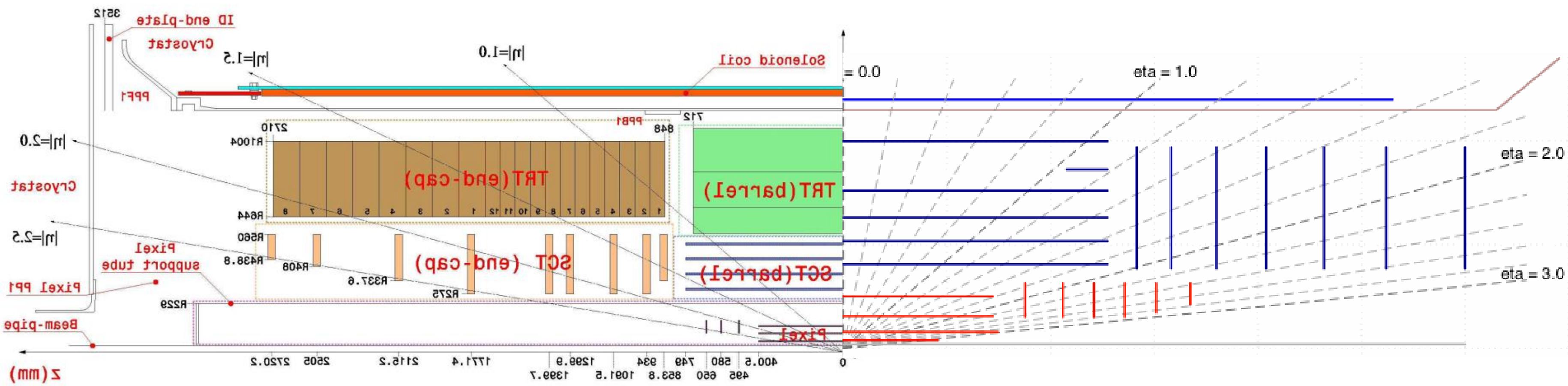
Planar P-type Pixel and Strip Sensors Development for HL-LHC in Japan

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

ATLAS Tracker Layouts

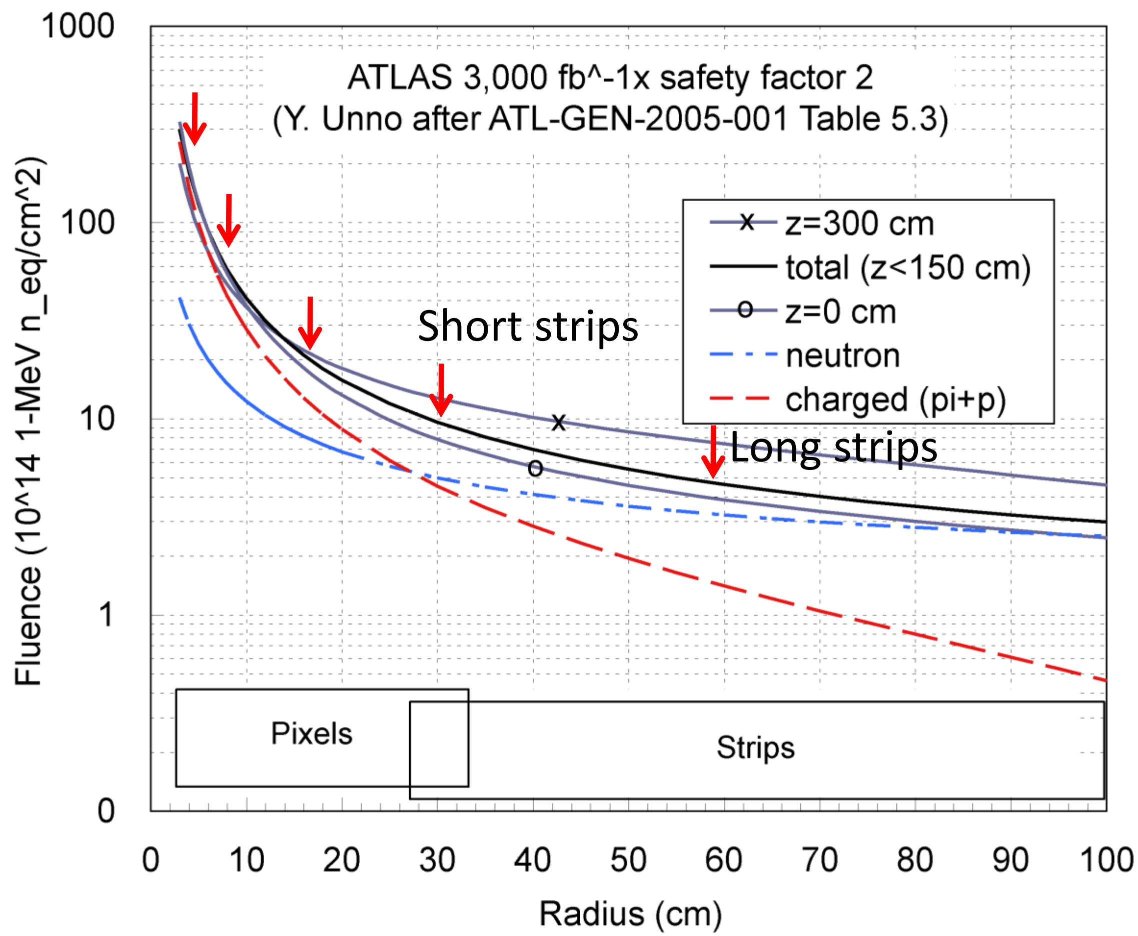


- Current inner tracker
  - Pixels: 5-12 cm
    - Si area: 2.7 m^2
    - IBL(2015): 3.3 cm
  - Strips: 30-51 (B)/28-56 (EC) cm
    - Si area: 62 m^2
  - Transition Radiation Tracker (TRT): 56-107 cm
    - Occupancy is acceptable for <3x10^{34} cm^{-2}s^{-1}
    - Phase-II at HL-LHC: 5x10^{34} cm^{-2}s^{-1}

- Phase-II upgrade (LOI)
  - Pixels: 4-25 cm
    - Si area: **8.2** m^2
  - Strips: 40.-100 (B) cm
    - Si area: 122 (B)+71(EC)=**193** m^2
- Major changes from LHC
  - All silicon tracker
  - Large increase of Si area
    - both in Pixels and Strips
    - ~3 × LHC ATLAS

Particle fluences in ATLAS

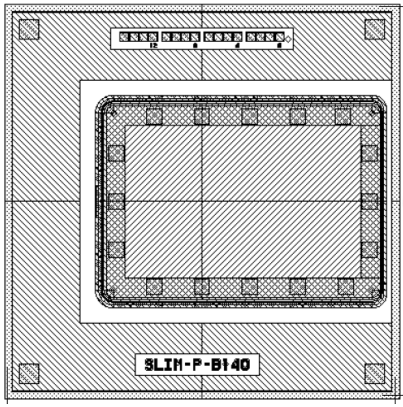
- ATLAS detector to design for
  - Instantaneous lum.: **$7x10^{34}$ $cm^{-2}s^{-1}$**
  - Integrated lum.: **6000 fb^{-1}** (including safety factor 2 in dose rate)
  - Pileup: **200** events/crossing
- **PIXELs (HL-LHC)**
  - Inner: r=3.7 cm ~$2.2x10^{16}$
  - **Medium: r = 7.5 cm, ~$6x10^{15}$**
  - Med/Out: r=15.5 cm ~$2x10^{15}$
  - Outer: r = 31 cm (?) ~$1x10^{15}$
  - Charged:Neutrons ≥ 1
- **STRIPs (HL-LHC)**
  - **Replacing Strip and TRT**
  - **Short strip: r = 30 cm, e.g.**
    - **~$1x10^{15}$**
  - Long strips: r = 60 cm,
    - ~5×10^{14}
  - Neutrons:Charged ≥ 1
- IBL (LHC)
  - Insertable B-layer pixel
  - r = 3.3 cm
    - Flunece ~$3x10^{15}$ neq/cm^2
    - at Int.L~300 fb^{-1}



Content

- Strip sensors (ATLAS12)
  - R&D's
  - Latest fabrication and 1st result
- Pixel Structure
  - "Old" design (1st try)
  - "New" design (1st Optimization)
- Other R&D's
  - Slim edges (DRIE+...)
  - HV protection (Irradiation test of post-process material)
- Bump-Bonding
  - Latest issue
  - Improvements
- One more thing...

R&D's on Edge Width and PTP



Edge width varied

CYRIC irradiations
70 MeV proton

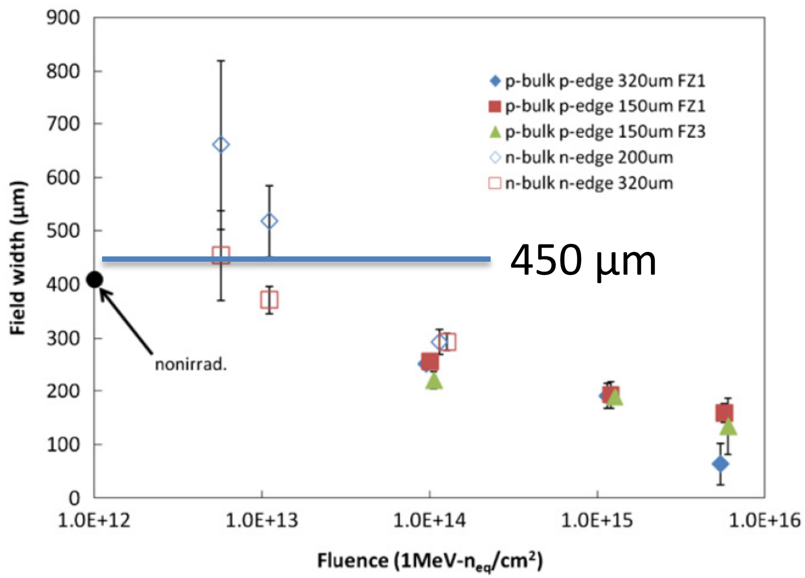
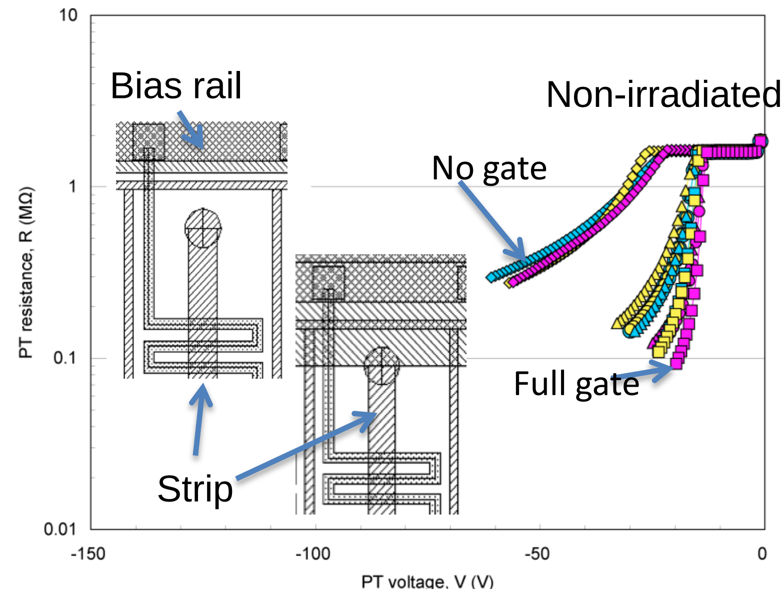
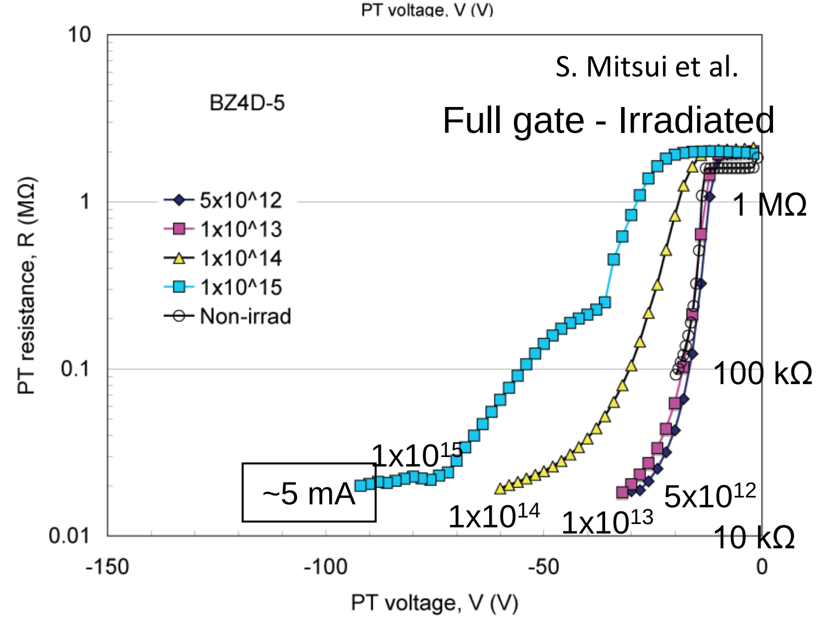


