Development of n-on-p Silicon Microstrip Sensors for Very High Radiation Environment

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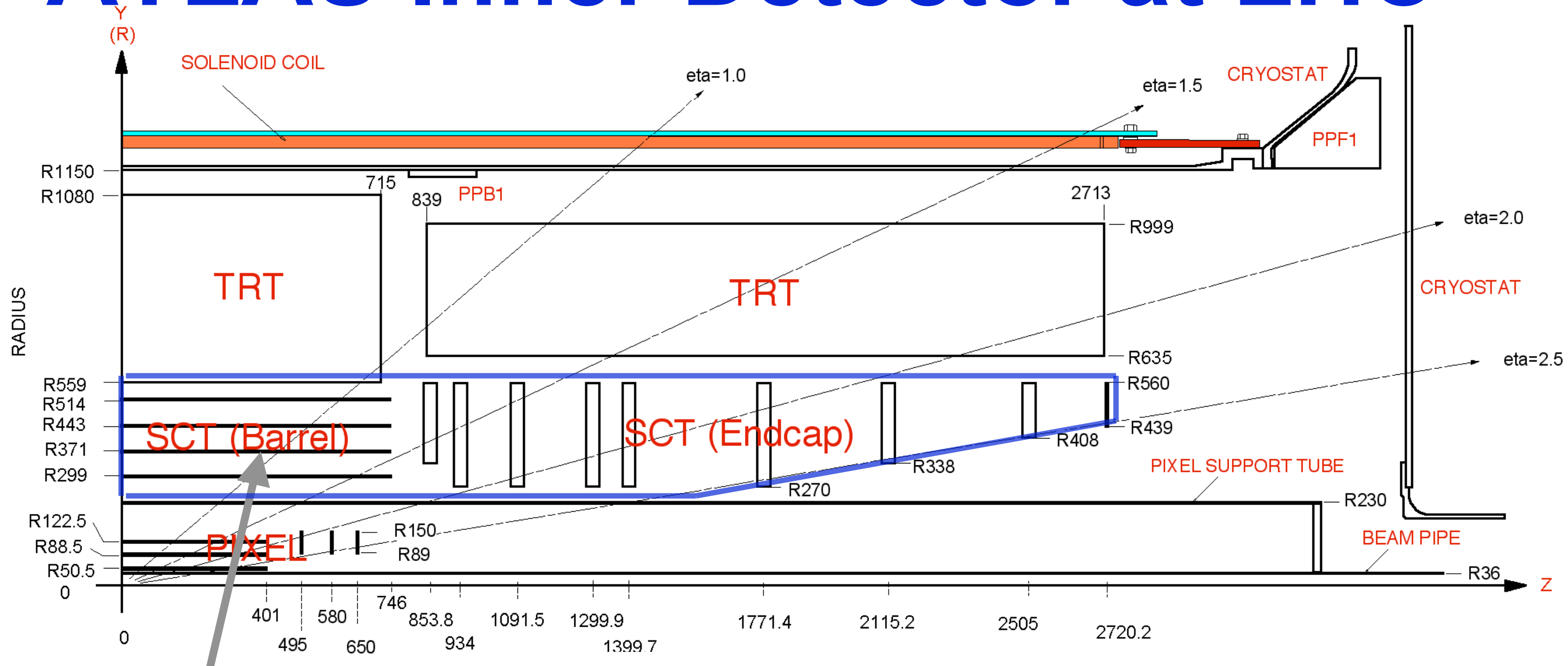
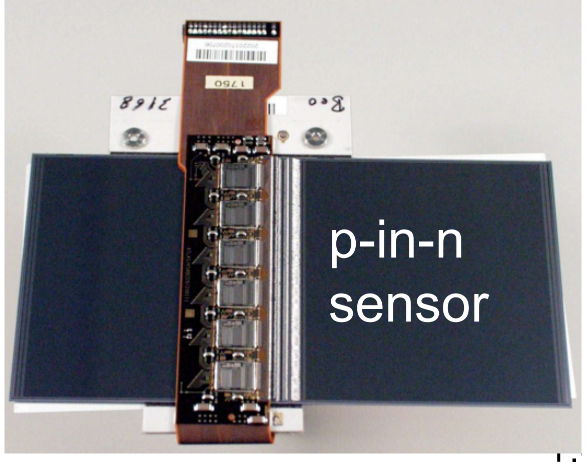
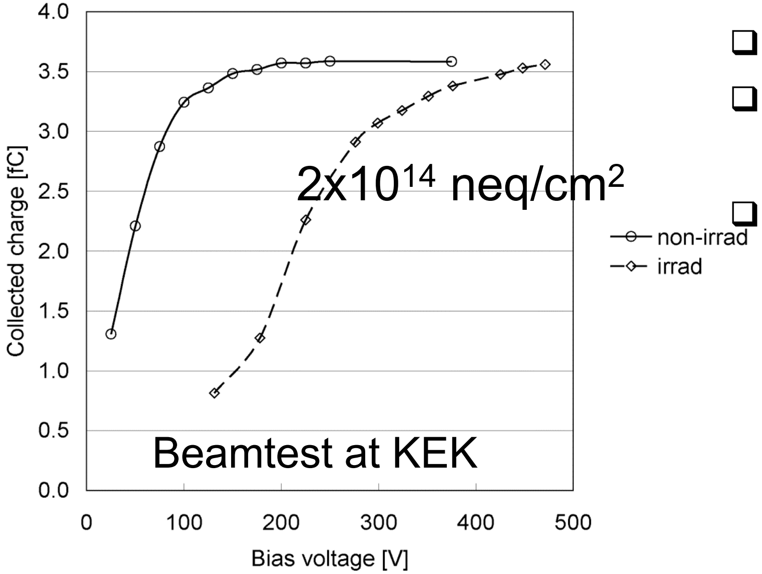
Very High Radiation Environment

- Primary target is SLHC (Inner Detector of ATLAS experiment)
  - Luminosity, $\mathcal{L} \sim 10^{35}$ cm^{-2}s^{-1}
    - Other applicable area
      - High intensity fixed target experiments, e.g.
- Silicon as the detecting medium
  - Silicon microstrip sensors (this presentation)
    - Fluence, $\Phi \leq 1\text{x}10^{15}$ 1-MeV neutrons equivalent (neq)/cm^2
  - Silicon planar pixel sensors (not covered here)
    - Fluence, $\Phi \leq 1\text{x}10^{16}$ neq/cm^2
    - Number of groups have already working on the development

