Development of n^+-in-p planar pixel sensor flip-chip modules with quad FE-I4 readout ASIC's

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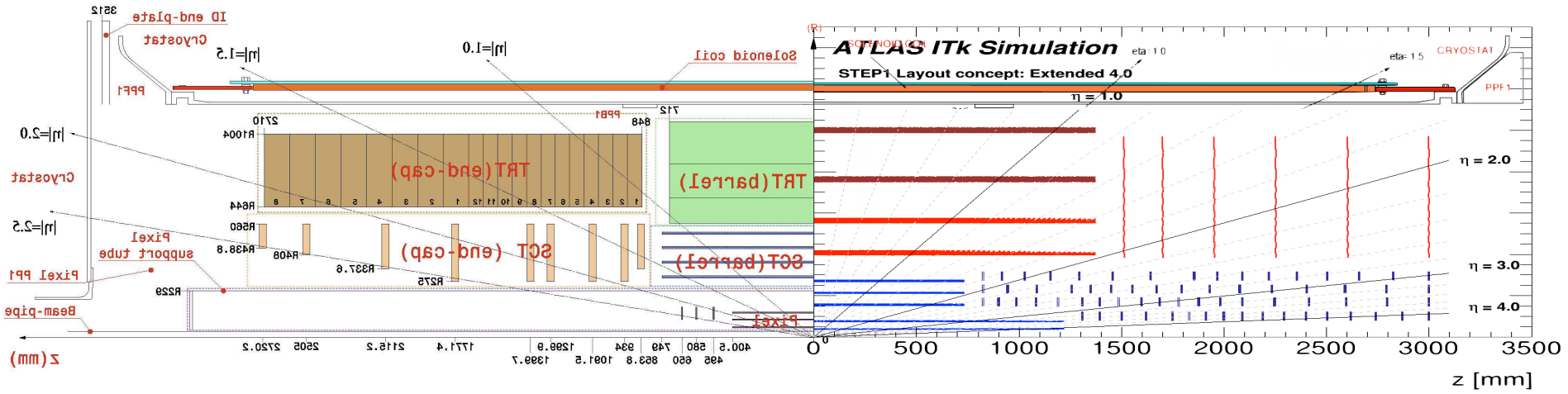
and
ATLAS-Japan Silicon Collaboration

ATLAS Tracker Layouts

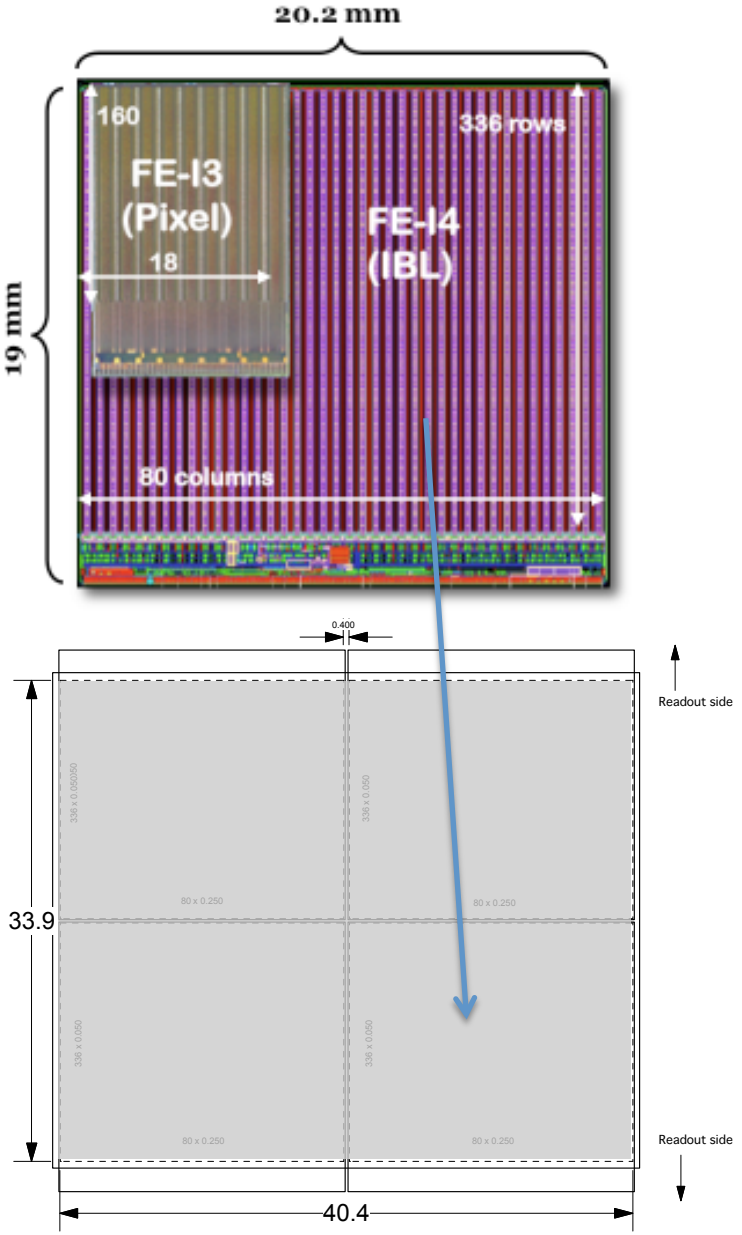


- Current inner tracker
  - Pixels: 5-12 cm
    - Si area: **2.7** m^2
    - IBL(2015): 3.3 cm
  - Strips: 30-51 (B)/28-56 (EC) cm
    - Si area: **62** m^2
  - Transition Radiation Tracker (TRT): 56-107 cm
    - Occupancy is acceptable for <3x10^{34} $cm^{-2}s^{-1}$
    - Phase-II at HL-LHC: 5x10^{34}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

