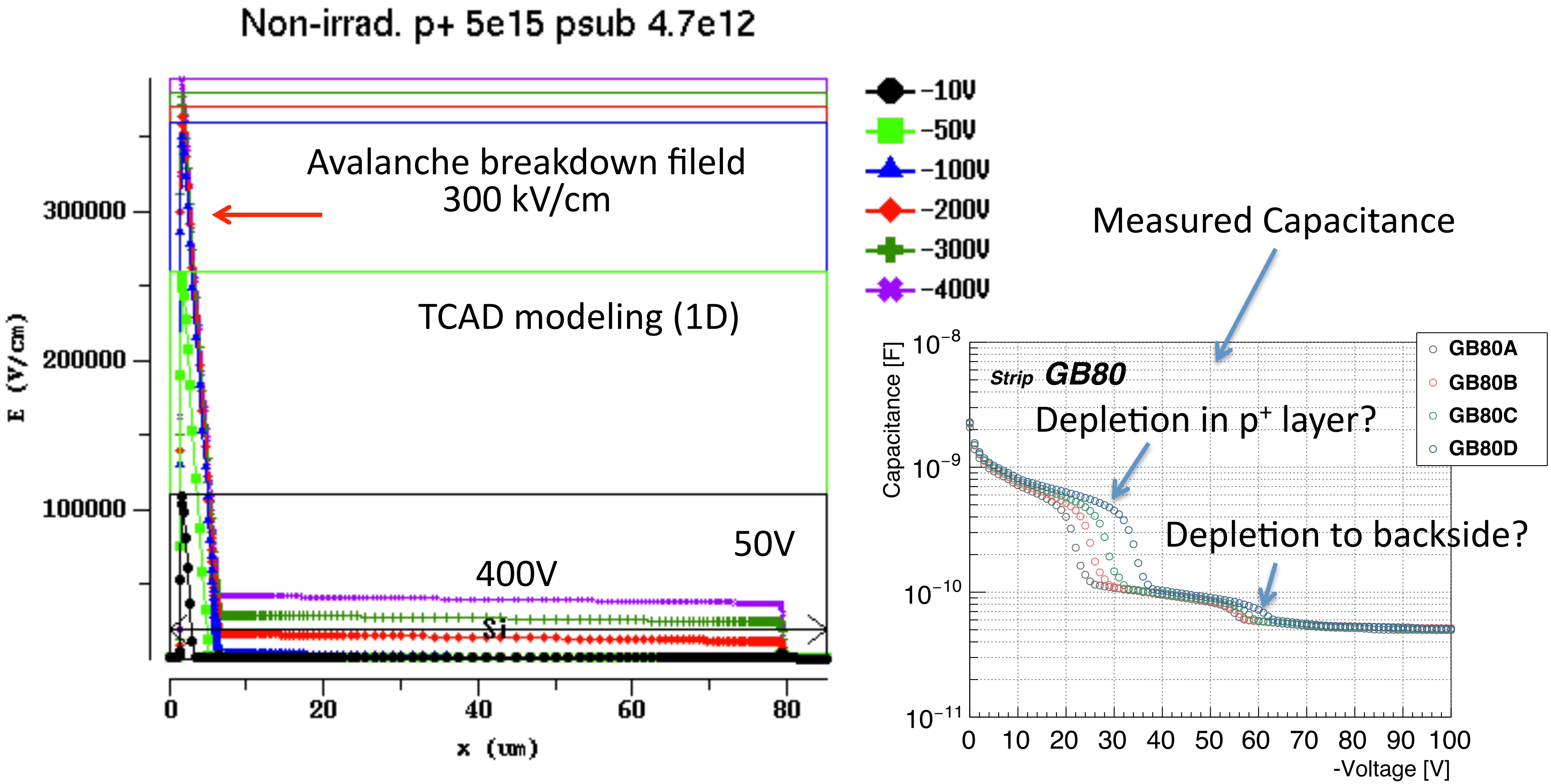




Sample Name	P+ density	Physical Thickness [μm]	Active Thickness [μm]
50A	A (low)	150	50 (3~8kΩcm)
50B	B		
50C	C		
50D	D (high)		
80A	A		80 (1kΩcm)
80B	B		
80C	C		
80D	D		

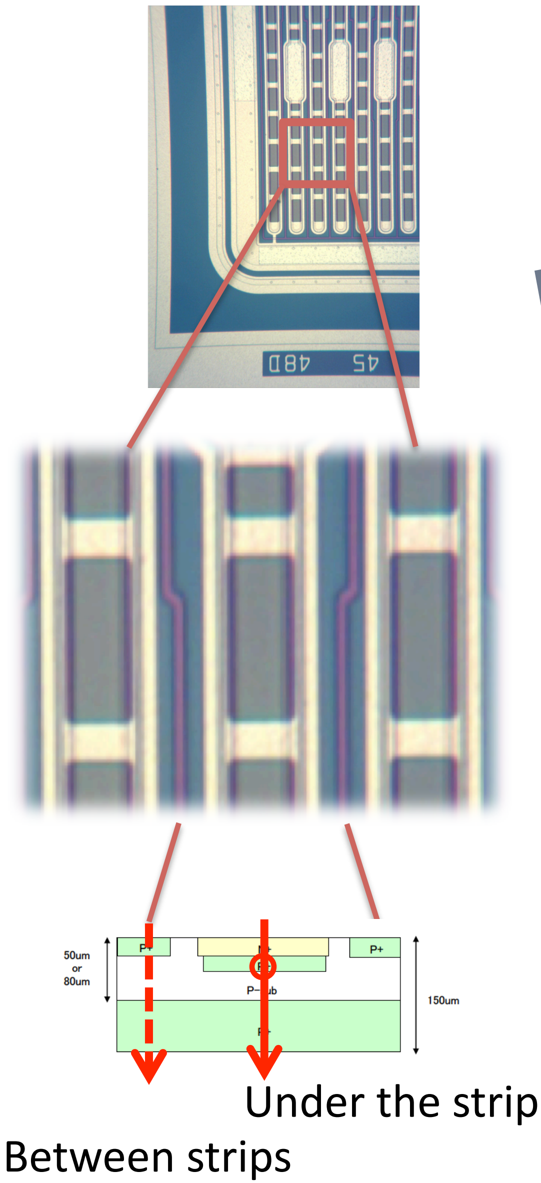
- Diode
- Chip size:
  - 2.5 × 2.5 mm^2
- Window: 1 mm ϕ