ATLAS Inner Detector at LHC

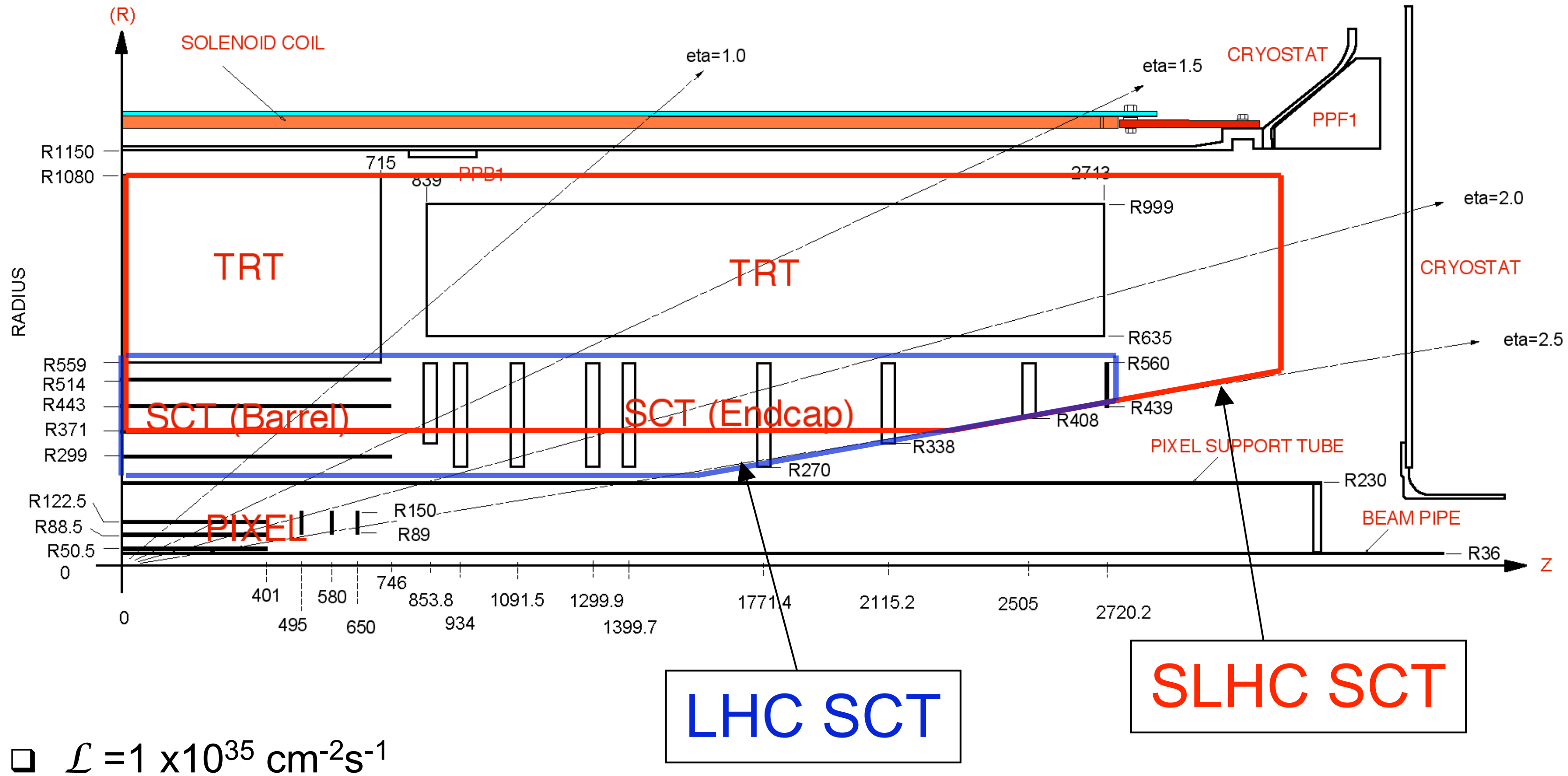






- ❑ $\mathcal{L}$ =1 to 3x10^{34} $cm^{-2}s^{-1}$
- ❑ Φ~ 2x10^{14} neq/cm^2
  - ❑ r~30 cm
- ❑ SCT : Microstrip sensor
  - ❑ p-in-n and
  - ❑ Full depletion is required (V_{bias} >350 V)