- Phase-II upgrade (LF Step1 e.g.)
  - Pixels: 4-27 cm, 5 layers
    - Si area: **16.4** m^2
  - Strips: 40.-100 (B) cm, 4 layers
    - Si area: 122 (B)+71(EC)=**138** m^2
- Major changes from LHC
  - All silicon tracker
  - Large increase of Si area
    - Pixels: ~ 6 × LHC ATLAS
    - Strips: ~2.2 x LHC ATLAS

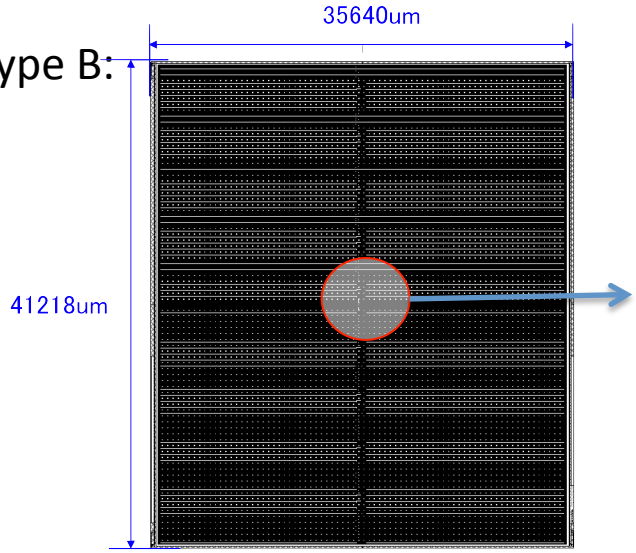
Quad FE-I4 ASIC FC module

- Less assembly cost
  - Less parts == larger objects
- ASIC
  - Full reticle size ~ 20 x 20 mm^2 (in 6-in. wafer)
  - ATLAS IBL: FE-I4 ASIC [Ref.[1]] (50x250 μm^2 pixel, 330x80 pixels, 19x20.2 mm2)
  - Phase-II upgrade: RD53 ASIC (50x50 μm^2 pixel, 330x400 pixels(?))
- Sensor
  - Large enough but not too large(?)
  - Size: quad FE-I4 ASIC,
  - ≥ 34x41 mm^2, depending on edge space
- Bumpbonded object
  - called “quad-sensor flipchip (FC)” modules

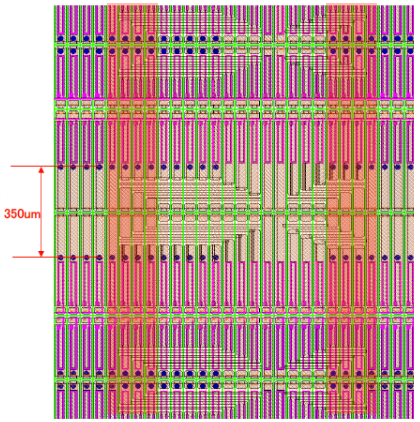


5th-1 wafer layout -Quad Sensors

Type B:

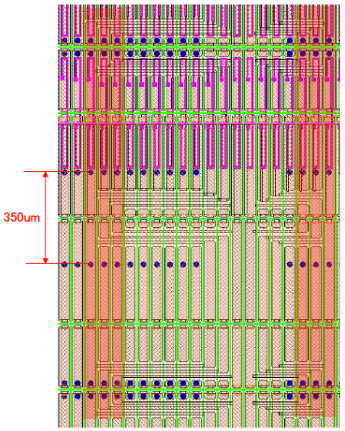


Type A:
(Pixel structure #10)



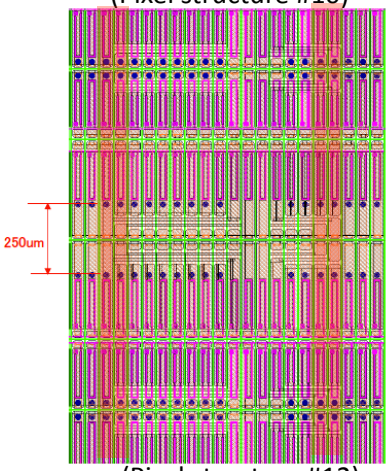
(Pixel structure #12)

Type B:
(Pixel structure #9)



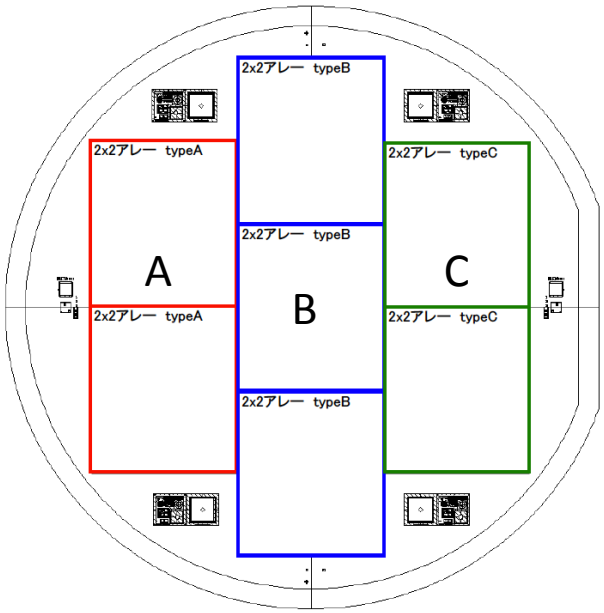
(Pixel structure #19)