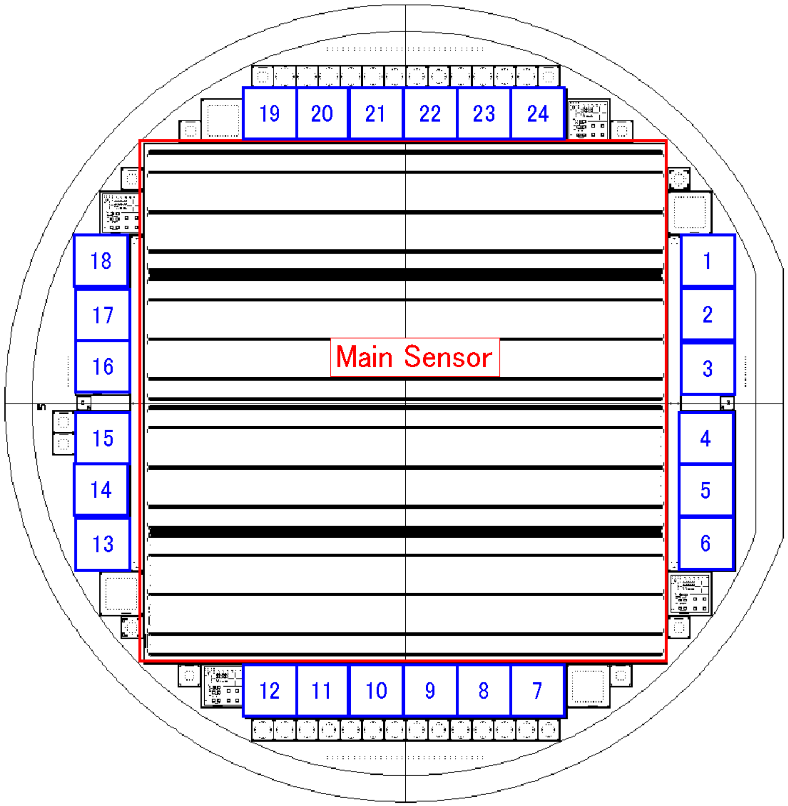
Fig. 5. Fluence dependence of field width hold up to 1000 V.

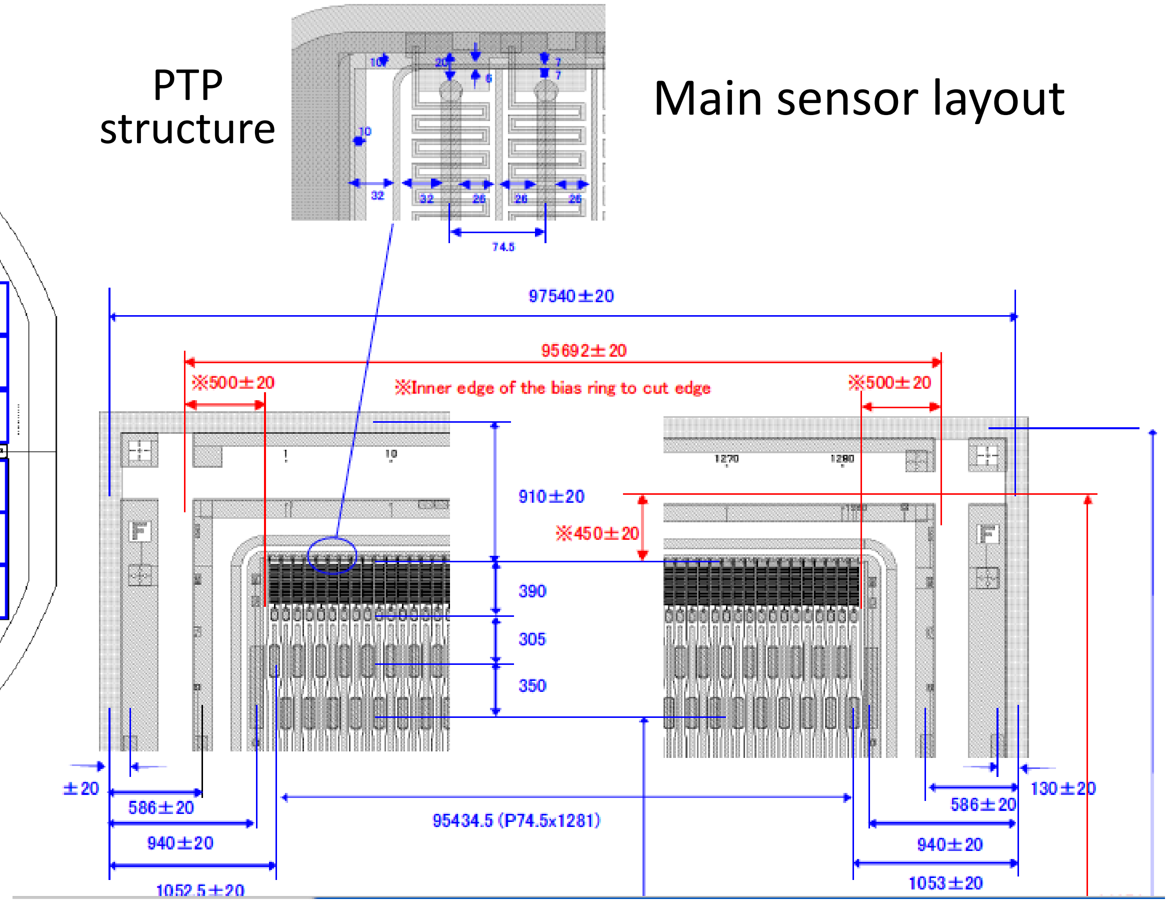




- S. Mitsui et al., NIMA699(2013)36-40

ATLAS12 Sensors





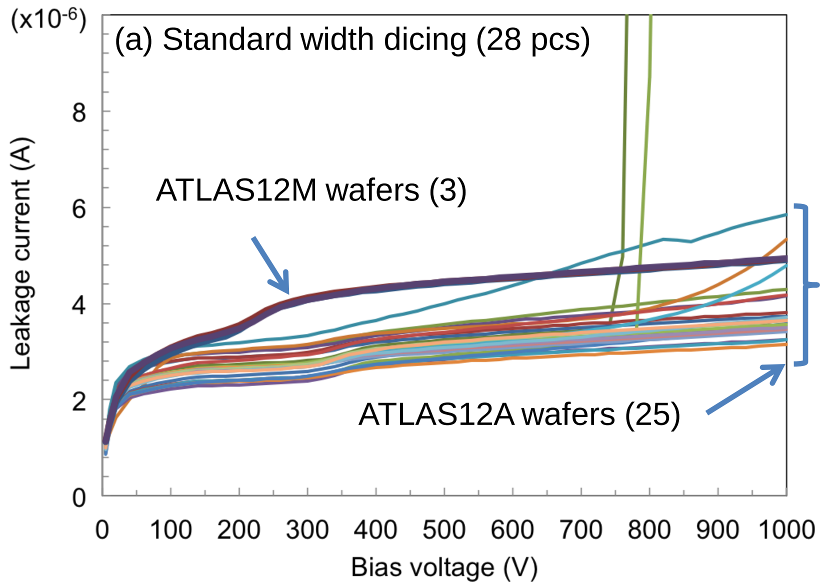
6-in. wafer, 320 μm thick
p-type FZ <100>

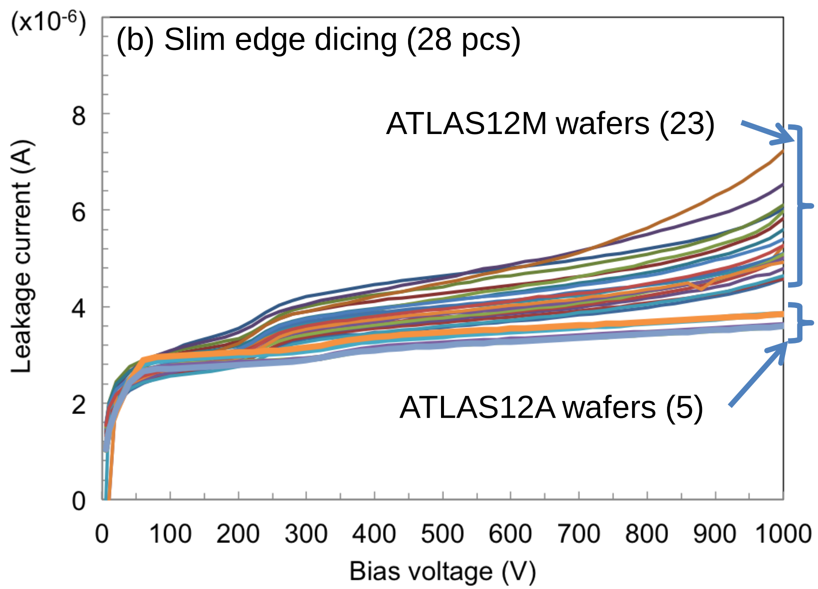
Main: 9.54 × 9.54 cm^2
Mini's: 1 × 1 cm^2

- PTP structure
- Slim edge - Two dicing lines:
  - Nominal (Blue): 910-950 μm
  - Slim (Red): 450-500 μm
- and others...