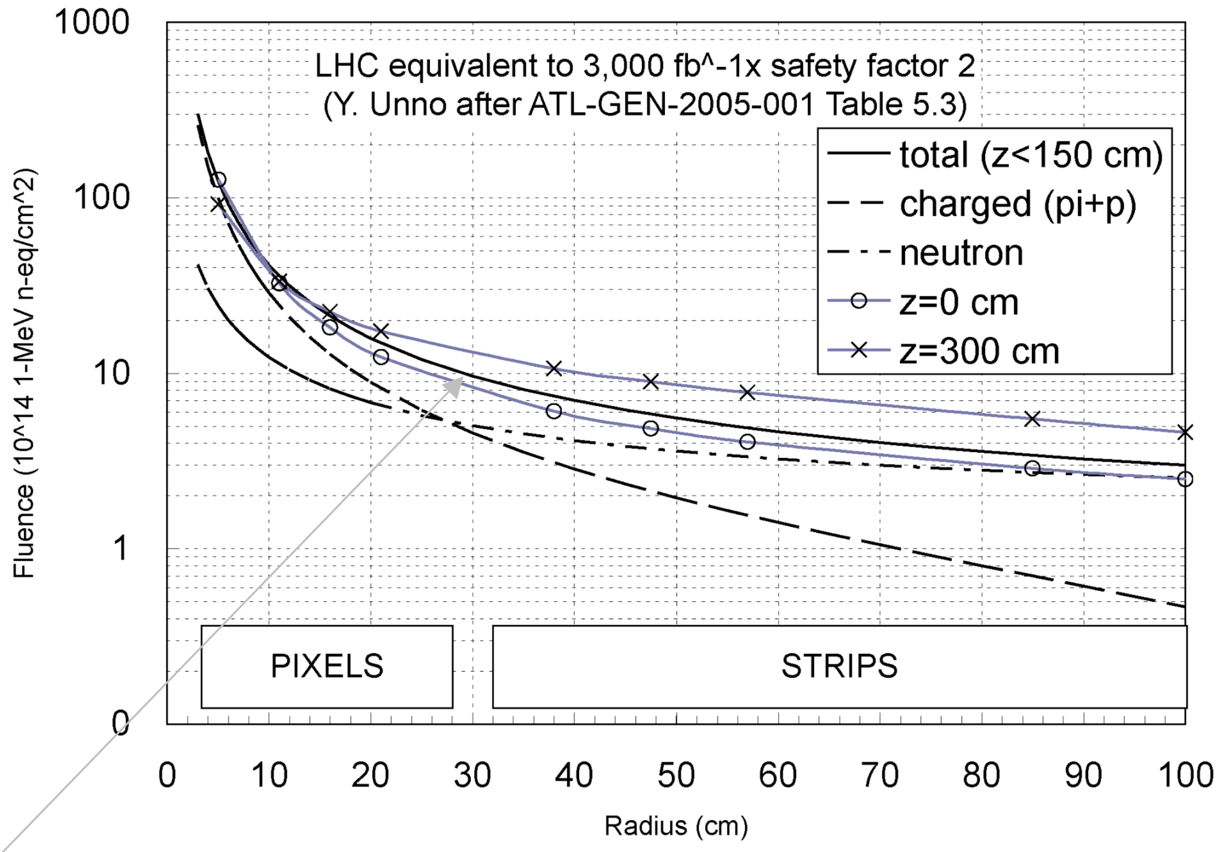
ATLAS Inner Detector at SLHC



- $\mathcal{L}$ =1 x10^{35} cm^{-2}s^{-1}
- Φ~ 1x10^{15} neq/cm^2
  - r~30 cm
- SCT : Microstrip sensor
  - n-in-p
  - Operation at partially depleted mode

SLHC Challenges

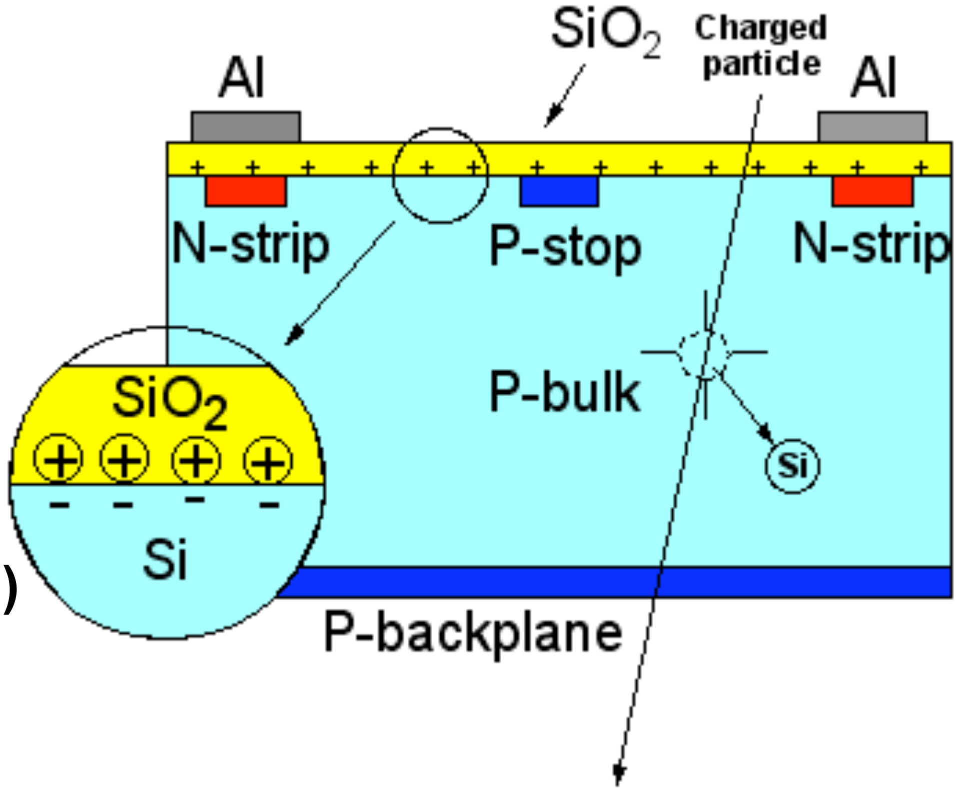
- > x10 higher luminosity
  - **300-400 pile-up events**
    - cf. 20 (LHC)
- > x4 integrated luminosity
  - **3,000 fb^{-1}**
    - cf. 700 fb^{-1} (LHC)
- Particle fluences
  - **with safety factor 2**



- Radiation damage!
  - **~1x10^{15} neq/cm^{2} @ R ~30 cm, Z~150 cm**
  - Charged : n < 1:1
    - Neutrons: ~5x - 3x 10^{14} 1-MeV neq/cm^{2} @ R ~30 cm - 90 cm

Silicon Sensor in SLHC

- Signal collection
  - **High Voltage operation**
    - radiation damage in bulk
- Full depletion not achievable?
  - **Junction side readout**
- Large area coverage
  - **Low cost device**
    - **Single side sensor**
- **N-strips in P-bulk wafer (n-in-p)**
  - Always depleting from strip side
  - no full depletion required
  - Collecting electrons
    - faster signal, less charge trapping
  - **N-strip isolation**
    - Interrupt electron inversion layer due to positive oxide charges
  - **Protection for beam splash**
    - Punch-through protection structure



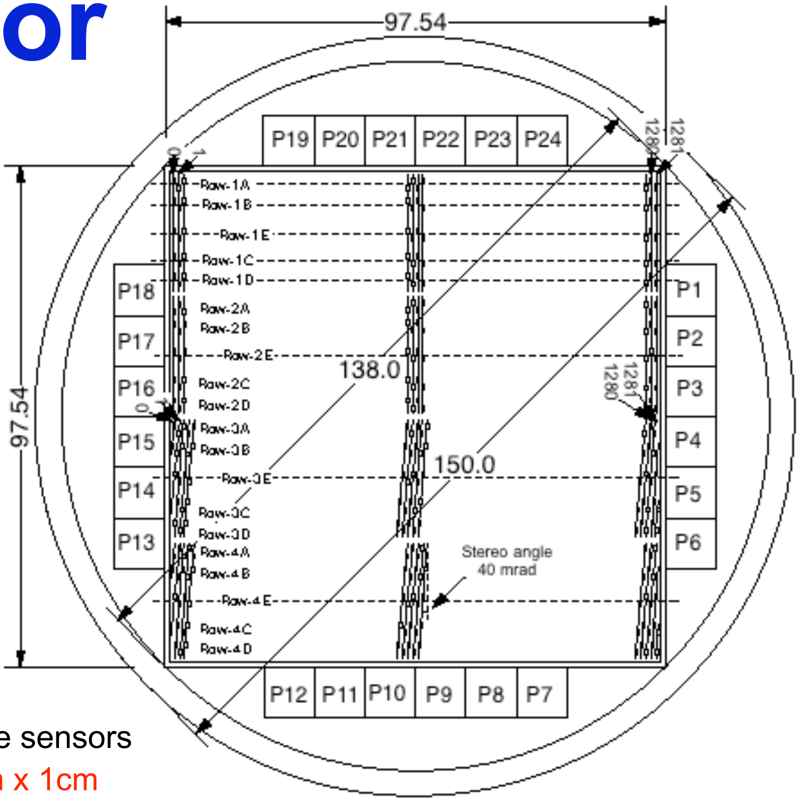
Other factors...