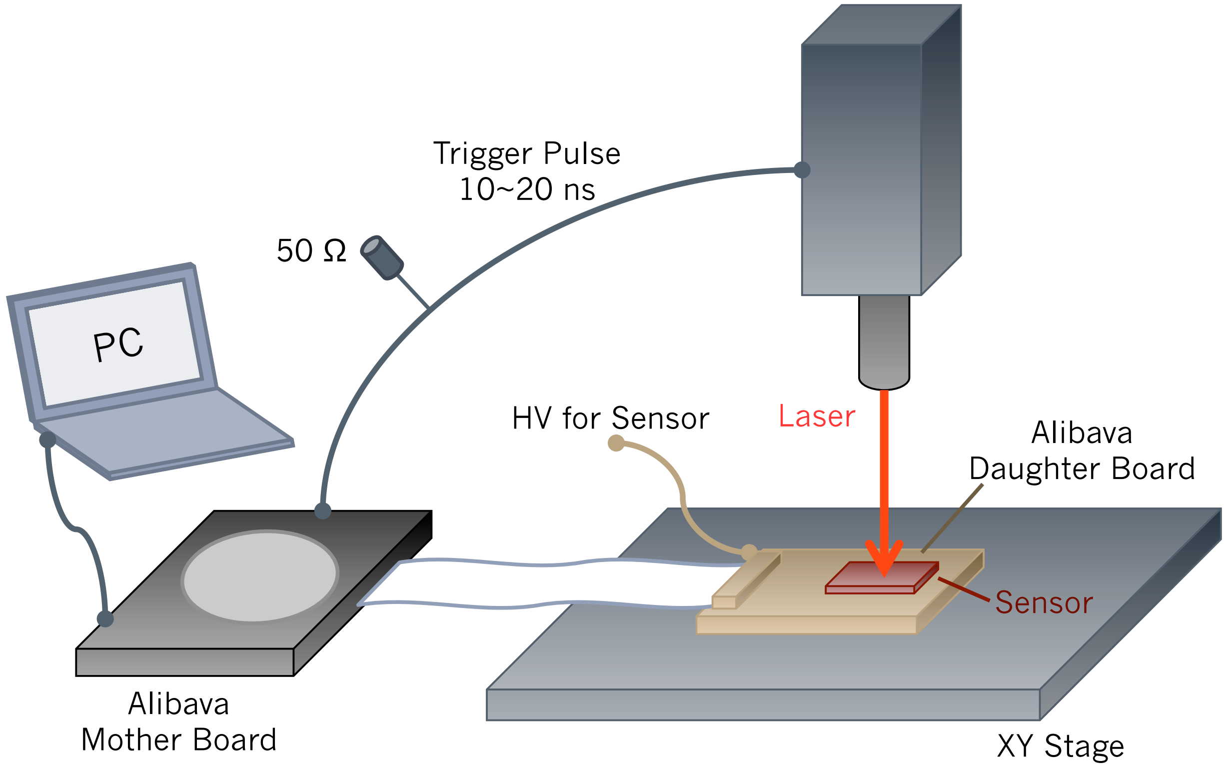
Some Basics – Electric field



- Electric field calculations with a TCAD program
- Critical electric field for avalanche breakdown – 30 V/μm

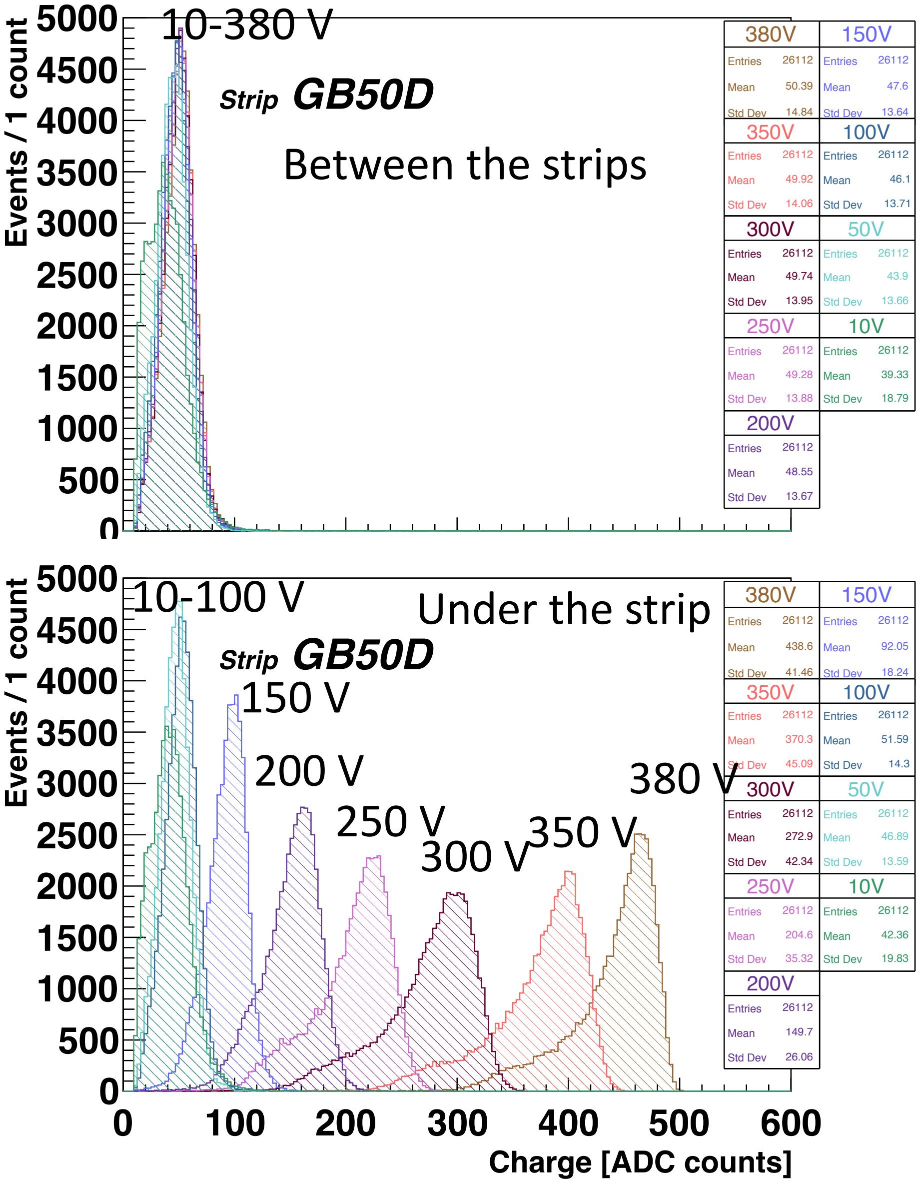
Charge Amplification (Gain)-Strip Sample