ATLAS12 I-V after Dicing

- Process finished for ATLAS12A 120 pcs and 12M 45 pcs
- ATLAS12-A 30 and –M 26 wafers were diced to
  - 28 “Standard” width (950 µm) and 28 “Slim” (450 µm)

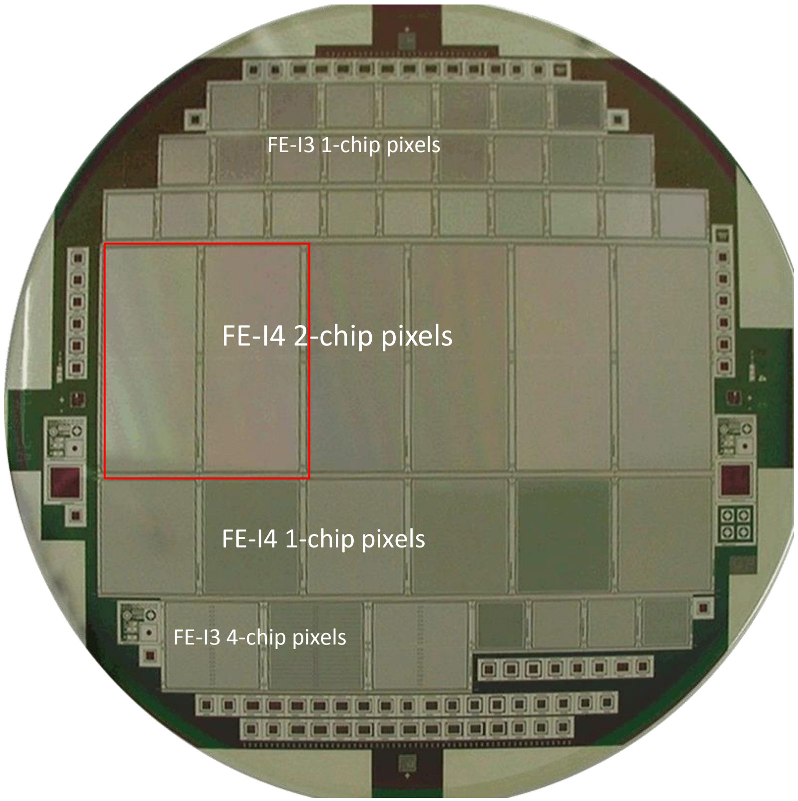




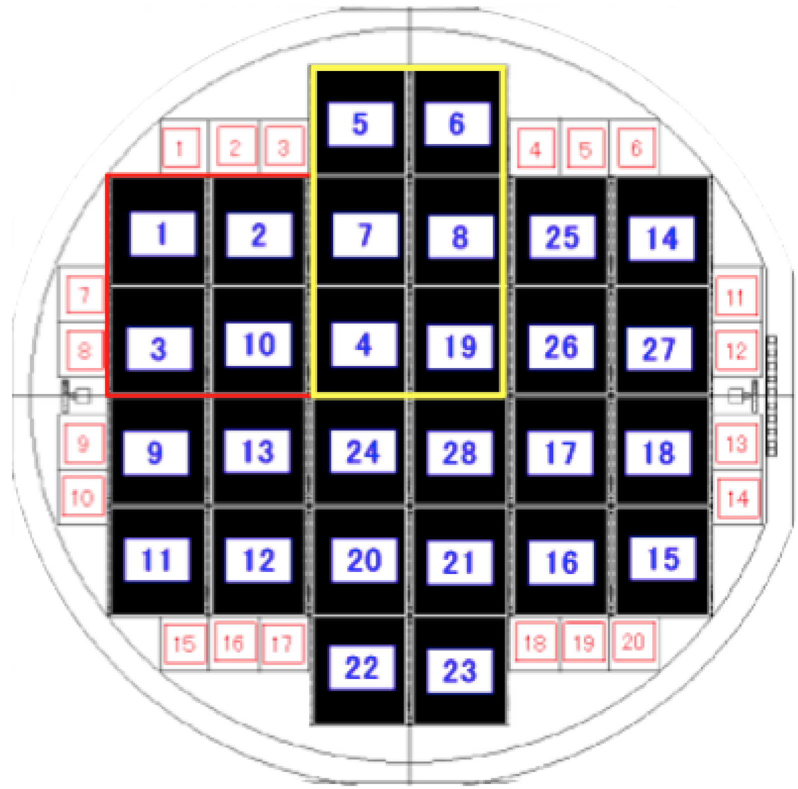
- “Standard” edge dicing
  - Most are flat up to 1000 V
  - MD (~750V) 2pcs (7(±5)% of 30)
- “Slim” edge dicing
  - Success
  - Some tendency to increase current over 800 V in 12M, not 12A
  - Subtle wafer/process dependence(?)

- I-V “wiggle”s
  - 12A at 300-400 V
  - 12M at 200-300 V
  - associated with full depletion of the bulk

KEK/HPK n-in-p Pixel Sensors

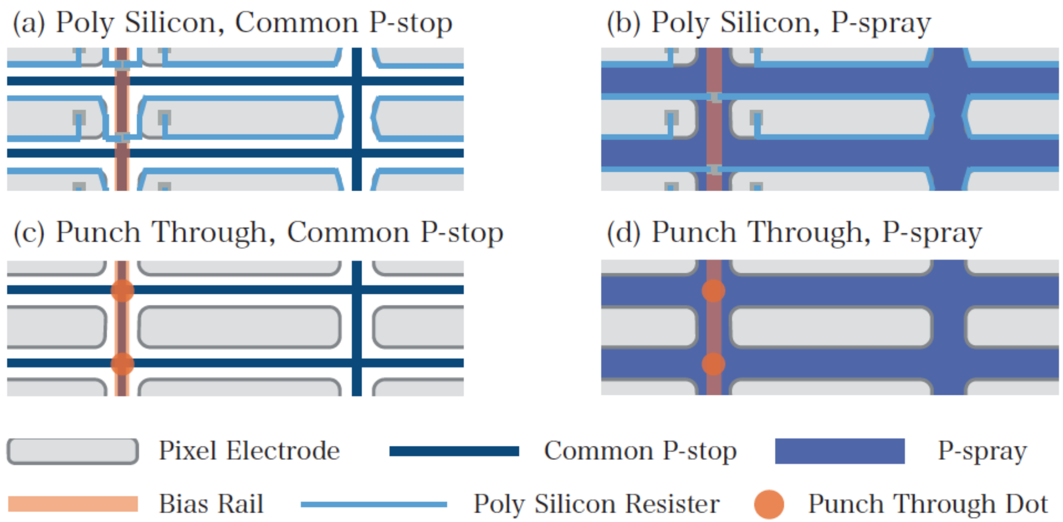


n-in-p 6" #2 wafer layout
("Old" pixel structures)



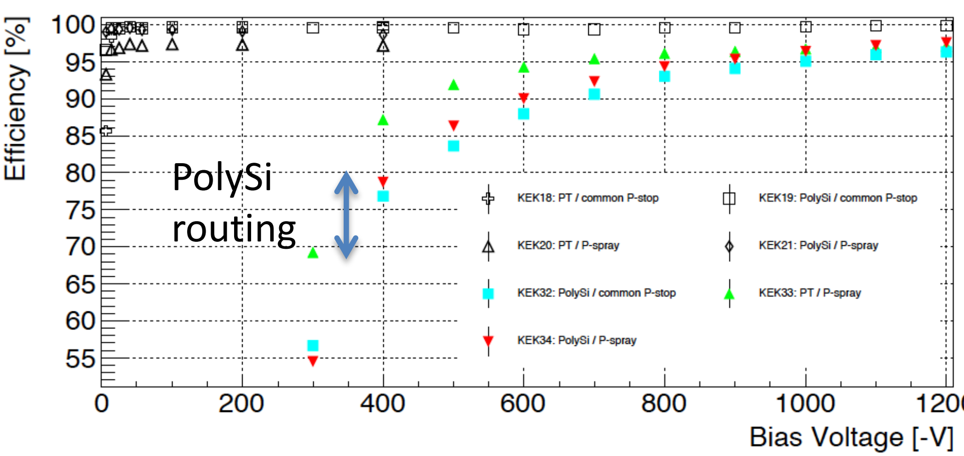
n-in-p 6" #4 New wafer layout
("New" pixel structures)

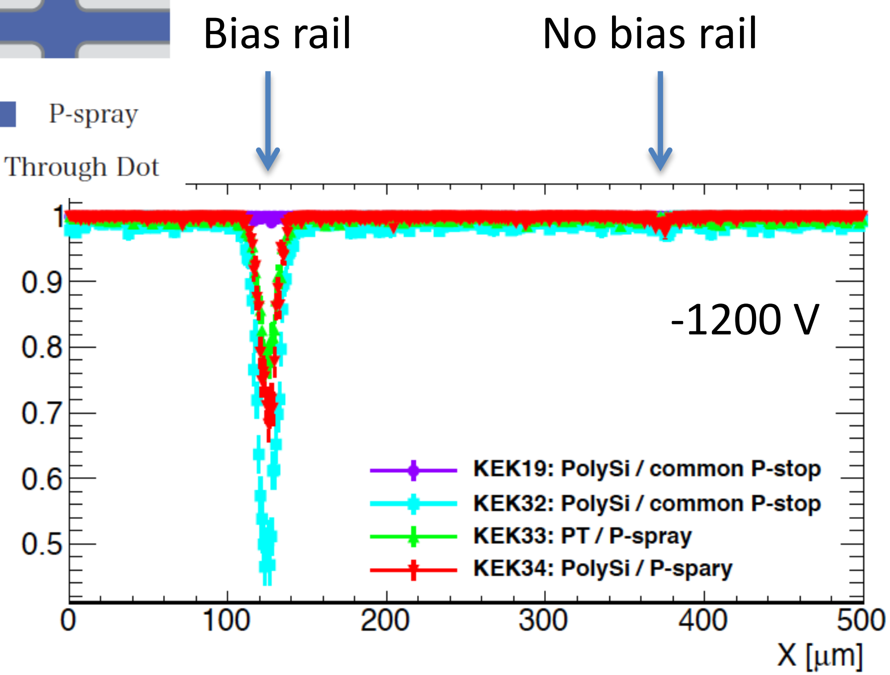
"Old" Pixel Structures



K. Motohashi et al. HSTD9

Irradiation: n 1×10^{16} neq/cm^2 at Ljubljana

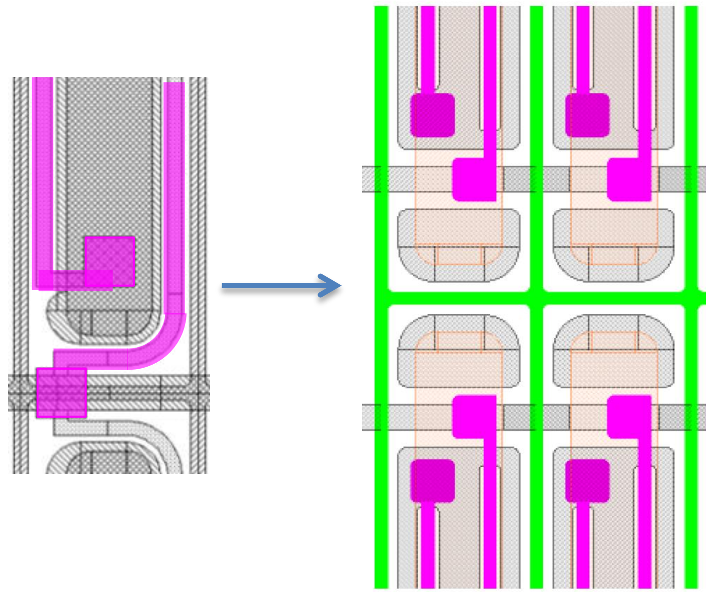




- Severe efficiency loss in the pixel boundary with bias rail
- Subtle efficiency loss with the routing of bias resister