Type C:
(Pixel structure #10)



(Pixel structure #12)

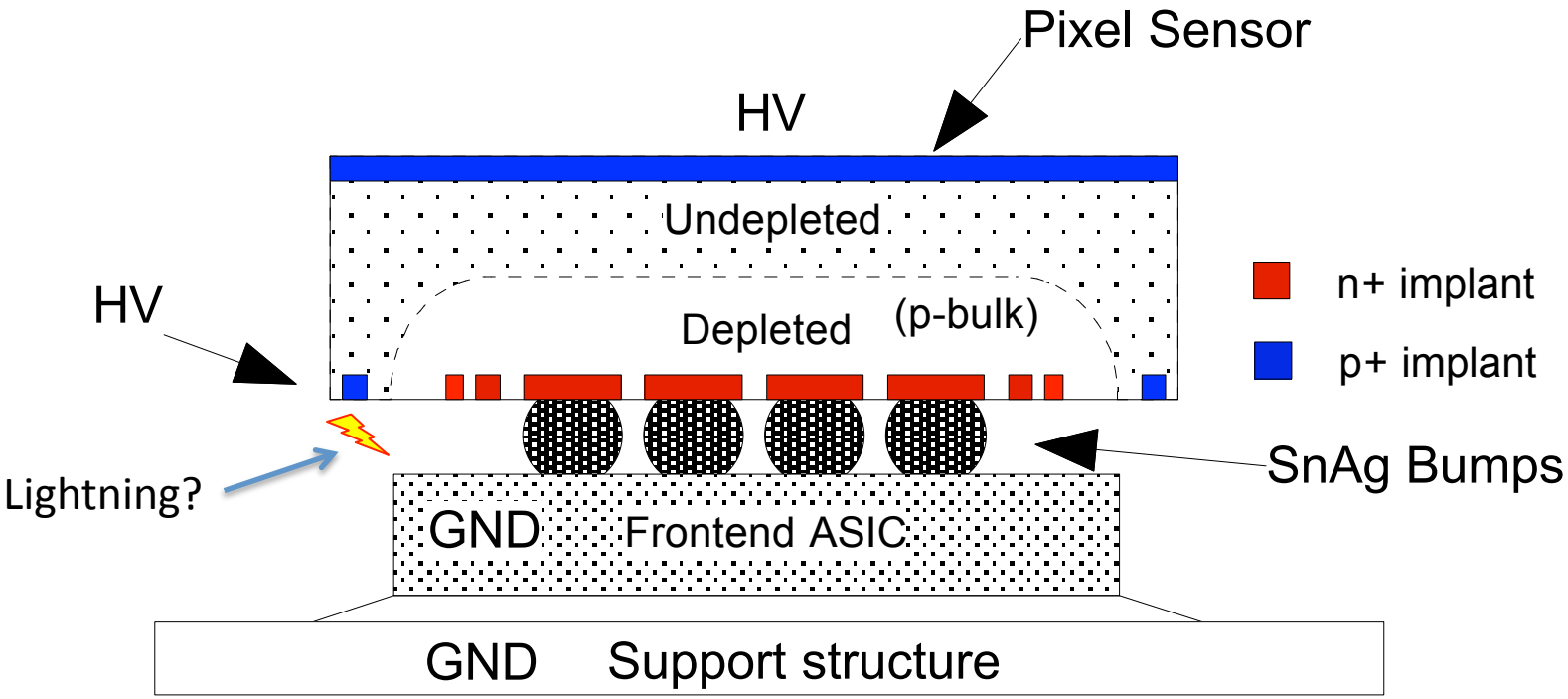
Readout pixels of the ganged pixels



6-in. wafer

Type	A	B	C
Pixel structure Ref.[2]	#10, #12	#9, #19	#10, #12
No. ganged pixels	4/4	3/3	2/2
No. pixels in interval	8/3	8/3	8/3
Readout Pixels with ganging	6^{th}-9^{th}/ 1^{st}-4^{th}	7^{th}-9^{th}/ 2^{nd}-4^{th}	8^{th}-9^{th}/ 3^{rd}-4^{th}
Bump gap (μm)	450, 350	350, 350	250, 250
Pixel length at boundary (μm)	400	400	350