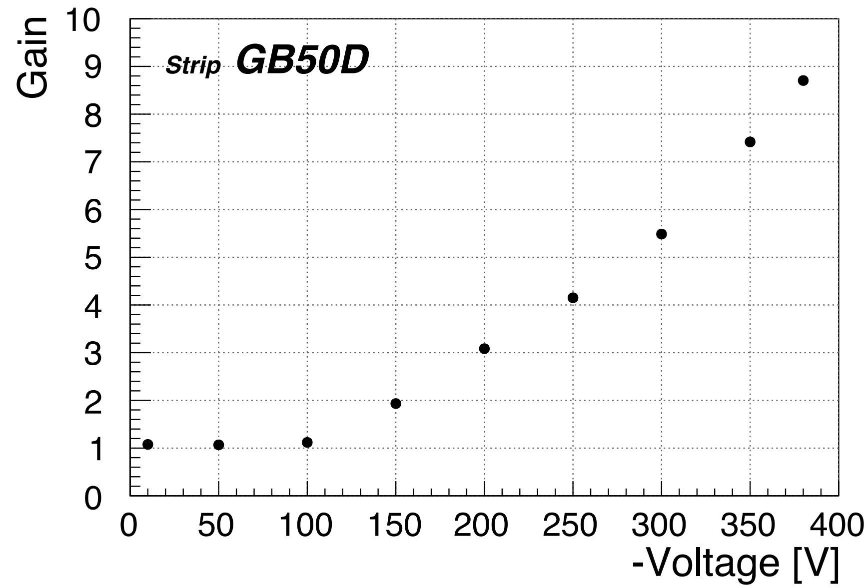




- Strip:
  - chip size:6×12 mm^2
  - strip pitch: 80 μm
- IR-Laser
  - λ=1064 nm, D~1 mm
  - Penetrate fully