PolySilicon Bias Resistor Routing

(#2 Wafer Layout)

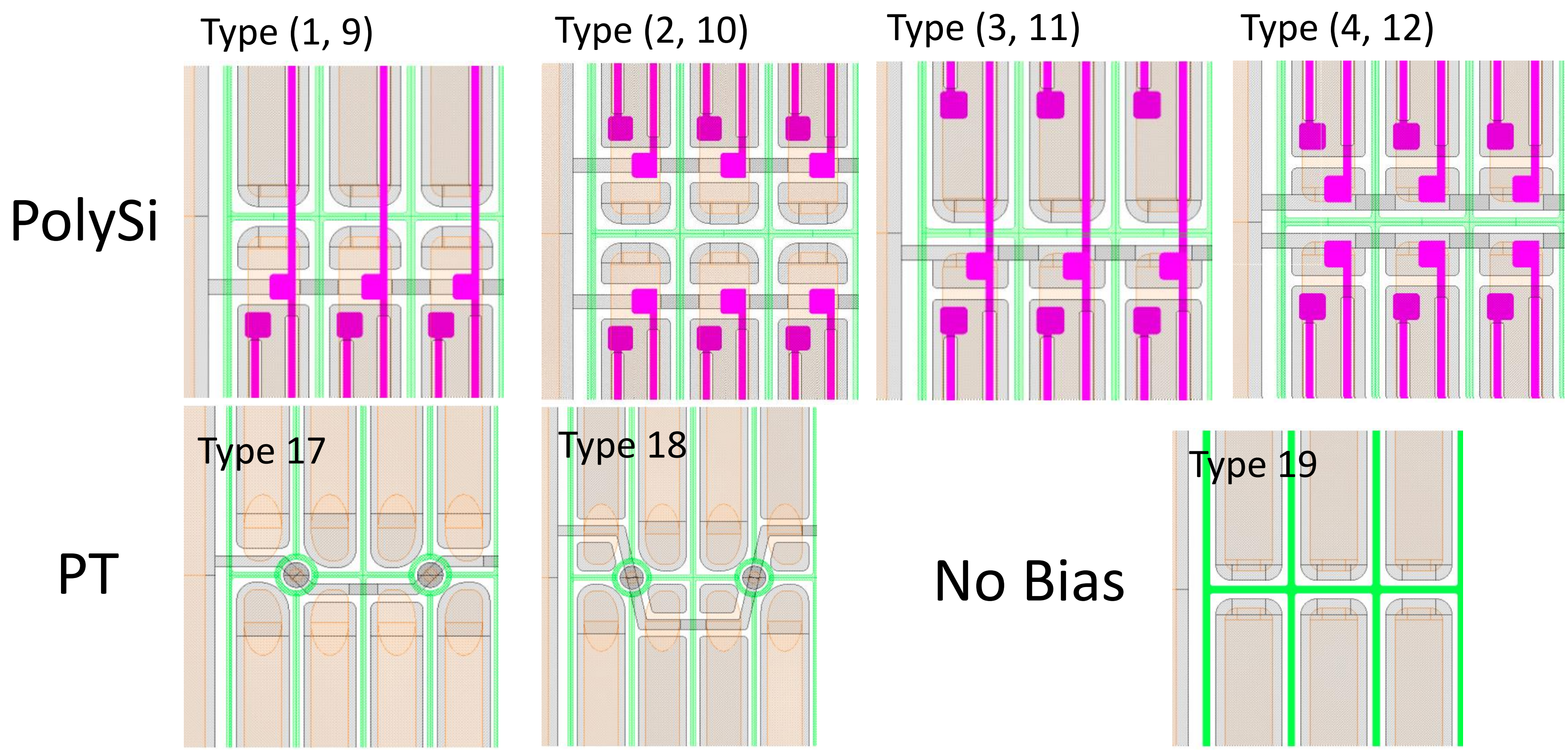


(#4 Wafer Layout)

- PolySi encircling "outside" the pixel implant
  - causes inefficiency
  - by reducing the electric field under the polysilicon, very much similar to the effect of the "bias rail"
- Move the routing of the PolySi "inside" the pixel implant

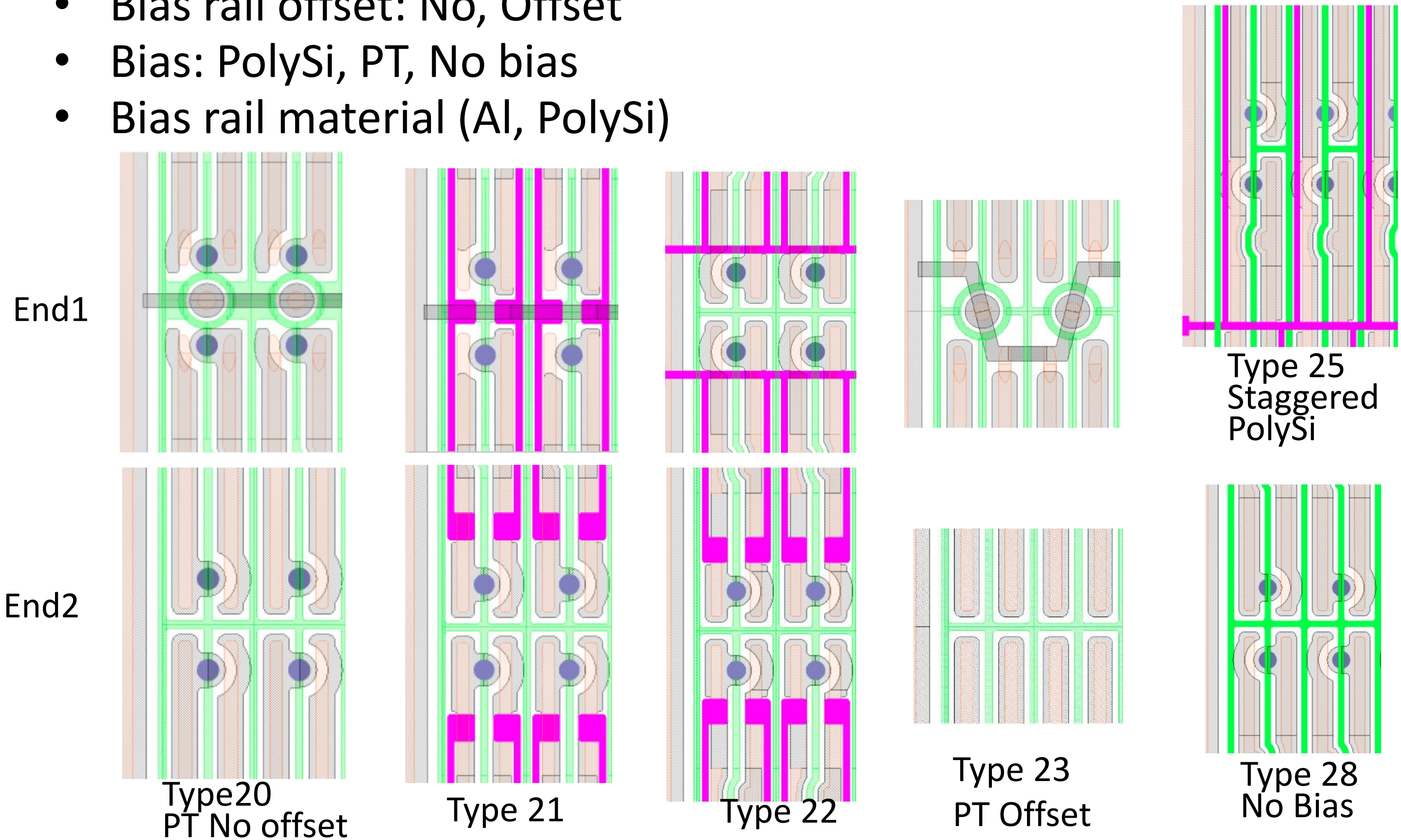
#4 Wafer Layout - Bias Rail Routing

- Bias rail to offset from midway: Large, Small
- Bias Type: PolySi, Punch-Thru (PT)
- Number of bias rail: Single, Double, None
- Bias rail material (Al, PolySi)



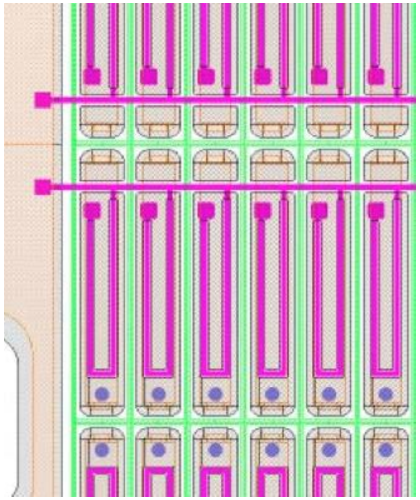
Narrow pitch 25 µm pixels

- Bump pads at the midway of the pixels
- Bias rail offset: No, Offset
- Bias: PolySi, PT, No bias
- Bias rail material (Al, PolySi)

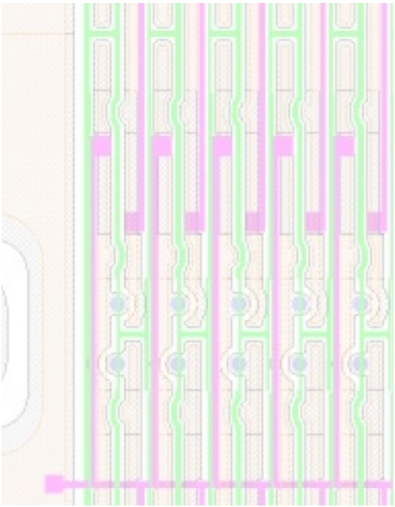


Beamtests of New n-in-p Pixels

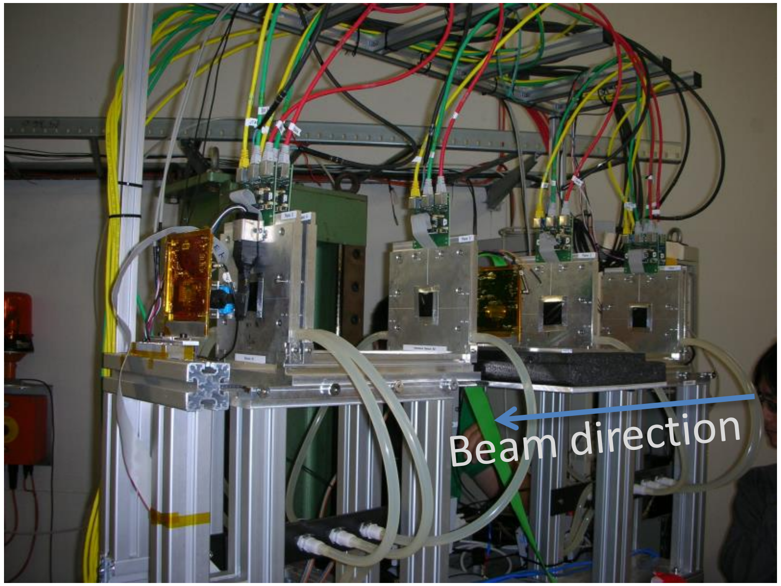
- New pixel structures
  - Fabricated.
  - Being irradiated and in testbeams for evaluation
  - Pixel pitch: 50 x 250 μm^2 (normal), 25 x 500 μm^2 (half pitch)
- FE-I4 (and FE-I3) modules were in testbeams in2013 at DESY.
  - Mar.: non-irrad (FE-I4: KEK9, 22), irrad (FE-I4: KEK18, 19, 20, 21)
  - Aug.: non-irrad (FE-I4: 1chip(KEK38,39,40,41), 4chip(KEK35,36,37)), FE-I3: KEK10), irrad (FE-I3: KEK11, 17)
  - Nov. : irrad (FE-I4: 4chip (KEK39(Type27), 46(Type10)))