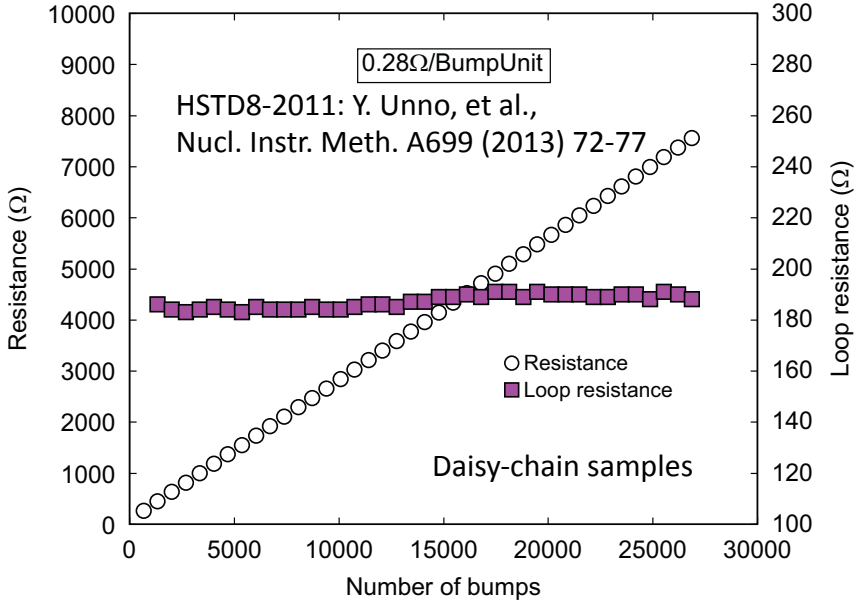
Hybrid Planar Pixel Sensor Module

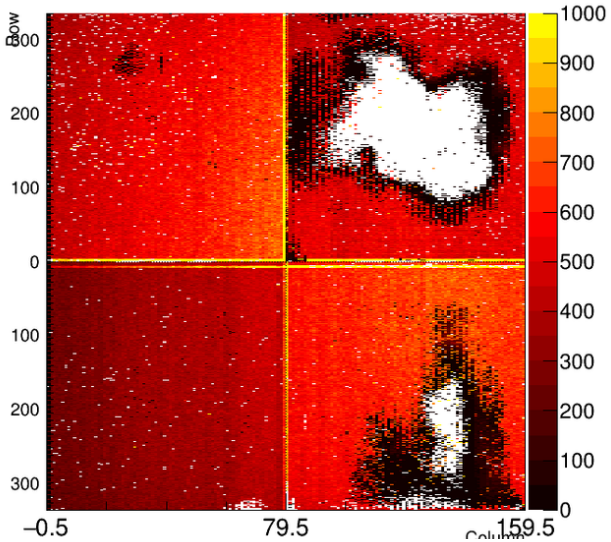


- Advantages:
  - ASIC and Pixel sensor can be optimized independently.
  - Versatility of sensor material
    - could be a real advantage in industry, e.g. infra-red light detection with InGaAs pixels
    - in turn, we (HEP) benefit from the industrialized technology

R&D of Bumpbonding (BB)

- PIXEL2010 Ref.[2]
  - **Lead (PbSn)** solder bumps
    - **Thick Sensor**/ASIC: 320 µm/~700 µm
    - Basically, **no issue**
- HSTD8-2011 Ref.[3]
  - **Lead-free**（**SnAg**) solder bumps
    - Lead-free is mandatory in industry
  - Observed large **bump-resistance**
  - Solved with
    - new under-bump-metalization (**UBM**)
    - together with the **removal of surface oxide** layer with **Plasma etching** (top-right Figure)
- 2012-2015
  - **Thick** sensor/**Thin** ASIC: 320 µm/150 µm has been **successfu**l, but
  - **Thin** sensor/**Thin** ASIC: 150 µm/150 µm, and **four** ASIC's
    - Observed **disconnected bumps** in large area
    - Then, sequence of R&D's ... this report





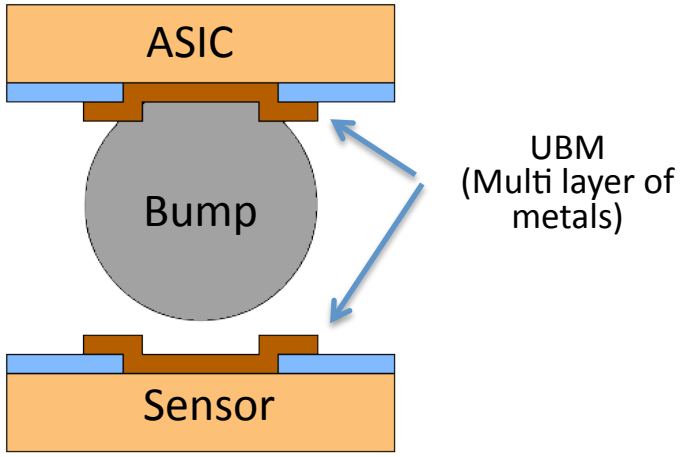
2x2 FE-I4

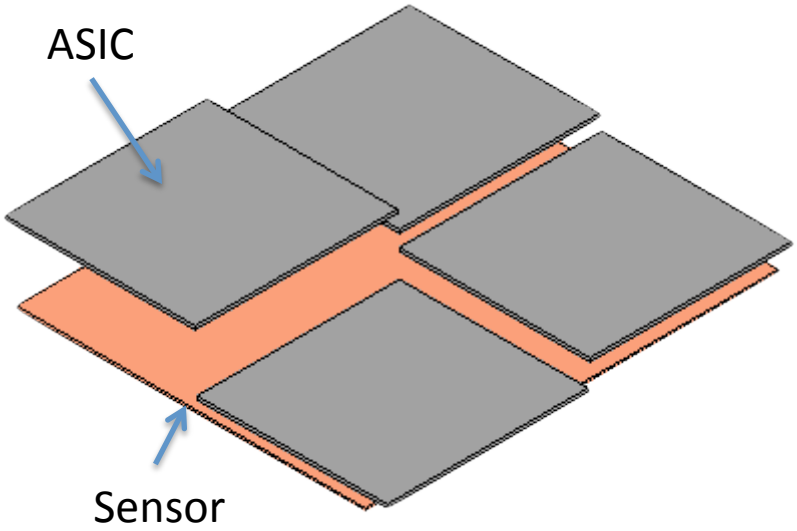
^{90}Sr source response

Example of disconnected bumps in SnAg BB

Bumpbonding technology in HPK

- BB objects:
  - ASIC's with UBM+bumps
  - Sensor with UBM
- BB steps:
  - Vacuum-chuck jig (top&bottom) to hold and flatten the object
    - Jig size: 20 x 20 mm^2 = one FE-I4 size
  - ASIC's are bump-bonded one-by-one, with heat process while bumping
- Issues identified:
  - Warpage of objects
  - Surface oxidation
    - Application of plasma-etching (PE) was effective but oxidated after certain time after PE, then observed BB deficiency
    - Not only of SnAg bumps but also of the UBM on sensor
    - UBM of sensor experiences several times of heating – **multi-chip bumpbonding**