Gain, Non-irrad. – Strip sample

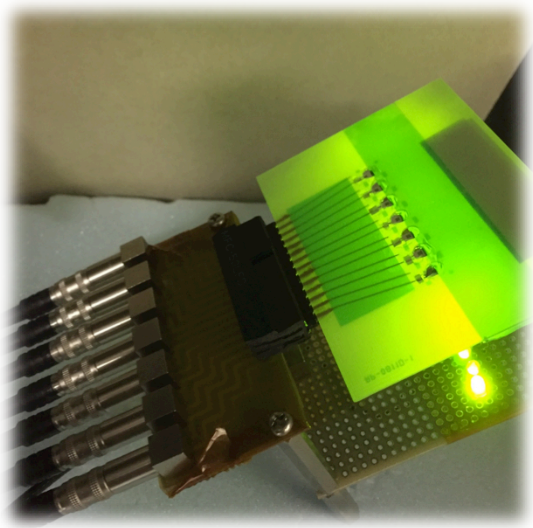




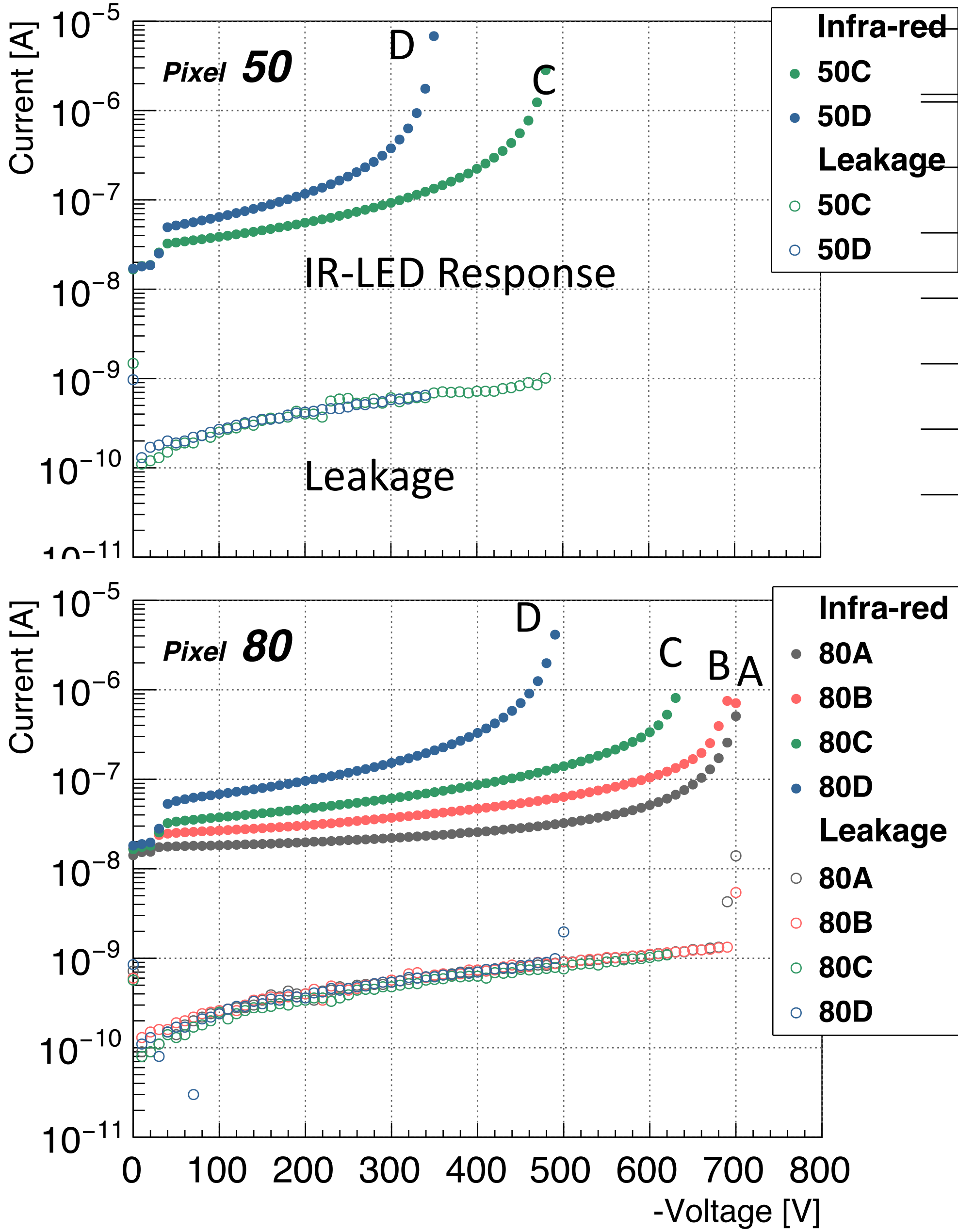
- Gain is observed at ≥ 100 V

Measurements – Diode samples

- Leakage currents
- Current generation by LEDs
  - Blue (λ=464nm, D=0.5μm)
  - Green(λ=565nm, D=2μm)
  - Red (λ＝627nm, D=3μm)
  - Infra-red (λ＝850nm, D=20μm)
  - LED power control: Amplitude of 5 kHz square pulses (50% duty cycle)
- Dependence on
  - p^+ density
    - Values (confidential to HPK)
  - temperature
- Before and after irradiation
  - gamma (at Takasaki)
  - neutrons (at Ljubljana)
  - Annealing: 60 °C – 80 min.



p+ density Dependence – Non irrad.



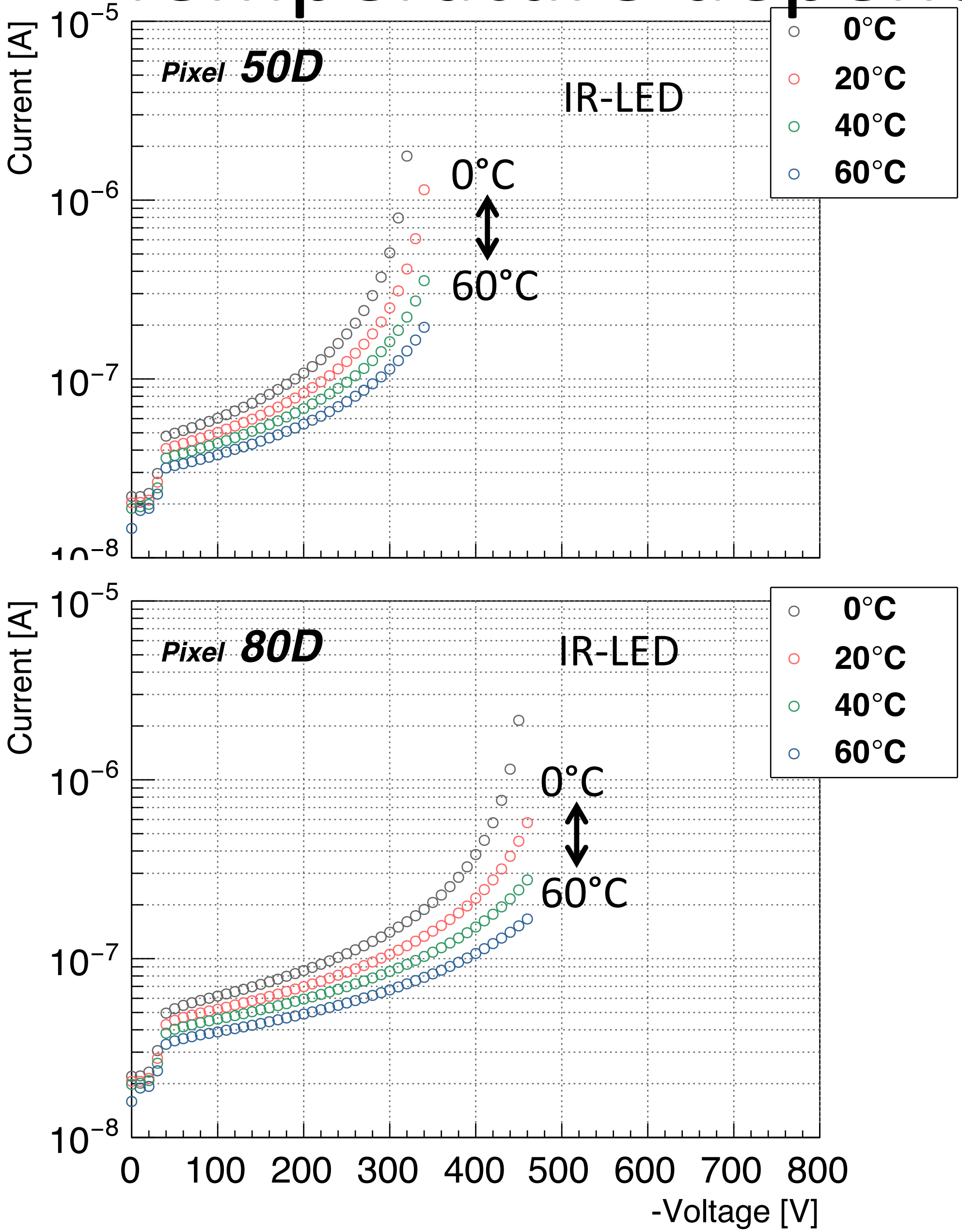
Sample Name	Voltage[V]	Gain
50C	470	31.9
50D	340	27.2
80A	680	9.4
80B	680	14.6
80C	620	13.8
80D	490	29.0

Definition of "Gain": *I*(Voltage)/*I*(100V)

LED power is controlled by the amplitude of the pulses (5kHz square pulses) sent to the LED.