Type10, 50 x 250 μm^2

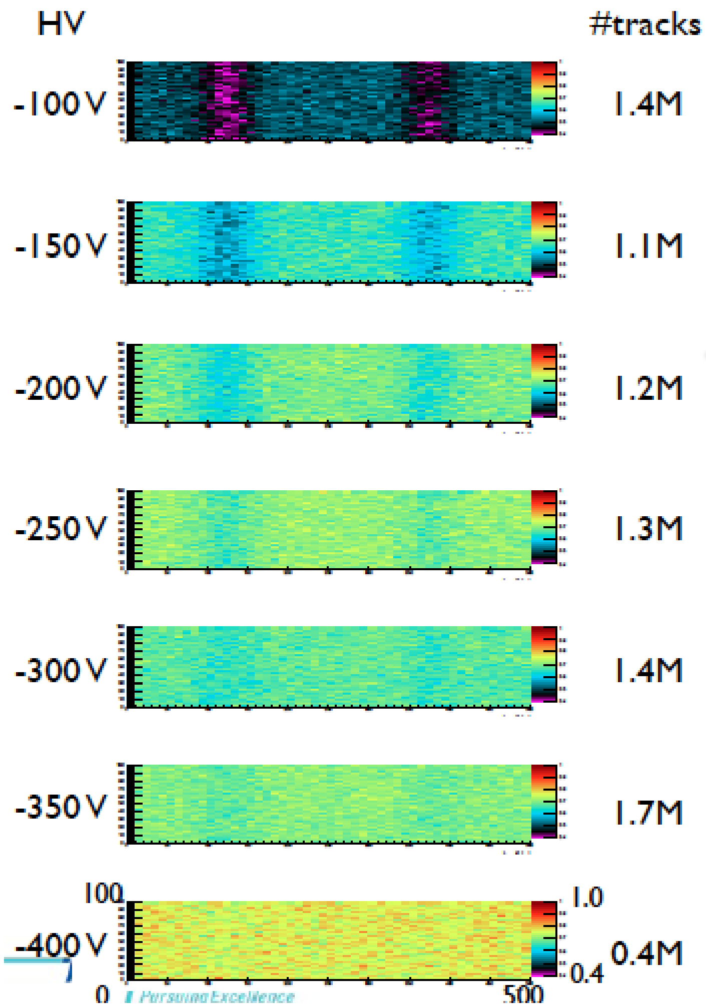


Type27, 25 x 500 μm^2 staggered



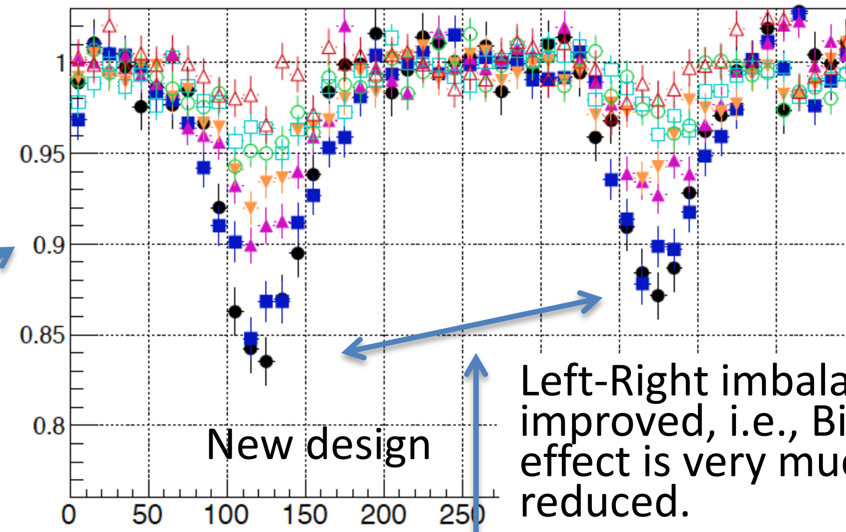
Preliminary Results

- Efficiency Pixel Map



- After Irrad.

Irrad. KEK46 (Type10)



Left-Right imbalance is improved, i.e., Bias rail effect is very much reduced.

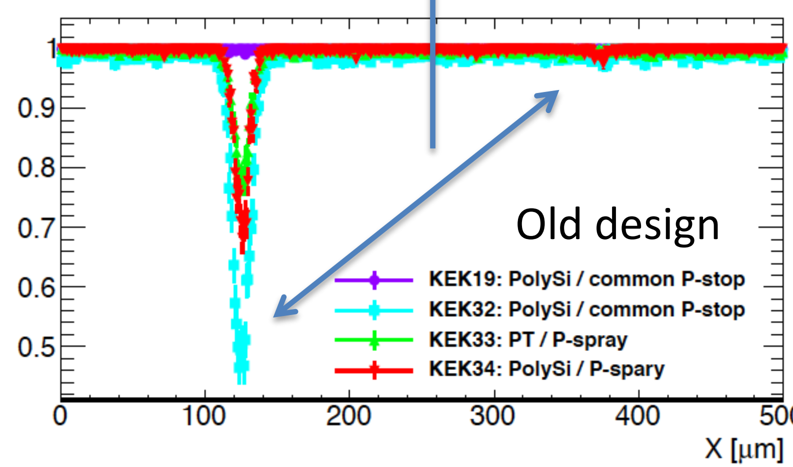


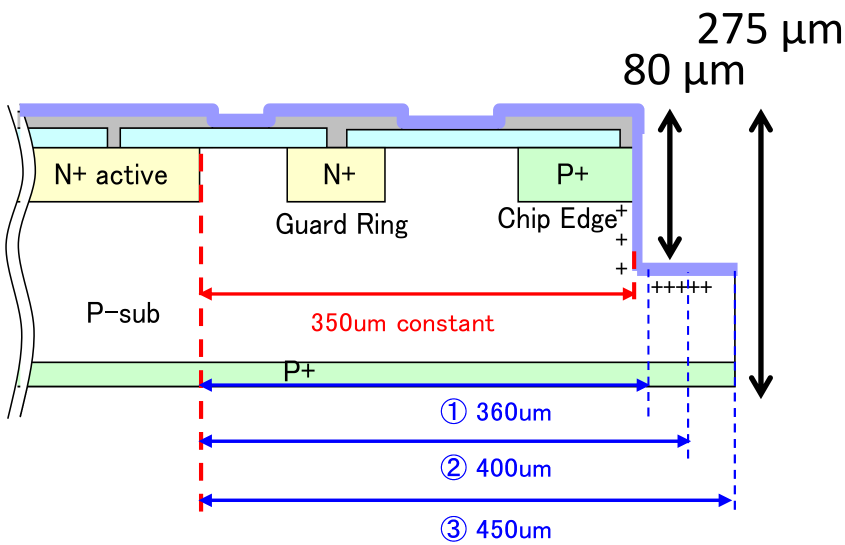
Figure 6: The projection of efficiencies of the regions with $45 < y < 55$ to long pixel direction (x) for the bias rail effect measurement. The results with bias voltage at -1200 V in batch 2 is plotted.

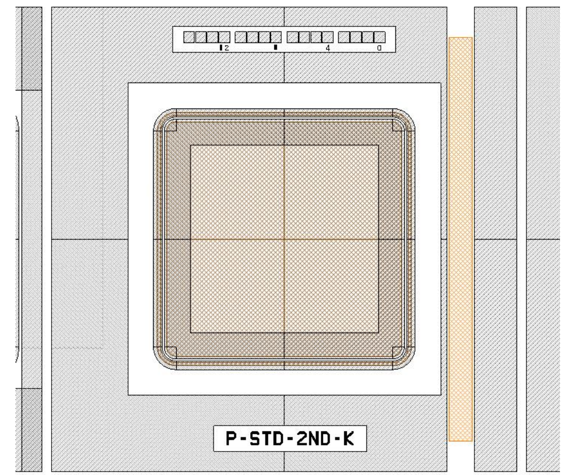
See D. Yamaguchi's presentation

Towards Slim Edge

- DRIE and Alumina passivation
- Half and Full penetration
- Irradiations
- (In future, ion-implantation in the side wall = active edge.)

DRIE Trench and Al_2O_3 passivation

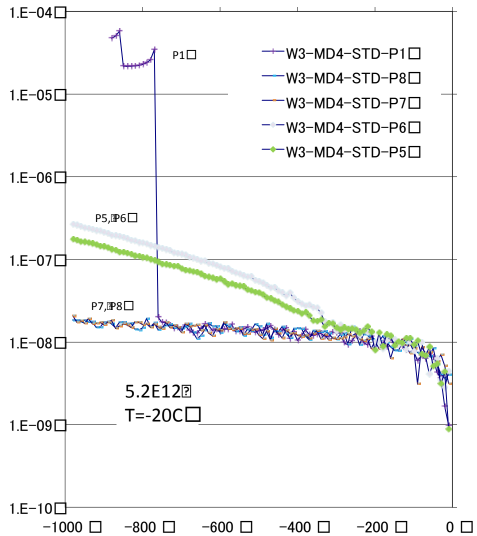


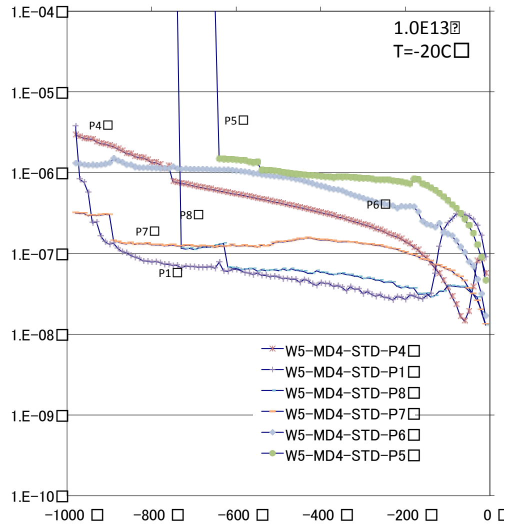


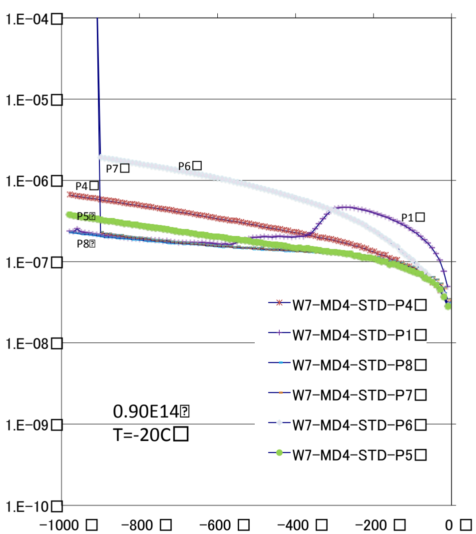
			受光部エッジからの距離		GRエッジからの距離	
		トレンチ幅	トレンチ壁	SD	トレンチ壁	SD
1	MD4−STD−1	200	351	451	271	371
2	MD4−STD−2	100	351	401	271	321
3	MD4−STD−3	50	351	376	271	296
4	MD4−STD−4	20	351	361	271	281