- **High rate of particles**
  - Fine segmentation
  - Data transfer rate limitation
- **Short strips**

n-in-p Sensor

- We have studied
  - 4 inch (100 mm) wafers
    - FZ<111> (~6k Ωcm)
    - MCZ<100> (~900 Ωcm)
  - 6 inch (150 mm) wafers
    - FZ1<100>(~6.7k Ωcm)
    - FZ2<100>(~6.2k Ωcm)
    - MCZ<100>(~2.3k Ωcm)
  - FZ, MCZ available at HPK

- Our **latest submissions** are
  - **6 inch (150 mm) wafers**
    - FZ1<100>(~6.7k Ωcm)
    - FZ2<100>(~6.2k Ωcm)



Axial-Stereo Sensor

- Miniature sensors
  - 1cm x 1cm
    - Irradiation studies
- Full size prototype main sensors
  - 9.75 cm x 9.75 cm
    - 4 segments
      - two "axial" and two "stereo" (inclined) strips
    - Short strips
      - 2.385 cm
    - Strip pitch x no. strips
      - 74.5 μm x (1280+2) strips

History of Submissions

Batch	X1FZ1		
	P-spray (R)	P-stop (P)	Main sensors
A	2E+12	8E+12	9
B	----	1E+13	0

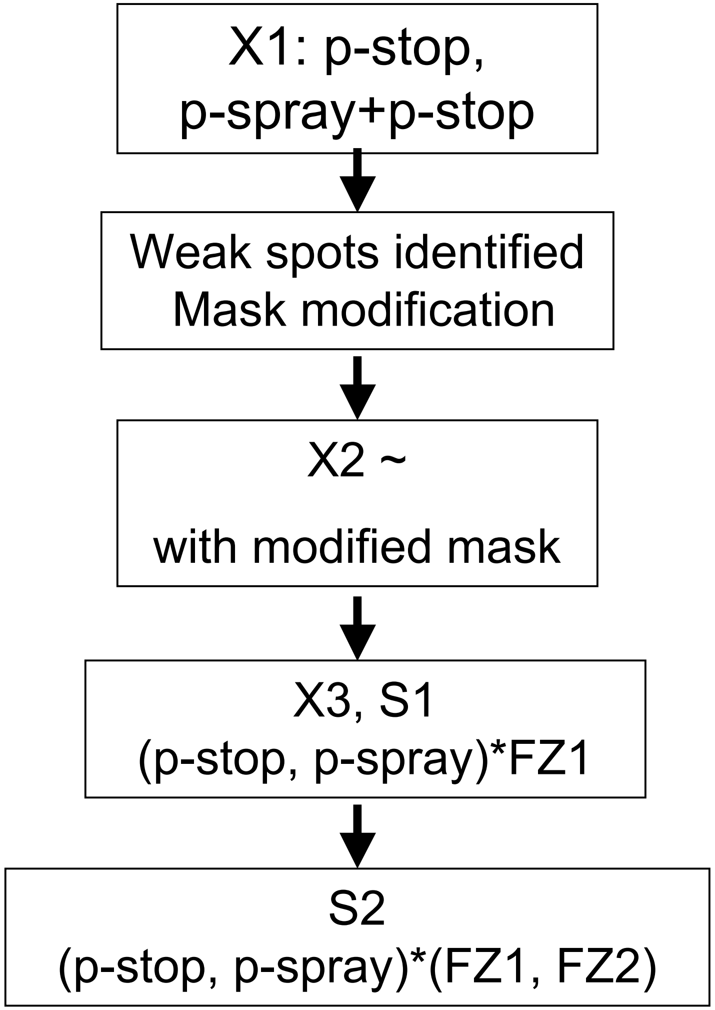
Batch	X2FZ1	Mask modified	
	P-spray (R)	P-stop (P)	Main sensors
A	2E+12	2E+12	0
B	---	1E+12	0
C	---	2E+12	0
D	---	4E+12	0
E	1E+12	---	0
F	2E+12	---	0
G	4E+12	---	0

Batch	X3FZ1		
	P-spray (R)	P-stop (P)	Main sensors
A	2E+12	2E+12	0
B	---	1E+12	1
C	---	2E+12	6
D	---	4E+12	3
E	1E+12	---	2
F	2E+12	---	1
G	4E+12	---	1
H	2E+12	8E+12	1

Batch	S1FZ1		
	P-spray (R)	P-stop (P)	Main sensors
A	---	4E+12	28
B	---	1E+13	1
C	---	2E+13	1

Batch	S2FZ1		
	P-spray (R)	P-stop (P)	Main sensors
A	---	4E+12	16
B	---	1E+13	10
C	2E+12	---	17

Batch	S2FZ2		
	P-spray (R)	P-stop (P)	Main sensors
A	---	4E+12	28
B	---	1E+13	11
C	2E+12	---	16