- Diode samples
- p+ density
  - A, B: too weak(?)
  - (C) D: good

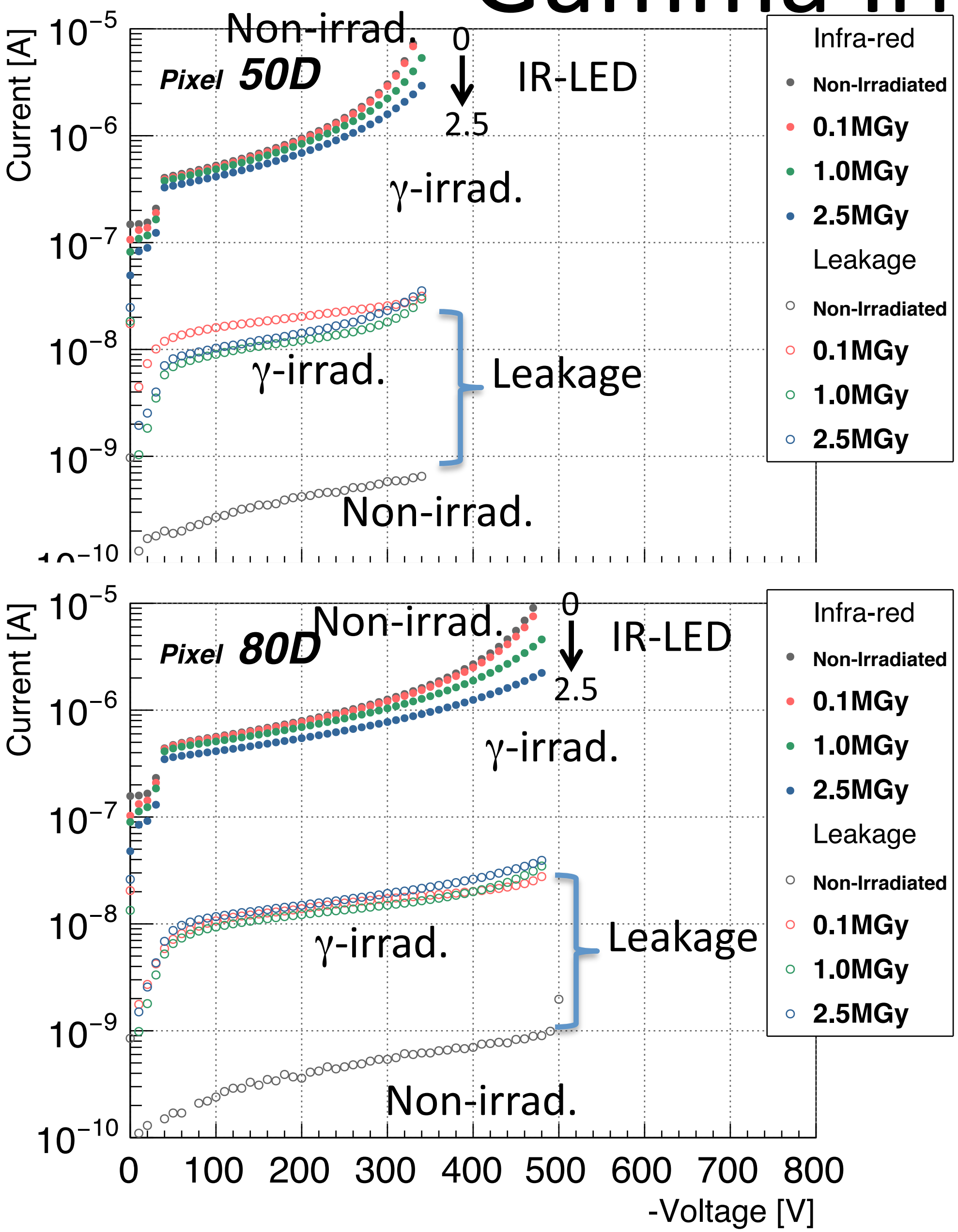
Temperature dependence – Non irrad.



- Currents generated by LED >> Leakage current
- No $T^2\exp(-Eg/2kT)$ dependence

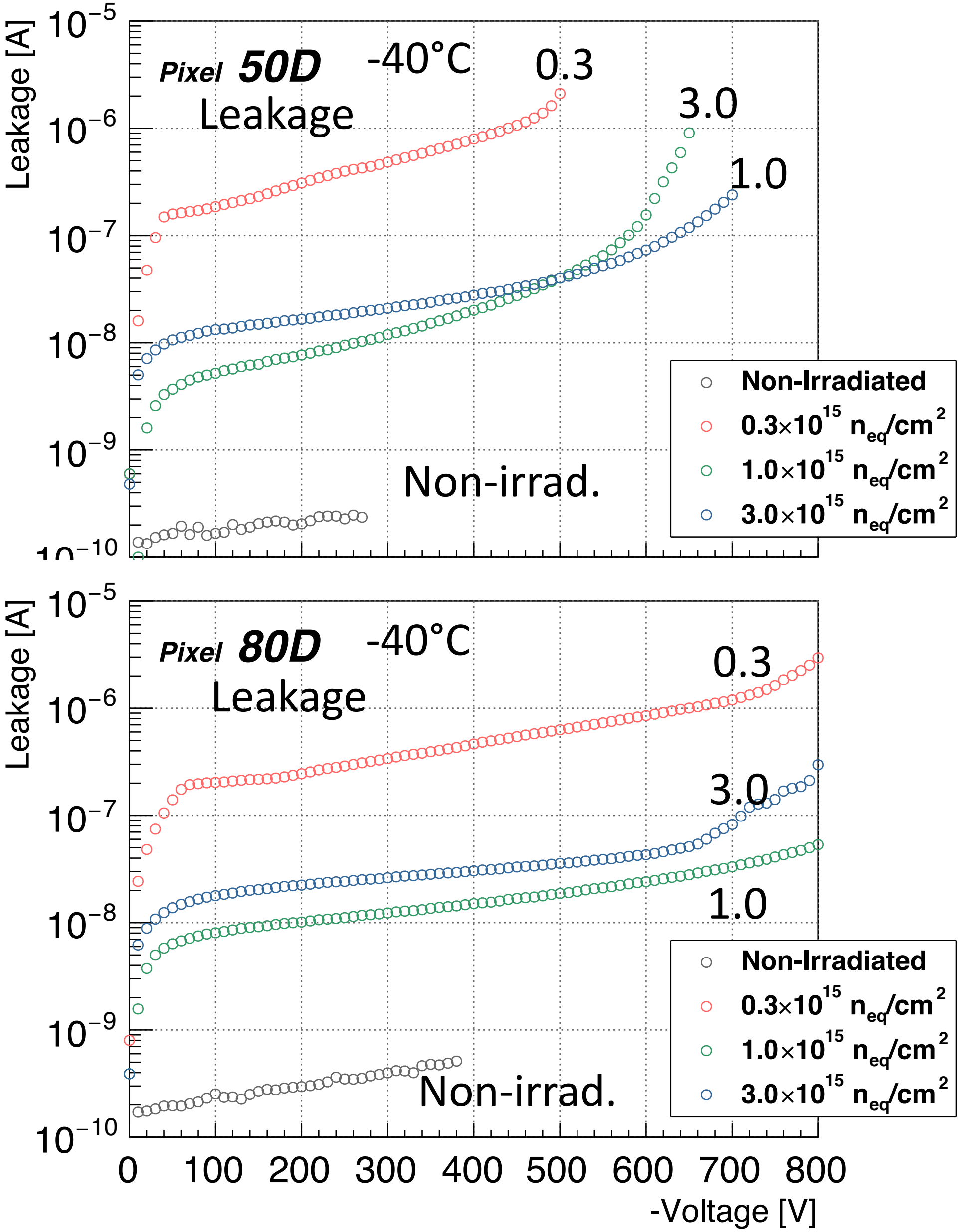
- Lower, temperature
  – higher, gain
- Because
  – longer, mean free path
  – higher, accelerated energy
  – more, impact ionizations