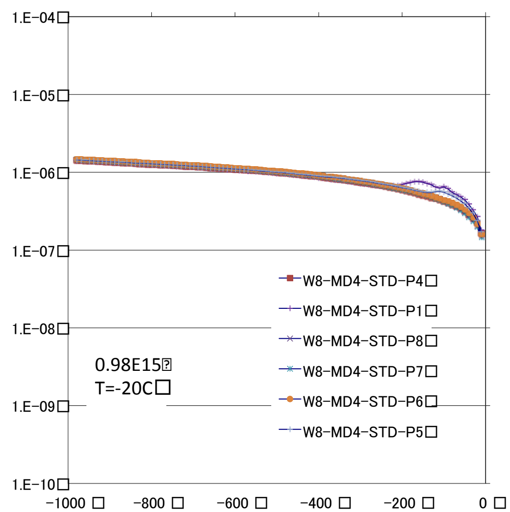
- Trench DRY etching
  - One side, depth: 80 µm etc.
- Alumina (Al_2O_3) passivation process (before dicing)
- Stealth-Dicing (SD) at a variation of distance, in the trench

After Irradiation





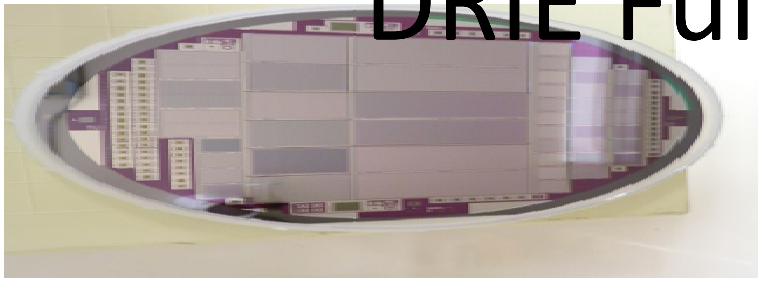


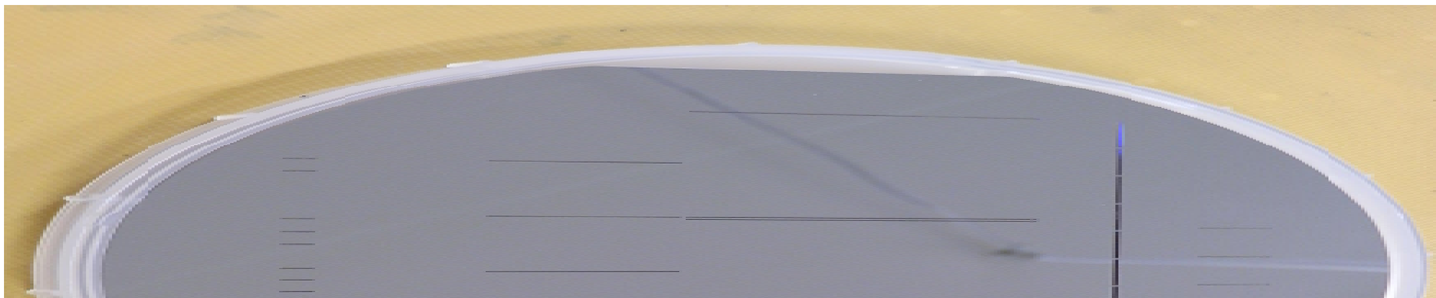


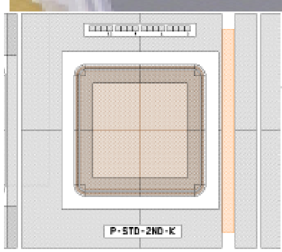
- CYRIC 70 MeV p
  - '13/7/25-7/26
  - 5.2e12, 1.0e13, 0.90e14, 0.98e15
- P5, P6 breaks at lower voltages
  - 450 μm edge width.
- P1(450 μm), P4(360 μm)
  - Weird leakage current behavior at low voltage in P1.
  - Larger currents at 1e13.
  - Less difference in higher fluneces; No difference in 1e15.
- With proton irradiation
  - Large and weird leakage current behaviour at low fluences.
  - Little difference in edge distances at high fluence(s).

Measurements by Y. Arai et al.

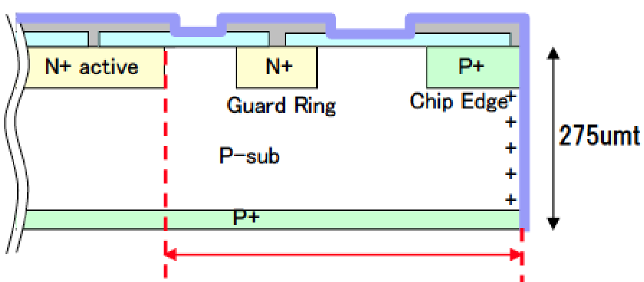
DRIE Full Cut



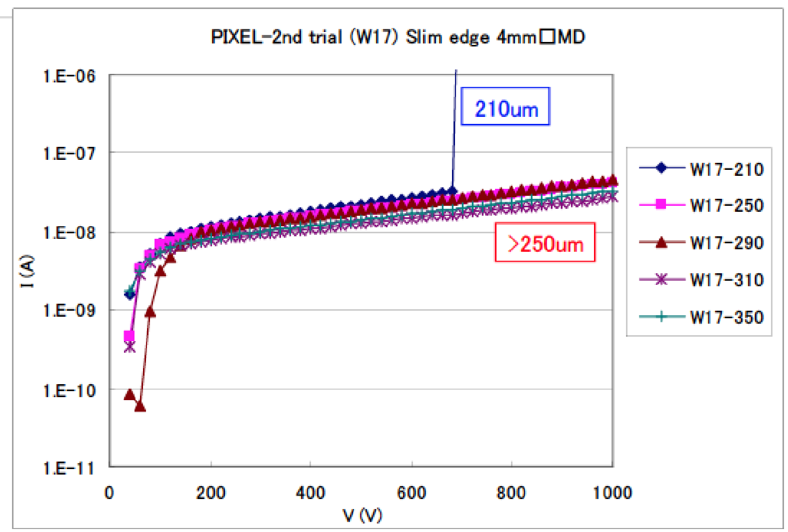




4mm□
Monitor Diode
1 side slim edge



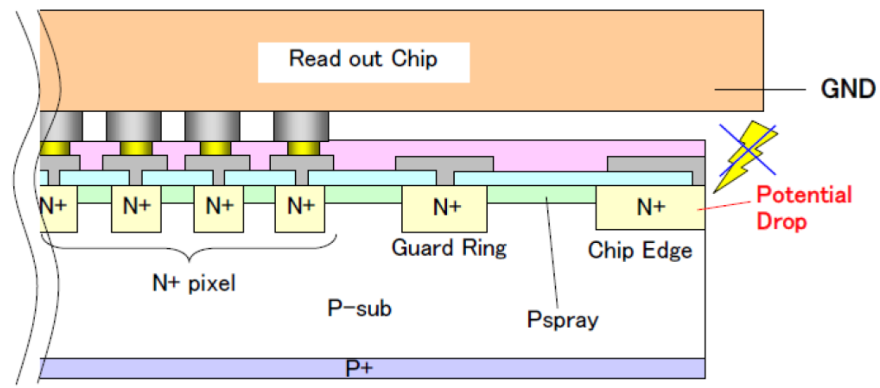
distance
from active edge to dicing edge
「210um/250um/290um/310um/350um」



- "210 µm" MD might due to narrow P-N gap
- Optimization is required for a slim edge ~200 µm
- **irradiation**
  - **'14/1/15-1/16**
  - **5e12, 1e13, 1e14, 1e15, 5e15**
  - **Transferred to KEK today (2/17)**
  - **Measurement to follow**

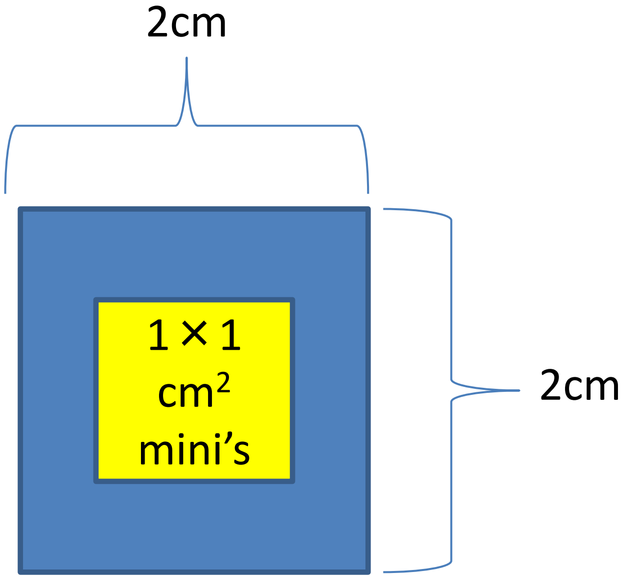
HV Edge protection

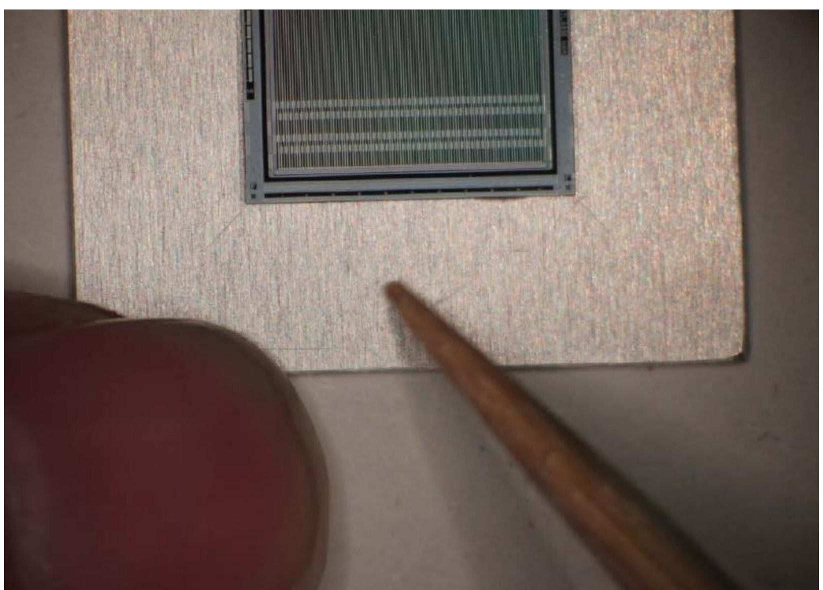
- “Post-process” so far
  - Silicone adhesive encapsulation
    - becomes hard and brittle at ≥10^{15} neq/cm^2
  - Parylene coating
    - Available: Parylene-C, -N, -HT
- Irradiation
  - At LANSCE, 800 MeV protons
    - With the help of Sally Seidel’s team
  - **New irradiation at CYRIC**
    - **2014/1/15-1/16**



In-process, high-tech solution is still to be made...