X1: p-stop,
p-spray+p-stop

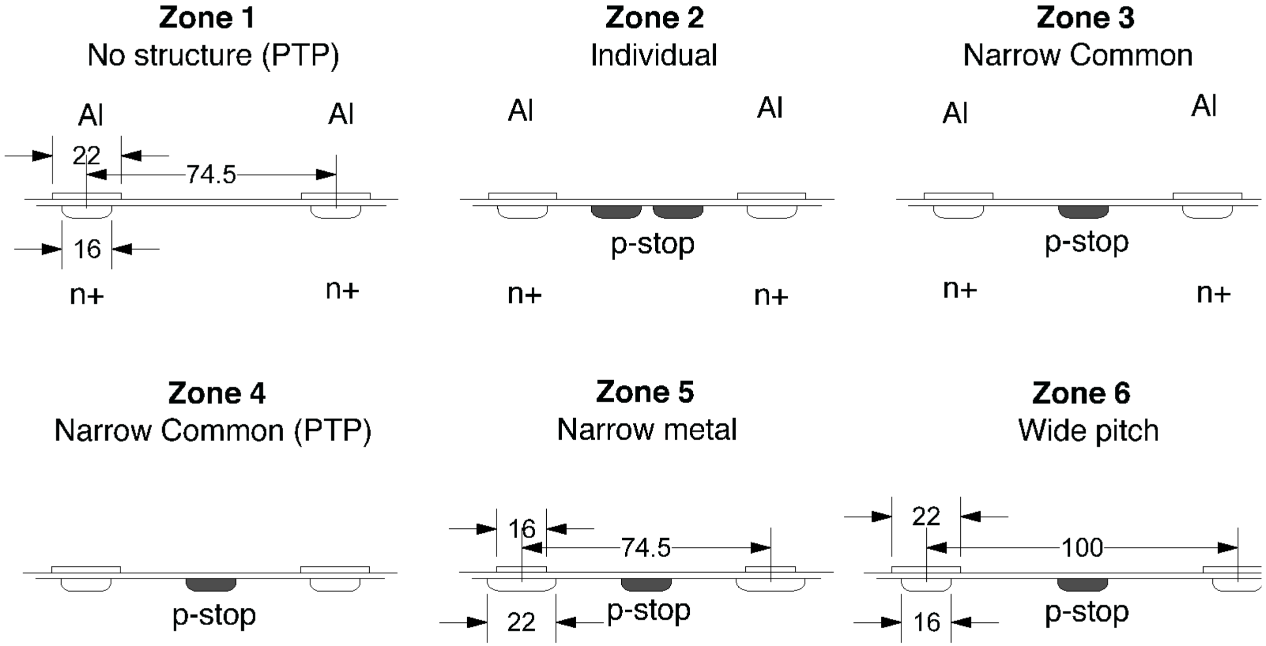
Weak spots identified
Mask modification

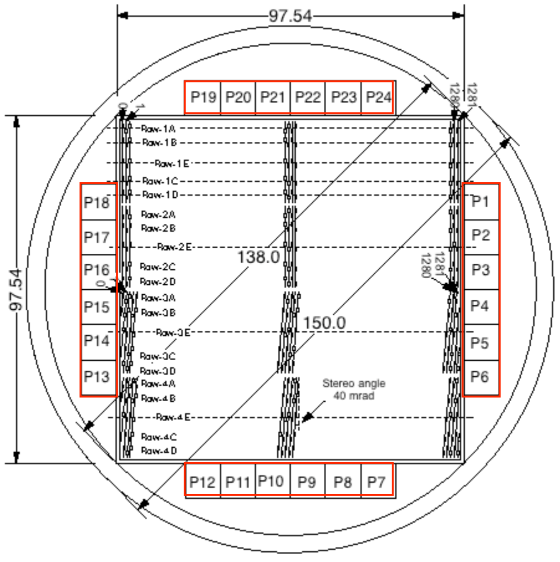
X2 ~
with modified mask

X3, S1
(p-stop, p-spray)*FZ1

S2
(p-stop, p-spray)*(FZ1, FZ2)

n-in-p Miniature Sensors





Axial-Stereo Sensor

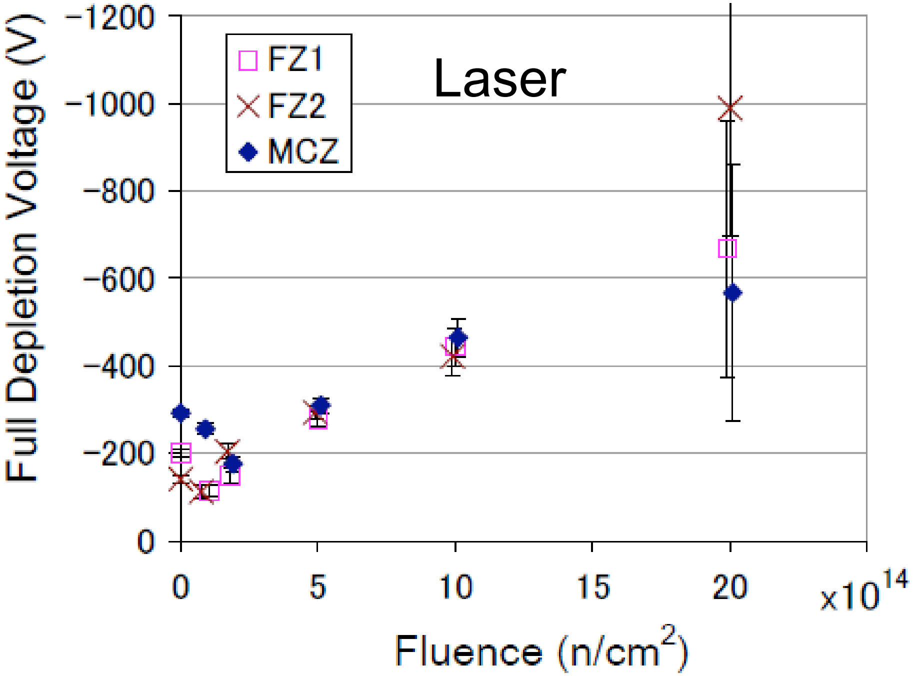
- Radiation damage study
  - Strip Isolation (Z1, Z2, Z3)
    - Structure: p-stop, p-spray, p-stop+p-spray
    - Density: 1x, 2x, 4x, 10x10^{12} ions/cm^2, ...
  - "Punch-through Protection" structures (Z4)
  - Narrow metal effect (Z5)
  - Wide pitch effect (Z6)