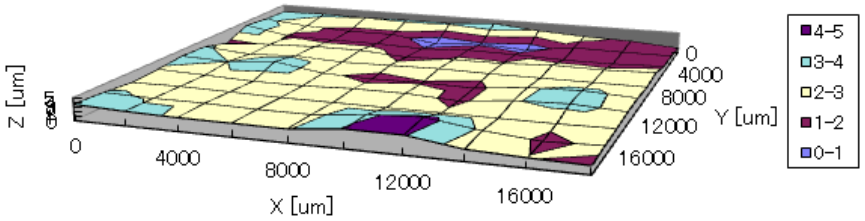




Warpage

- Bi-metal effect
  - Coeff. of thermal exp.:
    - Bulk (Si):Surface passivation (SiO_2)= 2.8-7.3 : 0.51-0.58 ppm/K
    - Oxidation process (high temp.) → room temp
  - Warpage ~ (thickness)$^{\sim 3}$
    - Sensor: 320 → 150 µm : 3 → 25 µm

Quad sensor
One FE-I4 area
凸30 µm →凸凹5 µm



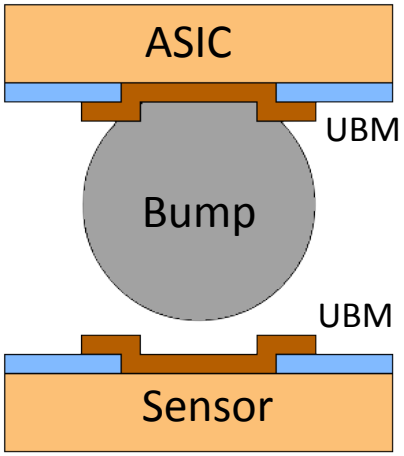
- Flatness in BB
  - HPK's BB uses vacuum-chuck jig to flatten the object
    - cf. Temporarily support wafer (thick glass) attachment and removal
  - Warpage needs to be <<BB gap (~20 µm)
    - ASIC (150 µm, after reflow of bump deposition) ~40 µm
    - Another way of helping flattening - Deposition of compensation layer to backside of ASIC – effective but seems unnecessary

(Active face top)	Free	After reflow	Vacuum chuck
Sensor (150 µm)	~30 µm凸	N/A	~5 µm凸凹
Sensor (320 µm)	~3 µm凸凹	N/A	N/A
ASIC (150 µm)	~10-15 µm凹	~50 µm凹	~5 µm凹
ASIC (150 µm)+Backside compensat'n	~10 µm凸凹	~10 µm凸凹	~8 µm 凸凹

Identifying and solving the issue of surface oxidation

- R&D's
  - Using solder flux, Indium BB, Hydrogen-reflow

	Method	Quad samples (#ASIC's)	Bump (ASIC)
1	Solder flux, with/without	2 (8), 1 (4)	SnAg
2	Indium BB	3 (12), 4 (16)	In, Ni-In
3	Hydrogen-reflow	4 (16)	SnAg

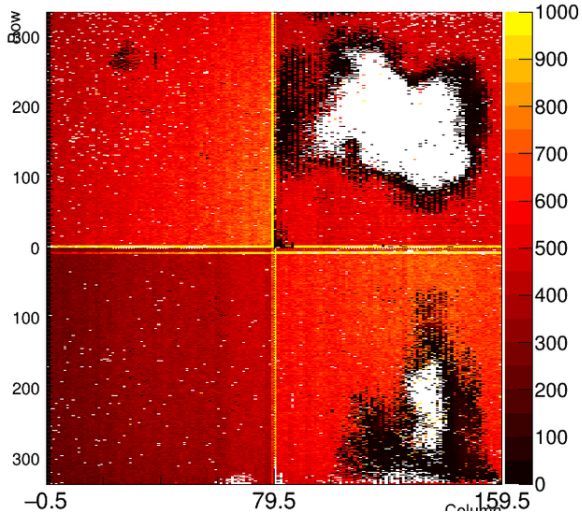


- Validation
  - Thermal cycling (TC): [-40, +40]°C, 5 times
  - Irradiation (IR): 3×10^{15} neq/cm^2 at -15 °C
    - Irradiated spot is heated to several 10 °C, induces thermal stress
  - ^{60}Co β source response for bump connection test (SS)