New Irradiation of Parylenes





- Parylene-C, -N, -HT
- Samples
  - with a 1×1 cm^2 mini's at center, glued
  - full coating over 2×2 cm^2 AL plate (0.5 mm)
- Irradiation
  - CYRIC '14/1/15-1/16
  - 1×15, 5×15, 1×16 neq/cm^2
- Evaluation
  - Visual: no discoloration in all samples for all fluences
  - No mechanical damage/scratch after poking with a bamboo stick
- Parylene is radiation-tolerant to $1x10^{16}$ (!!)

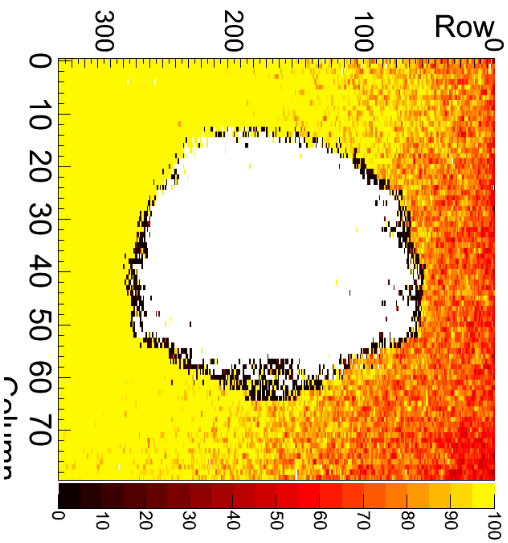
Bump-Bonding (BB)

- Thin sensor (150 μm) – Thin ASIC (150 μm) SnAg BB
- Our special - No glass support wafer
- We have experienced with "large area open bumps" in the center of chip.
  - 1^{st}-3^{rd} BB was no "large open" area – Thick-Thick BB
  - A summary table below.

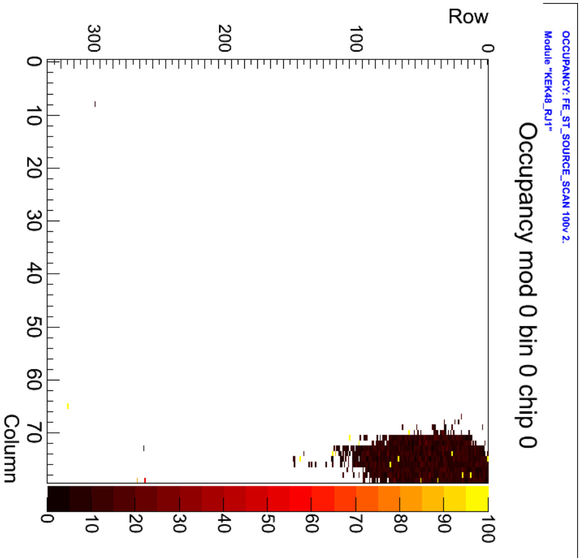
BumpBonding	Sensor (μm)	ASIC (μm)	UBM issue	Large area open bumps
1^{st}	320	700 (FE-I4"A")	N/A	No
2^{nd}	320	700 (FE-I4"A")	N/A	No
3^{rd}	320	150 (FE-I4"A")	N/A	No
4^{th}	150	150 (FE-I4"B")	Less wetness	Observed
5^{th} (repeat of 3^{rd})	320	150 (FE-I4"B")	Less wetness	Observed
6^{th} (impr'ved)	150	150 (FE-I4"B")	Less wetness	No

Bump-Bonding (BB)

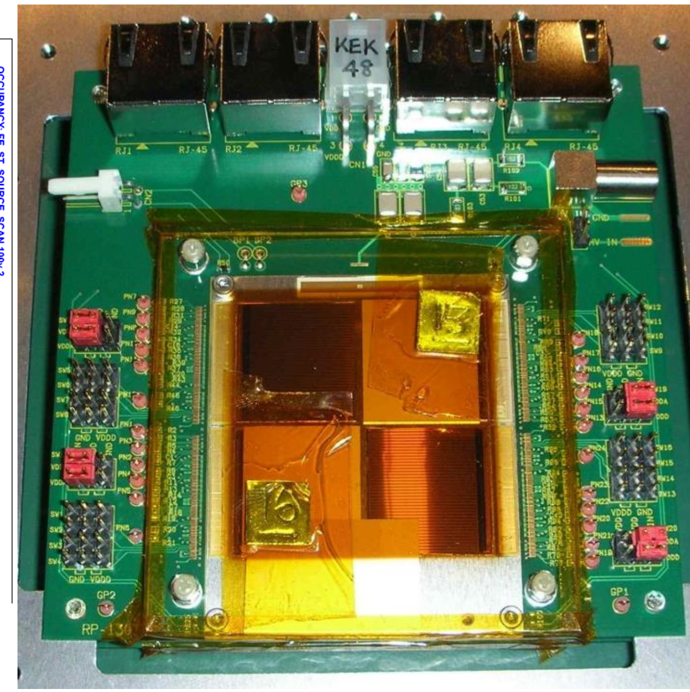
Before irrad



After irrad.



Even more... detached sensors



- β source scans
- Source of trouble
  - Weak shearing force(?)
  - Less-wetness of UBM
    - specific for 4th, 5th, (6th?)
  - Then, thermal stresses
    - Beam - higher localized heating
    - Internal stress (bowing)

Bump-Bonding (BB)

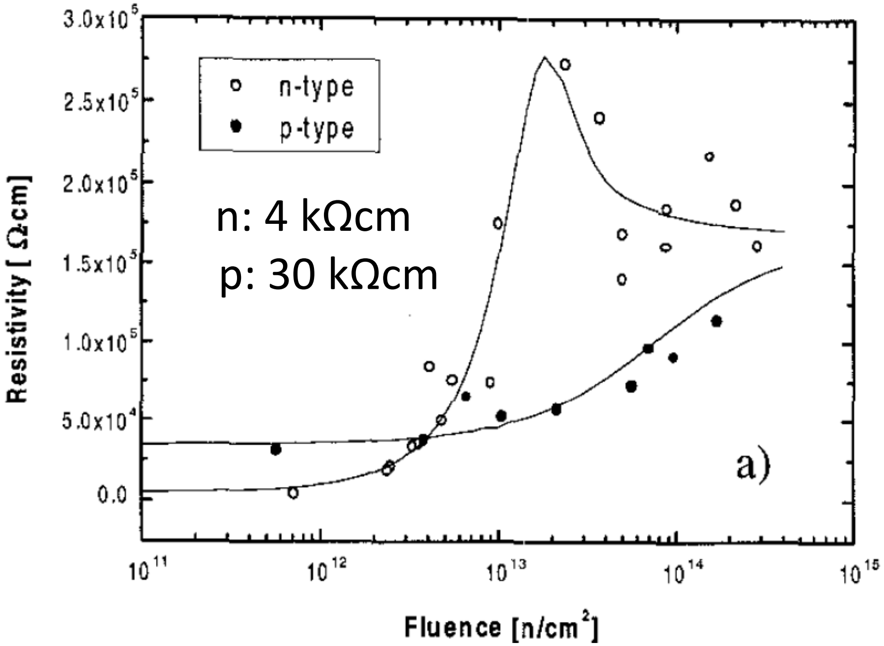
- Source of trouble(?)
  - Bowing of the sensors and the ASICs (See table)
  - (*1) requires improvement in chuck (small-hole at center→larger area vacuum)
  - (*2) shows that the backside deposition helps
- New BB samples
  - Delivered last week, being mounted on 4chip PCB this week to be delivered on Fri., 21st Feb.
  - Evaluation with beta source on 21-22nd, so far GOOD,
  - Into the 24th Feb. testbeam at DESY

(Active face top)	Free	Afer reflow	Vacuum chuck
Sensor (150 μm)	~25 μm凸	N/A	~25 μm凹(*1)
Sensor (320 μm)	~3 μm凸凹	N/A	N/A
ASIC (150 μm)	~10-15 μm凹	~40 μm凹(*2)	~30 μm凹
ASIC (150 μm)+Backside deposition	~10 μm凸凹	~10 μm凸凹(*2)	~8 μm 凸凹

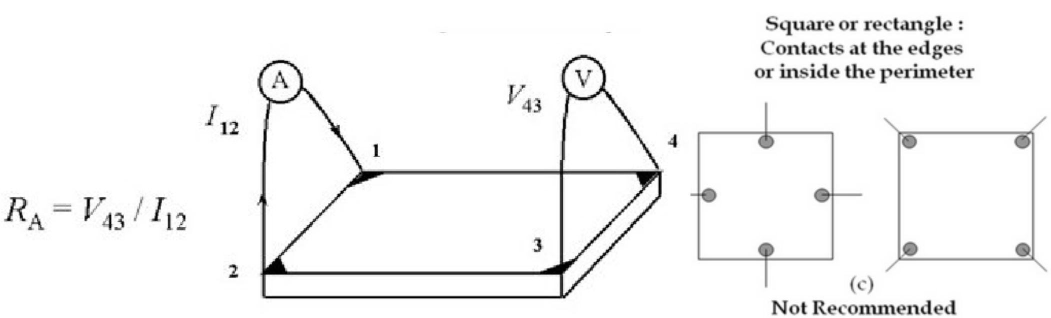
One more thing

Resistivity after irradiation,

E. Borchi et al., IEEE Trans. Nucl. Scie. 46 (1999) 302-305



- Resistivity measured by Van der Pauw method
  - Initially, n: 4 kΩcm, p: 30 kΩcm
  - Irradiation to ~3×10^{14} neq/cm^2 , saturation to 150-200 kΩcm
  - "Resistivity" *increases* with fluence.
- What is their "resistivity"?
  - In PDG, $\rho=1/(Ne\mu)$
    - ρ: resistivity (Ωcm)
    - N: Impurity concentration (cm^{-3})
    - e: electron charge (C)
    - μ: mobility (1350, 450 (cm^{2}V^{-1}s^{-1}) for e(n), h(p)-type
  - If 150 kΩcm, N(p-type)=9×10^{10}
    - with mobility (h)
    - N is near "intrinsic" (=1.45×10^{10})
- We have made "4 probe" samples...