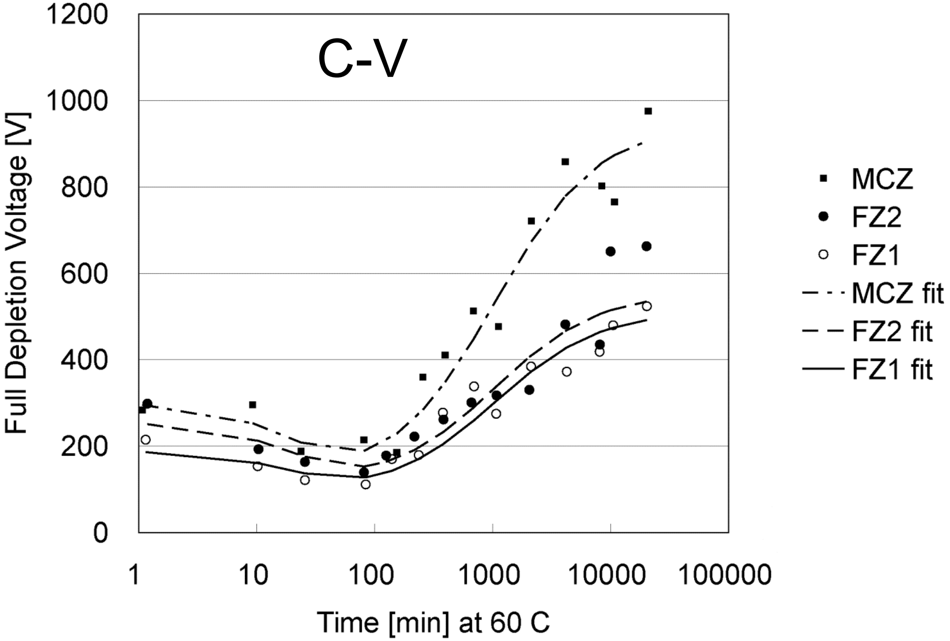
Evaluations

- Irradiations
  - **70 MeV protons at CYRIC (Tohoku Univ., Japan)**
  - **Reactor neutrons at Ljubljana (Slovenia)**
- Measurements
  - Full Depletion voltage
    - C-V
    - Laser (1064 nm)
    - Charge collection (^{90}Sr beta ray)
  - Charge collection efficiency (CCE)
    - Laser (1064 nm)
    - ^{90}Sr beta ray
  - Onset of Microdischarge
    - I-V
    - Hot electron
  - Strip isolation
    - Interstrip resistance
  - Punch-through Protection
    - Dynamic resistance with a constant bias voltage to the backplane

FZ vs. MCZ

K.Hara et al., IEEE Trans. Nucl. Sci. 56, pp. 468-473, 2009



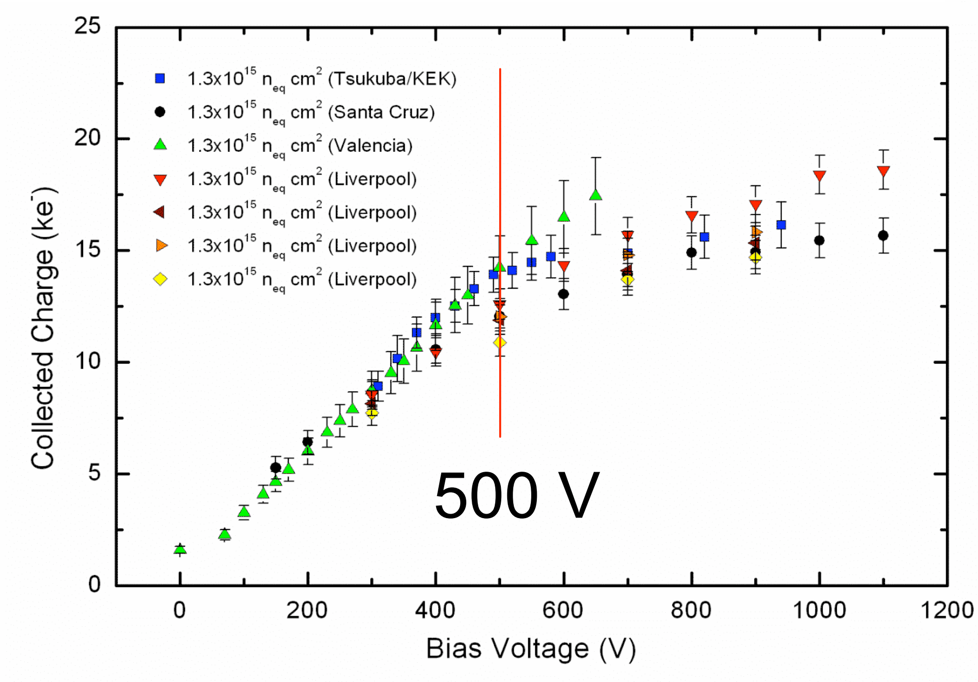


- CYRIC 70 MeV Protons
- Full depletion voltages (FDV)
  - Laser
- No significant difference in FZ (FZ1 or FZ2) or MCZ

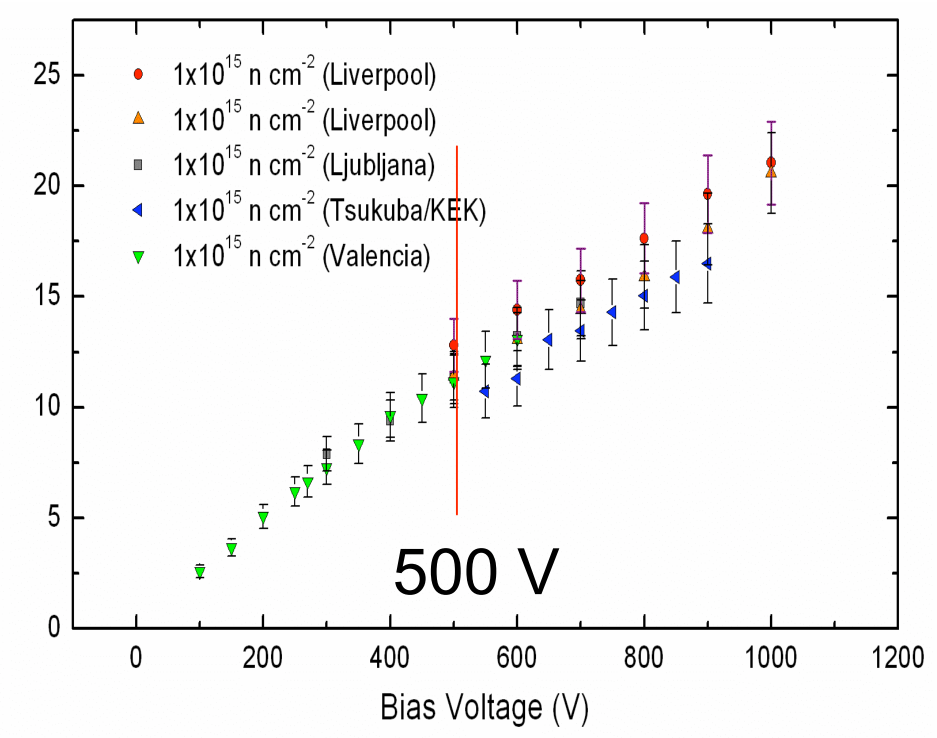
- Annealing
  - 2×10^{14} Samples
- Larger reverse annealing component in MCZ
  - using fixed beneficial and reverse annealing time constants