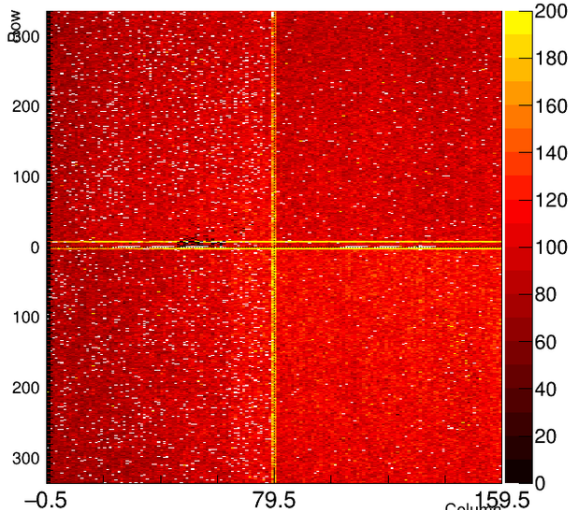
Solder flux

- Solder flux is known to remove surface oxidation
  - in retrospect, both surfaces (ASIC and sensor)
- Validation
  - Sample of “No flux” showed large-area bump disconnection in number of chips.
  - Samples “With flux” developed no large-area bump disconnection, in 2 quad-sensor FC’s (8 ASIC’s)
- Additional validation
  - Concerns:
    - Amount of flux – issue of BB QC
    - Residue after cleaning – ditto
      - tested in another one sample
      - TC [-40,+85]°C, 100 times – passed
      - Temp-Humidity test [+40°C, RH90%], 1000 hrs – passed, no short between pixels

SS after irrad.
KEK98 (No flux)



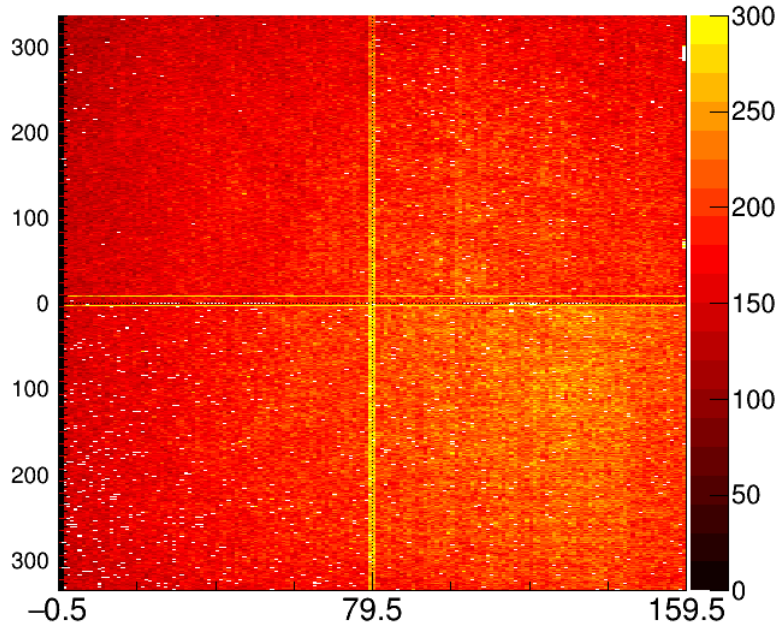
KEK99 (flux)



Indium BB

- Indium BB is a well-established technology.
  - (relatively) insensitive to surface oxidation
- Two indium bumps tried:
  - (1) Indium ball (abbreviated as “In”)
  - (2) Ni-pillar + Indium cap (“Ni-In”)
    - Reducing amount of In. for reducing cost and chance to capturing sharp-angle debris
- Validation
  - No large area bump disconnection in 7 quad-sensor FC’s (28 ASIC’s)

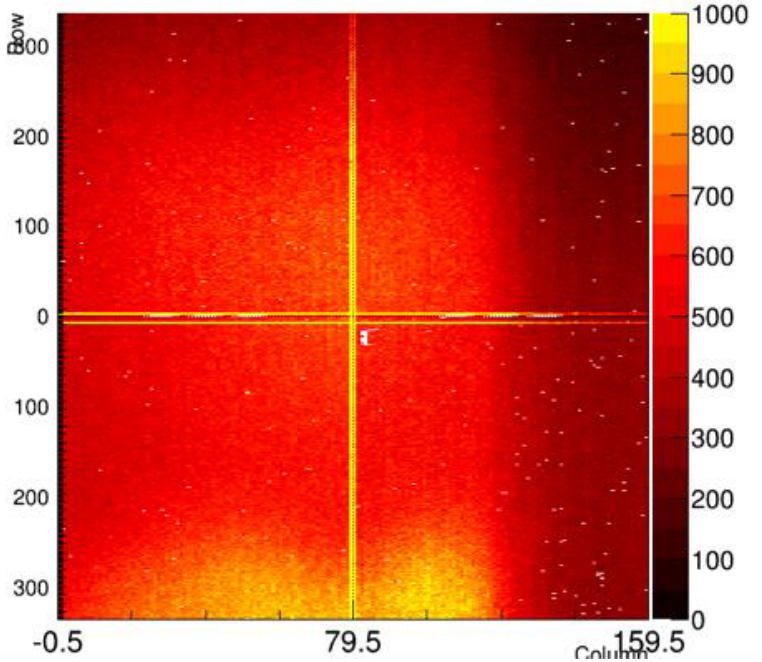
SS after irrad. – KEK97



Hydrogen-reflow SnAg

- No solder flux
- Hydrogen-radical reflow process
  - A technology to deoxidize the surface with Hydrogen-radicals (H*)
    - $4H^* + SnO_2 \rightarrow Sn + 2H_2O$
    - $2H^* + SnO \rightarrow Sn + H_2O$
  - Applied to the objects just before BB
    - Equipment is small enough to use at next to BB machine (No with plasma-etching)
- Validation
  - No large-area bump disconnection in 4 quad-sensor FC's (16 ASIC's)
  - In addition, we have had additional 16 single-sensor FC's (16 ASIC's) – No large area disconnections.