Gamma Irradiation



- 2016/11/25
  - at Takasaki (JAC)
  - 0.1/1.0/2.5 MGy
- Leakage currents:
  - 2 orders of mag.↑
  - (where?)
- Gain:
  - Decrease as dose↑
  - but not much.
- Surface effect is small.

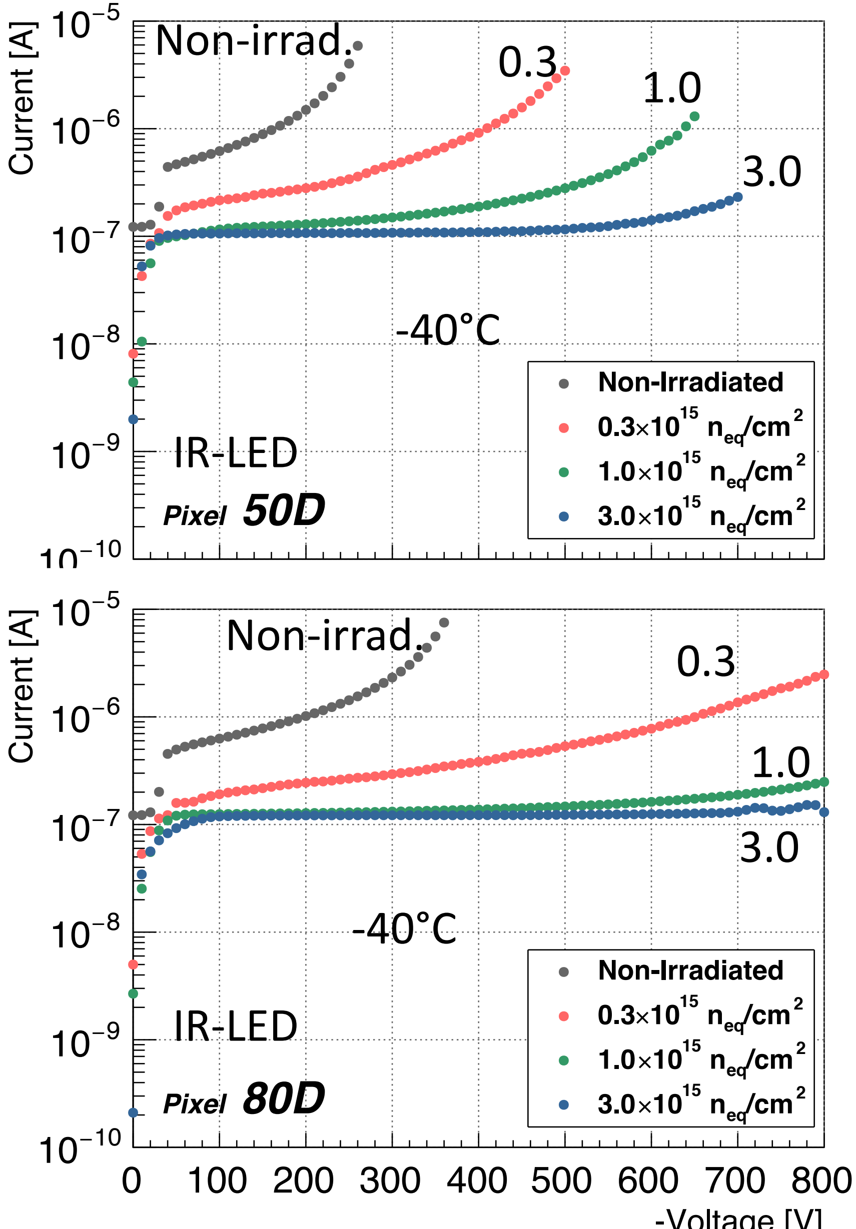
Neutron Irradiation – Leakage Current



- 2016.12.15 @Ljubljana
- 0.3, 1.0, 3.0×10^{15} neq/cm^2
- Annealed at 60°C-80 min.

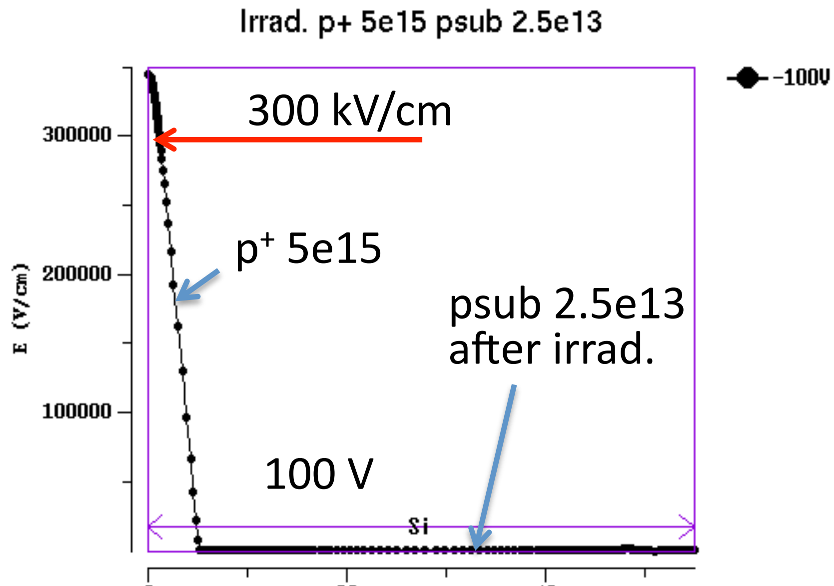
- No $\Delta I/V=\alpha\phi$ dependence
- Interplay (?) of
  - Bulk leakage current↑
  - Gain↓(see next page)