Charge Collection Measurements

1.3×10^{15} n_{eq} cm^{-2}
70 MeV Proton

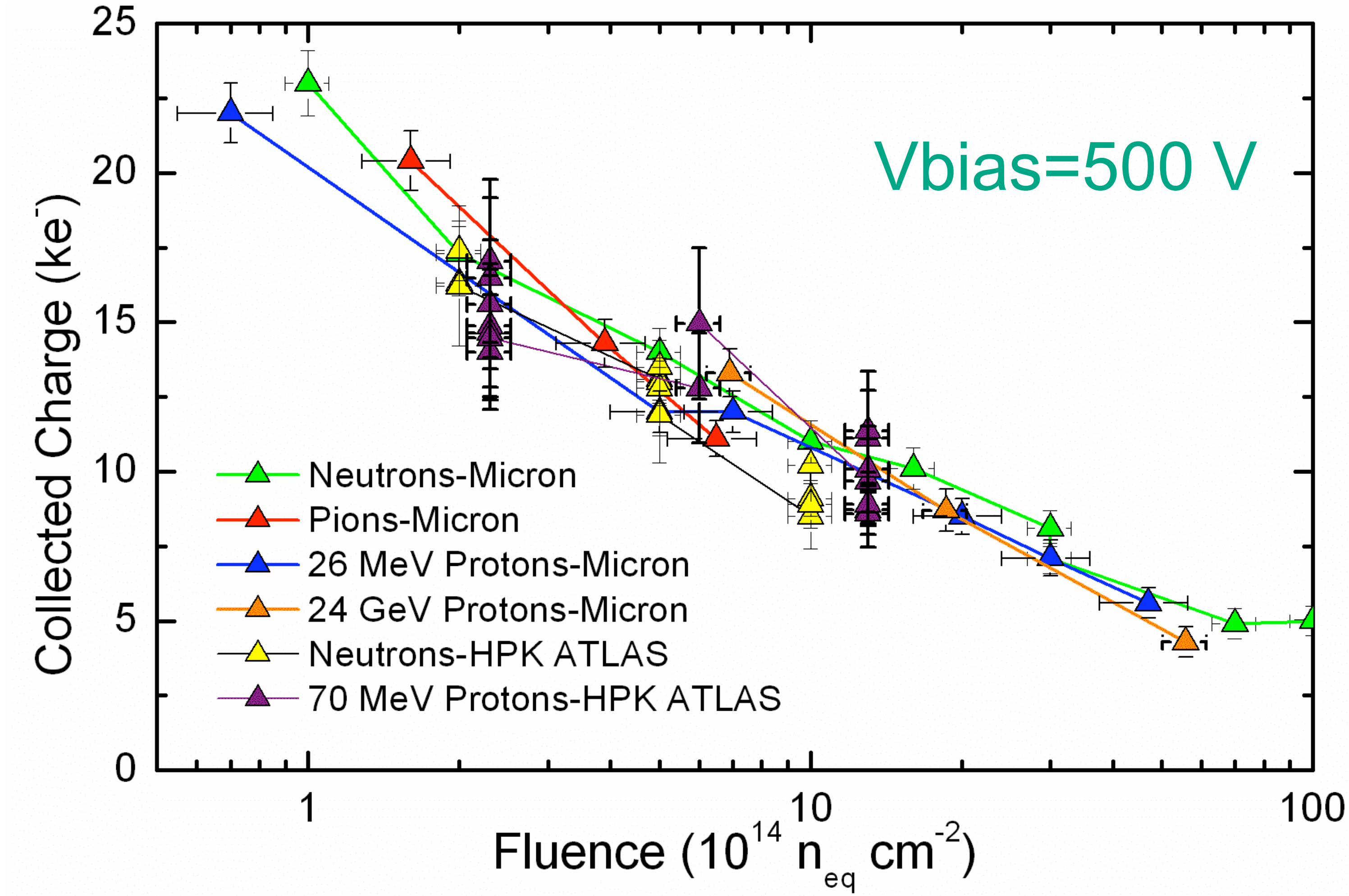


1×10^{15} n_{eq} cm^{-2}
reactor neutron



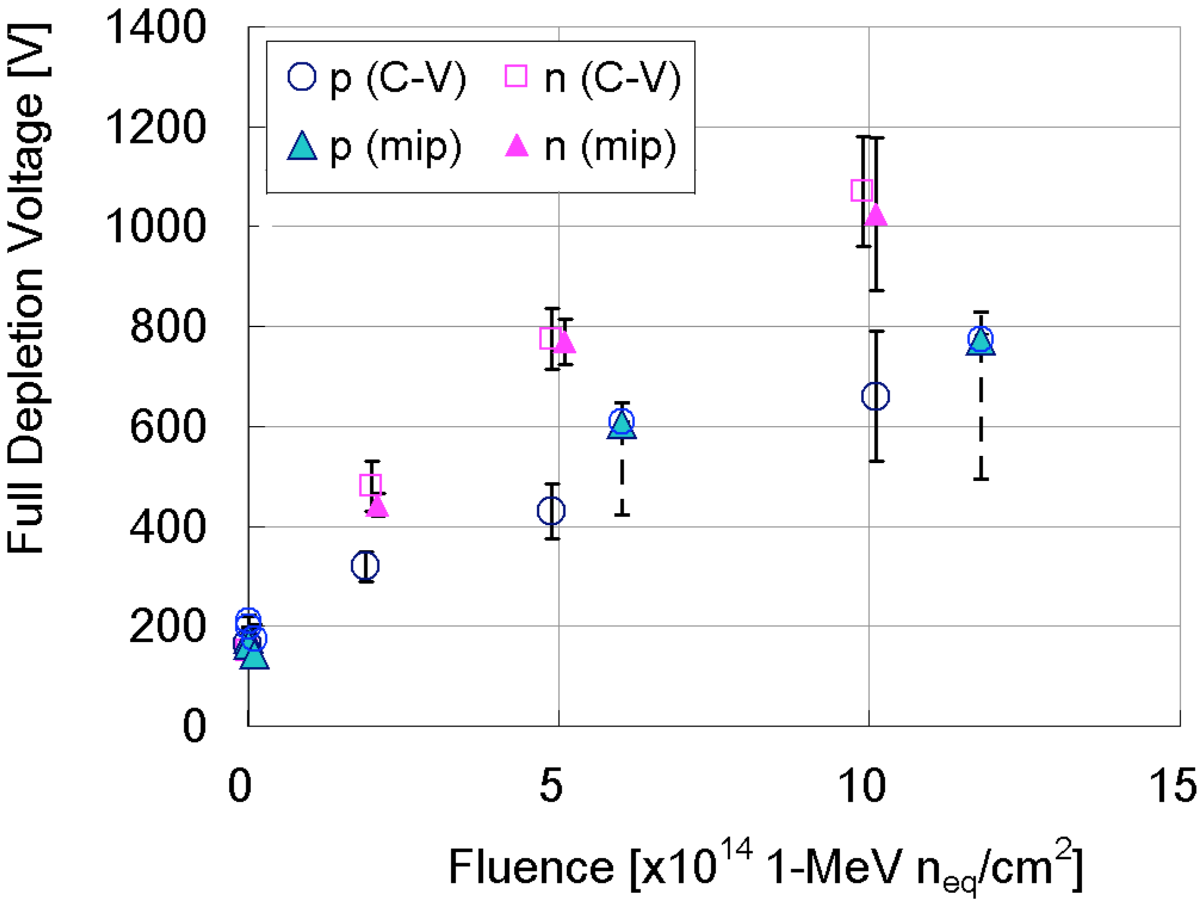
- ❑ Charge collection evaluated with penetrating β sources
  - ❑ Liverpool and Valencia data with no annealing
    - ❑ CC is corrected by +20% ± 10% for these data
  - ❑ Ljubljana and Tsukuba/KEK annealed for 80 minutes at 60°C