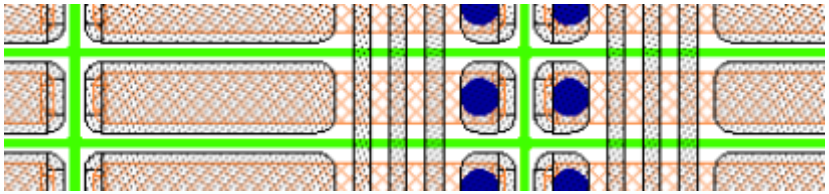
SS after irrad. – KEK107



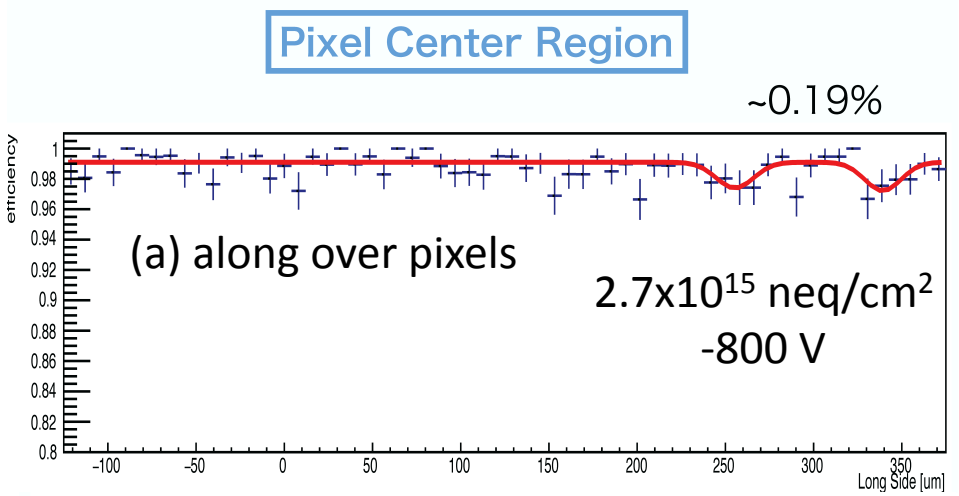
- HPK has established a technology for large-volume production of thin/ thin (150/150 µm) with SnAg bumps successfully.

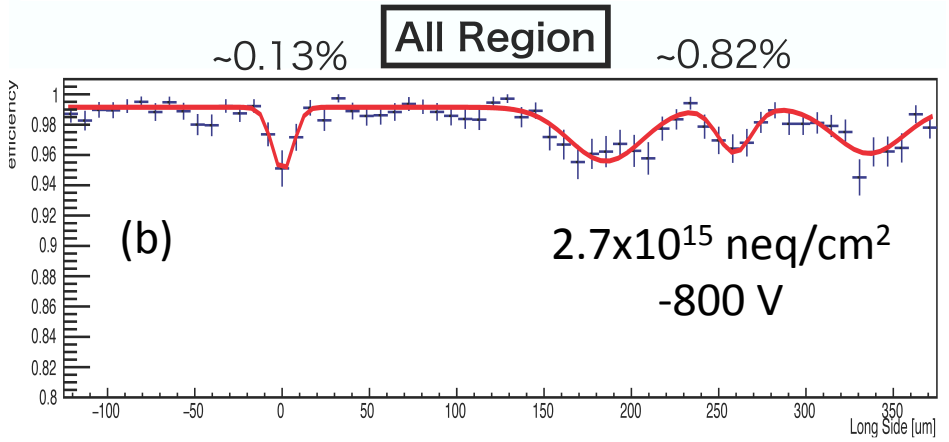
Evaluation with beams

(a)



Quad: TypeB
Pixel: Type19
Gang: 3





- POSTER by K. Nakamura
- Irrad.: 2.7x10^{15} neq/cm^2
- Under the traces ganging pixels, efficiency loss is confirmed at the boundary of pixels; little loss over pixels, as expected.
  - still eff. loss ≤ 1%
- Also, little loss in non-irrad. module.
- Explanation:
  - POSTER by Y. Unno and R. Hori

Summary

- We have produced 5th-1 wafer layout in a 6-in. wafer with 7 large-format of quad-FE-I4 n^{+}-in-p pixel sensors.
  - Pixel structures are adapted the designs of PolySi biasing resistor network mitigating the efficiency loss at the pixel boundary, together with those without biasing network for a reference.
- We have worked on the bumpbonding of thin (150 μm) sensor and thin (150 μm) ASIC's with lead-free (SnAg) bumps.
  - We have encountered BB deficiency of large-area bump disconnections, after thermal stress including irradiation.
  - The deficiency is identified to be caused by several factors: warpage, surface oxidation, multi-chip bumpbonding.
  - Warpage is mitigated with a better vacuum-chuck jig, without support wafer.
  - The surface oxidation is identified as a fundamental source of the issue with sequence of R&D's and solved, with using solder flux, with indium BB, or applying Hydrogen-radical reflow to the objects just before the bumpbonding in SnAg Bumps.
  - We have established a technology for large-volume production of thin/thin ASIC/sensor multi-chip flux-less SnAg bumbponding.