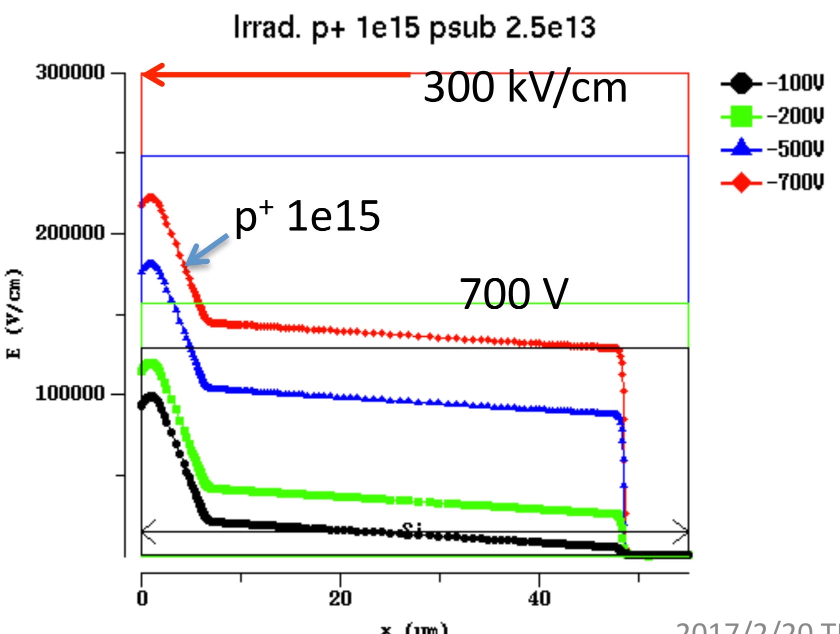
Neutron Irradiation – IR-LED



- 2016.12.15 @Ljubljana
  - 0.3, 1.0, 3.0×10[15] neq/cm[2]
- Annealed at 60°C-80 min.
- Full depletion voltage:
  - ~100 V@80 µm at 3×10[15]
- Gain↓ as fluence↑

Discussion





- Why the device looses the gain after neutron irradiation?

- If the p$^+$ density is <<5×10^{15} cm^{-3}, the peak E field won't reach the critical avalanche breakdown field of
  - ~30 V/µm (i.e. 300 kV/cm)

Summary

- Variations of pixel structures of 50×50 or 25×100 μm^2 were evaluated against efficiency loss due to the structures.
- All structures work (≥95%, e.g.) after irradiation of protons to 3×10^{15} neq/cm^2 expected at the HL-LHC.
- The elements of the structures where the loss occurs have been identified and can be improved in the next prototyping, including the threshold of ASIC (with RD53A chip).

- Amplification of charges ("Gain") were evaluated in the newly fabricated LGAD devices (diodes, strips).
- Only a small decrease of Gain was observed with the gamma irradiation, i.e., the surface effect is small.
- A large decrease of Gain was observed with the neutron irradiations. Understanding the physics behind is the next step.

Contributors & Acknowledgement

- ATLAS-Japan Silicon Collaboration
  - KEK, Uni. Tsukuba, Tokyo Tech., Kyoto Edu., Osaka Uni., Kyushu Uni.
- S. Kamada, Y. Abo, K. Yamamura, H. Yamamoto (HPK)
- ATLAS Planar Pixel Sensor (PPS) Collaboration
  - AS CR, Prague, LAL Orsay, LPNHE/Paris VI, Uni. Bonn, HU Berlin, DESY, TU Dortmund, Uni. Göttingen, MPP and HLL Munich, Uni. Udine-INFN, KEK, Tokyo Inst. Tech., IFAE-CNM, Uni. Geneva, Uni. Liverpool, UC Berkeley, UNM-Albuquerque, UC Santa Cruz
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- Takasaki Advanced Radiation Research Institute, Japan Atomic Energy Agency for gamma irrradiation
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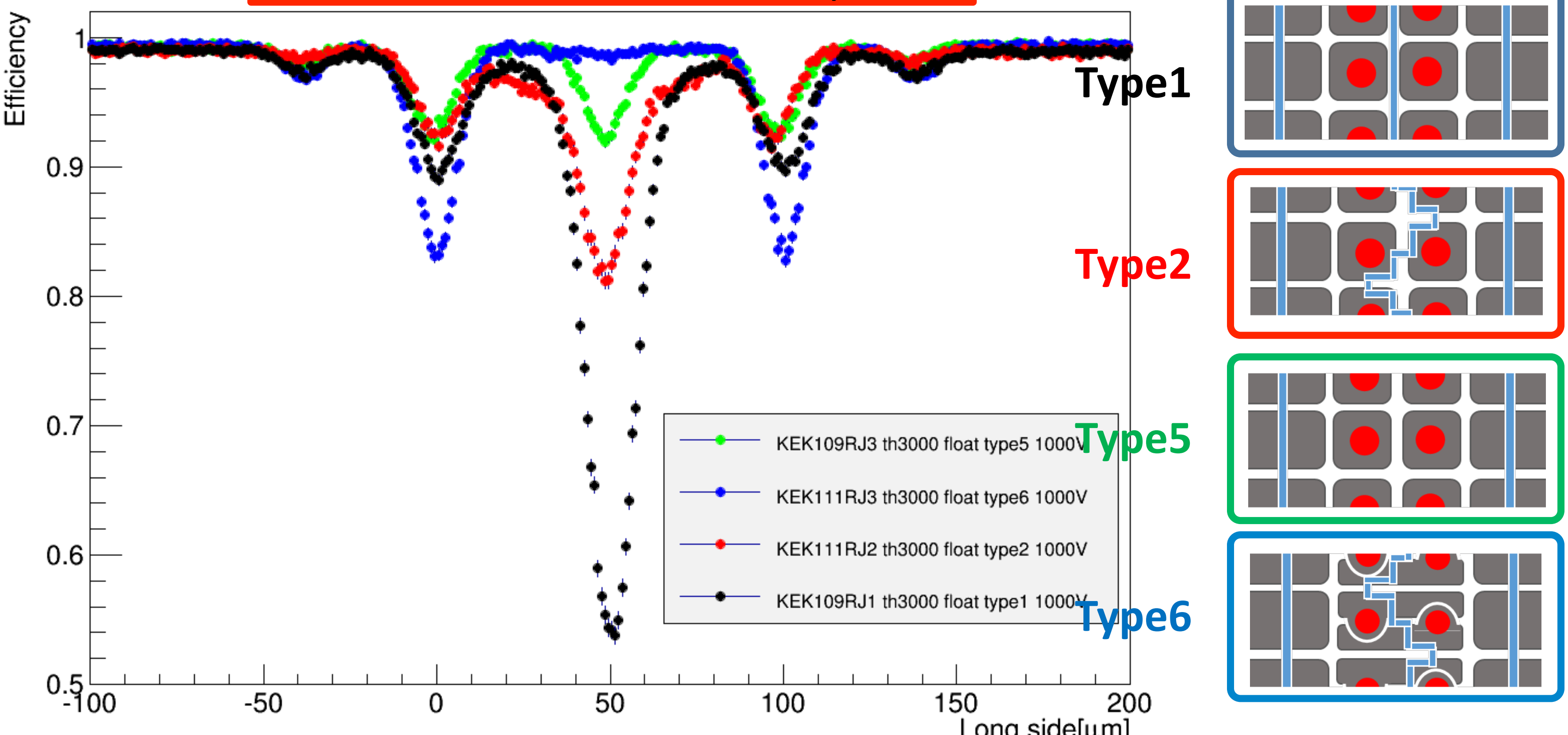
AIDA 2020