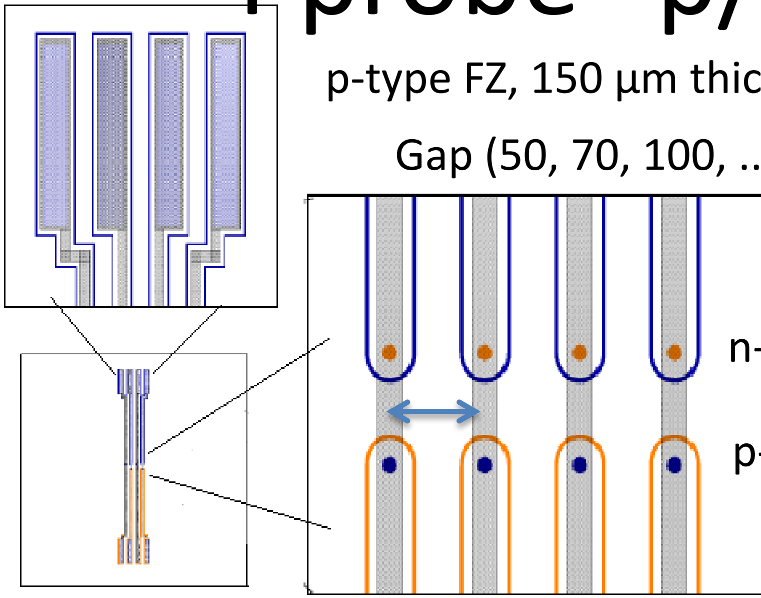


Van der Pauw method

"4 probe" p/n Contact Samples

p-type FZ, 150 µm thick

Gap (50, 70, 100, ... µm)

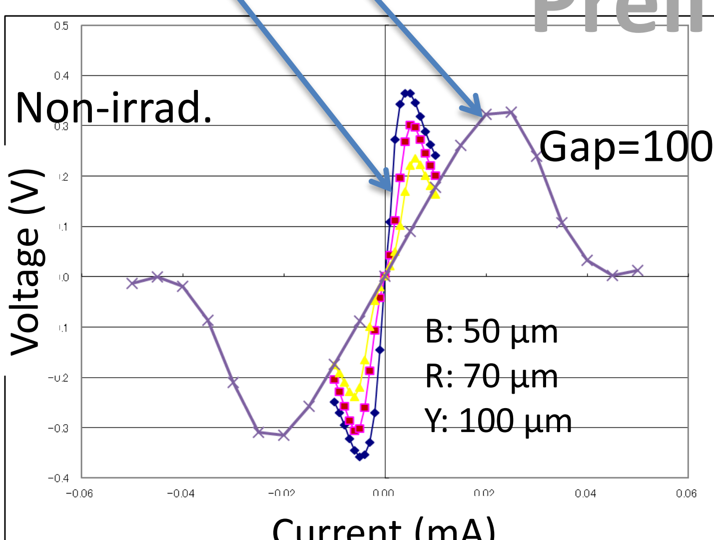


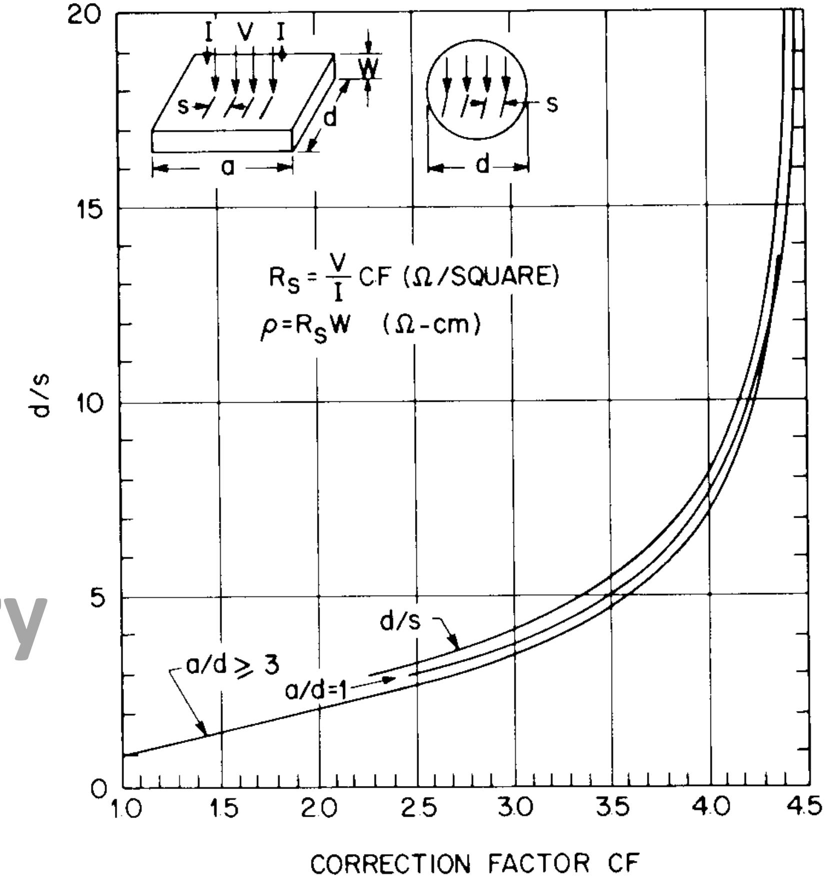
n-contact

p-contact

Sample (4×4、8×8 mm^2)

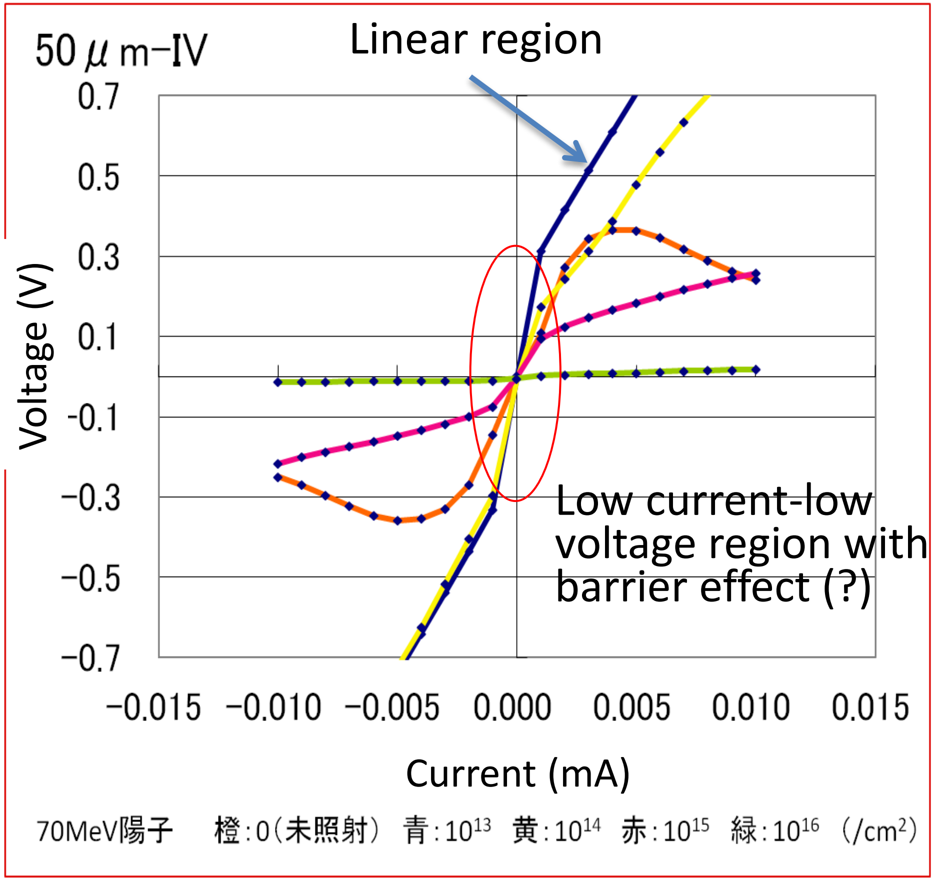
Preliminary



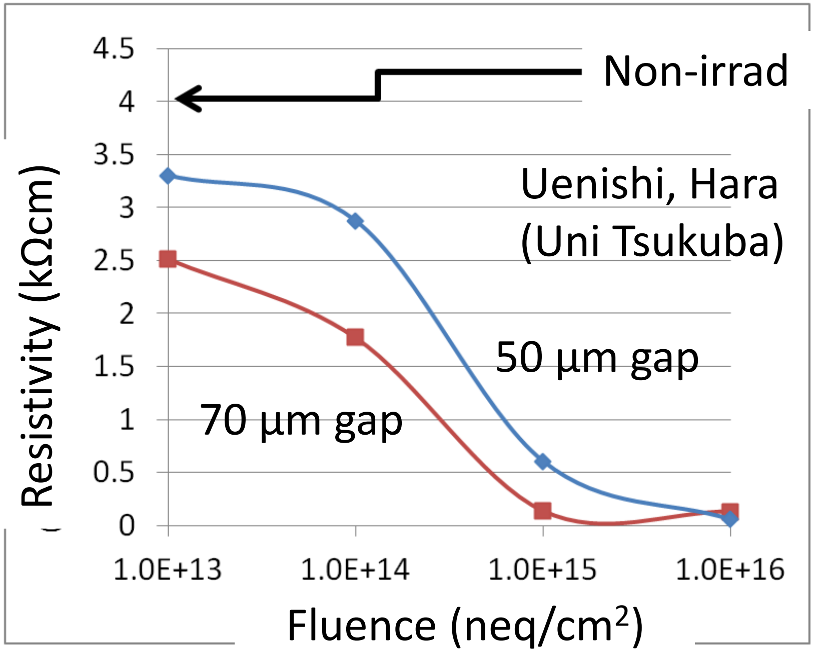


- Plot: d/s=4 mm/100 µm=40, CF~4.5
- Measurements (Uenishi, Hara (Uni Tsukuba))
  - Non-irrad: ρ=4 kΩcm known
  - Gap 50 µm, CF~2.3
  - Gap 70 µm, CF~4.5

Irradiated Samples



Preliminary



- Proton 70 MeV irradiation
  - CYRIC, 1×10^{13}, 1×10^{14}, 1×10^{15}, 1×10^{16} neq/cm^2
- Measurements are consistent with what we have known:
  - Resistivity *decreases* with fluence, from 4 kΩcm to ~0.5 kΩcm .

Summary

- Strip sensors (ATLAS12)
  - Slim dicing (450 μm edge) is successful. Leakage current smooth up to ~800 or 1000 V.
- Pixel Structure
  - "New" design (1^{st} Optimization)
  - Bias rail and bias resister routing effect is very much reduced. Success!
- Other R&D's
  - Slim edges (DRIE+...)
    - Need further study for the alumina passivation after irradiation.
  - HV protection (post-process material)
    - Parylene (C, N, HT) are radiation-tolerant to $\sim 1 \times 10^{16}$ neq/cm^2 .
- Bump-Bonding
  - We have identified the issue and iterating the method for coping with "bowing" of thin sensors and thin ASIC's (without glass support wafer).
- One more thing...
  - Preliminary, but "Resistivity" after irradiation is "decreasing" as expected.

Contributors

- ATLAS-Japan Silicon Group
  - KEK, Tokyo Inst. Tech., Osaka Uni., Kyoto Uni. Edu., Uni. Tsukuba, Waseda Uni.
- Hamamatsu Photonics K.K.
- PPS collaboration
  - AS CR, Prague, LAL Orsay, LPNHE / Paris VI, Uni. Bonn, HU Berlin, DESY, TU Dortmund, Uni. Goettingen, MPP and HLL Munich, Uni. Udine-INFN, KEK, Tokyo Inst. Tech., IFAE-CNM, Uni. Geneve, Uni. Liverpool, UC Berkeley, UNM-Albuquerque, UC Santa Cruz

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