References & Contributors

- References

[1] M. Garcia-Siveres et al., Nucl. Instr. Meth. A636 (Suppl.) (2011) S155-S159

[2] Y. Unno et al., Nucl. Instr. Meth. A650 (2011) 129-135

[3] Y. Unno et al., Nucl. Instr. Meth. A699 (2013) 72-77

[3] Y. Unno et al., Nucl. Instr. Meth. A831 (2016) 122-132

- ATLAS-Japan Silicon Group
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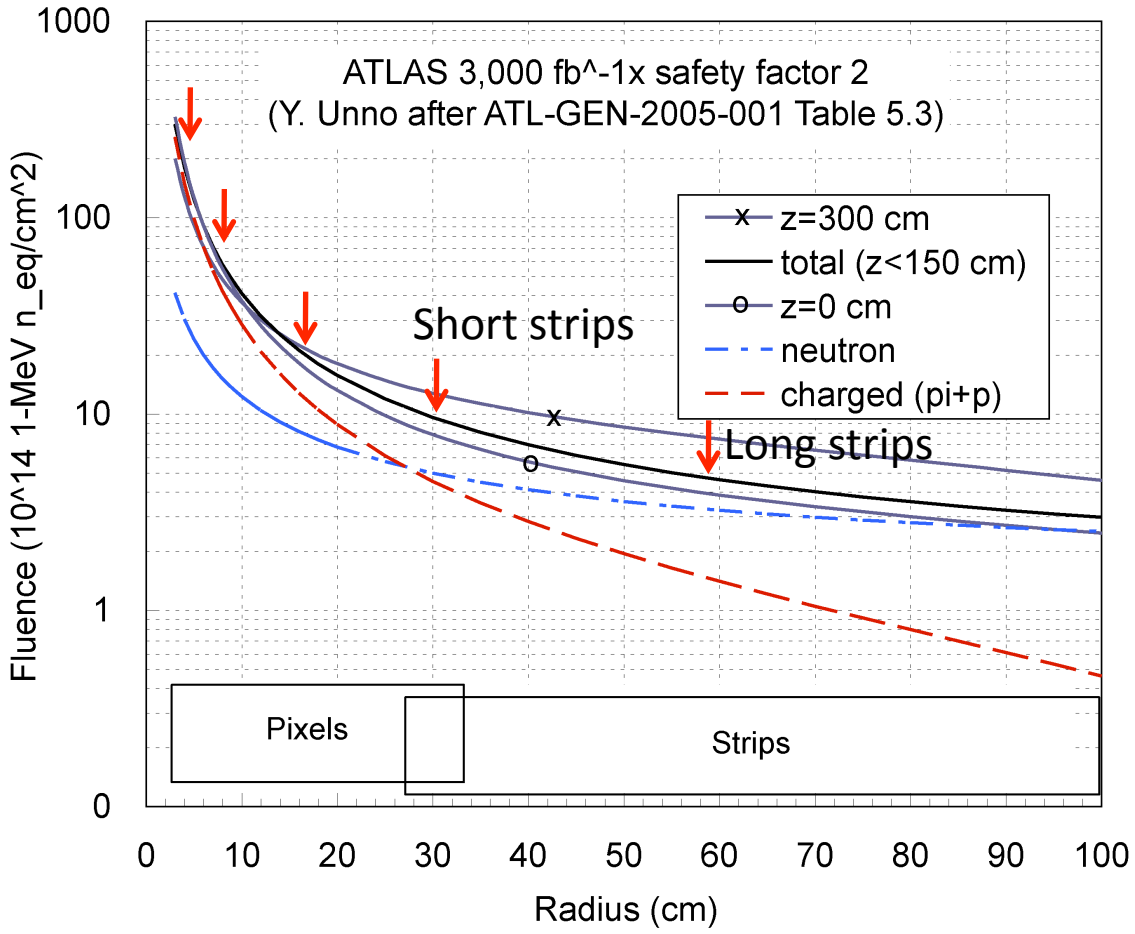
Corniglia, Cinque Terre, photo by Y. Unno

Backup Slides

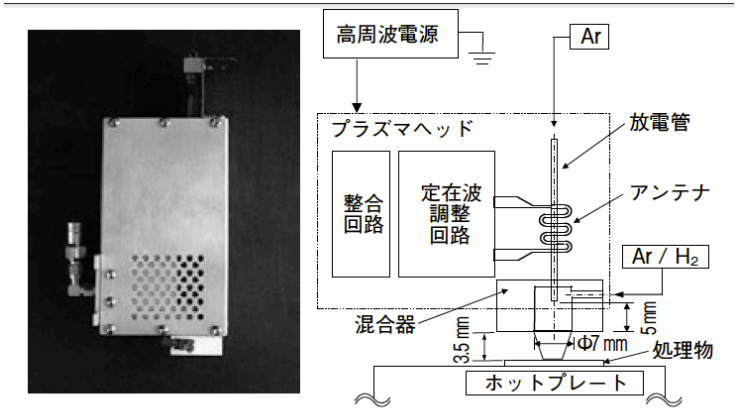
Particle fluences in ATLAS

- 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}



Towards “Flux-less” SnAg BB

- Issue in making good solder wetness is “removing surface oxide at the time of bumpbonding (BB)”
  - How can it be done?
  - Panasonic in literature:
    - M. Matsumoto et al., “High-Speed Reduction of Oxide Film Using Atmospheric-Pressure Inductively Coupled Microplasma Jet”, Panasonic Technical Journal Vol. 57 No. 2 Jul. 2011
  - Perhaps, the Panasonic Bumpbonder is equipped with this device



第1図　誘導結合型大気圧マイクロプラズマジェット

Fig. 1　Atmospheric-pressure inductively coupled microplasma jet

Ar plasma→ Ar/H_2 → H* radical

$SnO_2 + 4H^* \rightarrow Sn + 2H_2O$

$SnO + 2H^* \rightarrow Sn + H_2O$

HPK has a similar device and will try in the next SnAg BB.