Backup

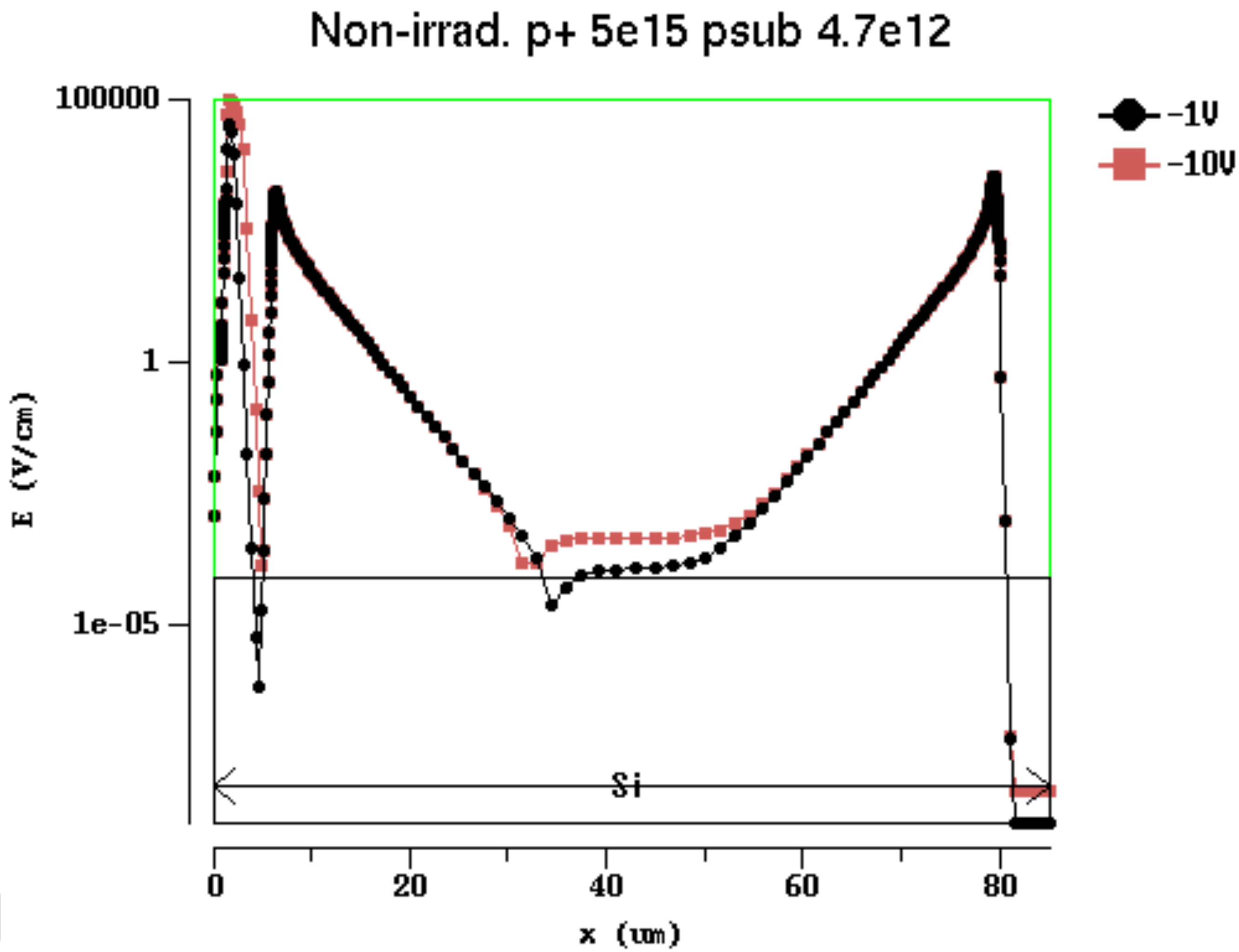
Efficiency Map Projection

- The loss at the boundary of pixels of 50 μm and 450 μm is the same for all devices
  - Basically the same structure (the four corner)
- Loss between 50 μm pixels: Type1 > Type2 > Type5
  - Geometry of the bias rail

Proton Irrad 3×10^{15} 1MeV n_{eq}/cm^2



Depletion with Low Bias Voltages



- psub is also depleted, partially...