Charge Collection Comparison



- ☐ HPK data shown from all sites (no annealing; proton CC reduced by -20%+/-10%). Pion irradiation measurements corrected for annealing during run.
- ☐ n-in-p FZ sensors (Micron and Hamamatsu) are the same after all measured irradiation sources.

Full Depletion Voltages

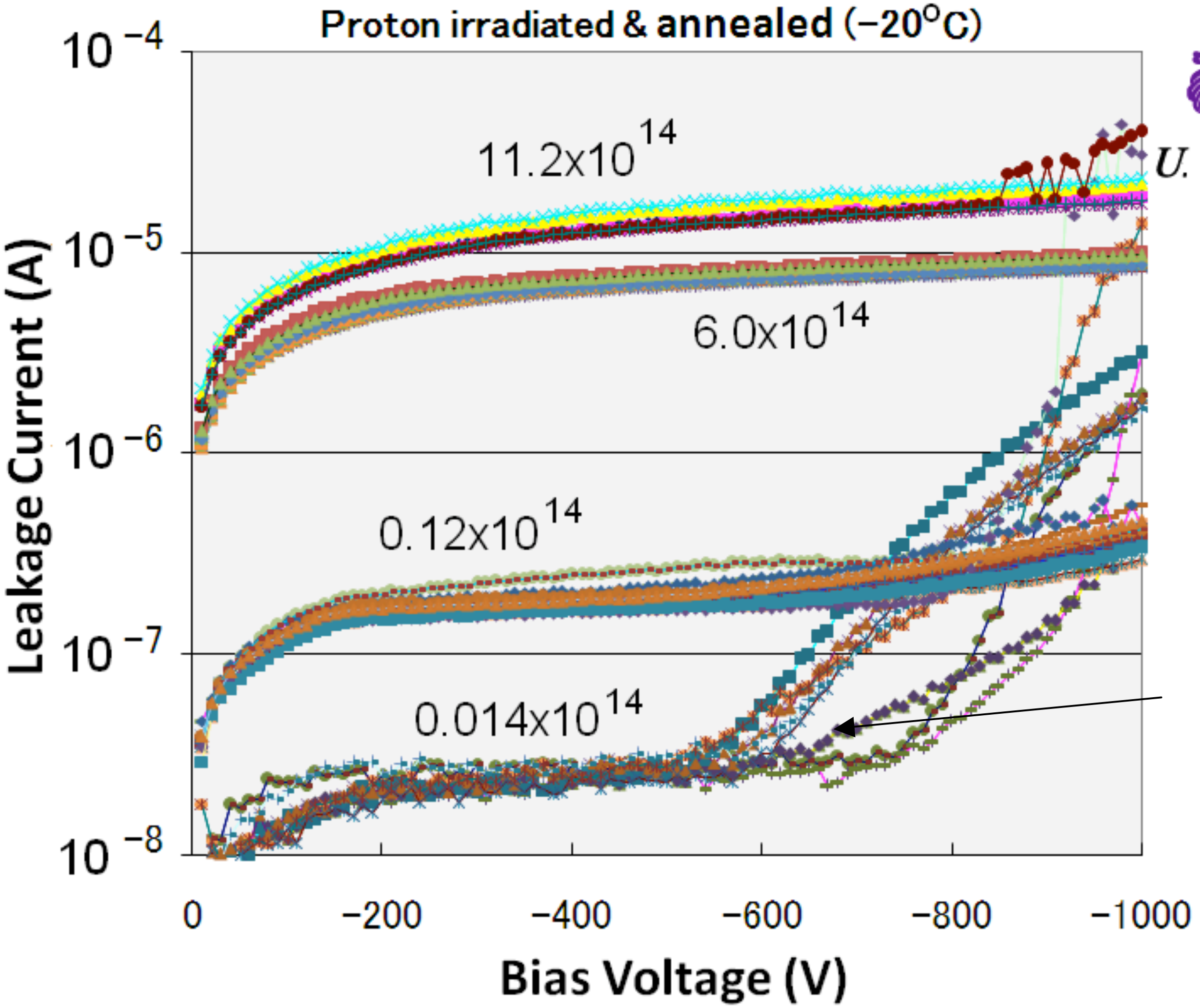


- ☐ Full Depletion Voltage after annealing
- ☐ Protons
  - ☐ ~700 V @ **1x10^{15}**
- ☐ Neutrons
  - ☐ ~800 V @ **5x10^{14}**

K. Hara et al., "Testing of bulk radiation damage of n-in-p silicon sensor for very high radiation environment", HSTD7 presentation

Leakage Currents After Irradiation

Hamamatsu FZ wafers (FZ1) Series Sensors

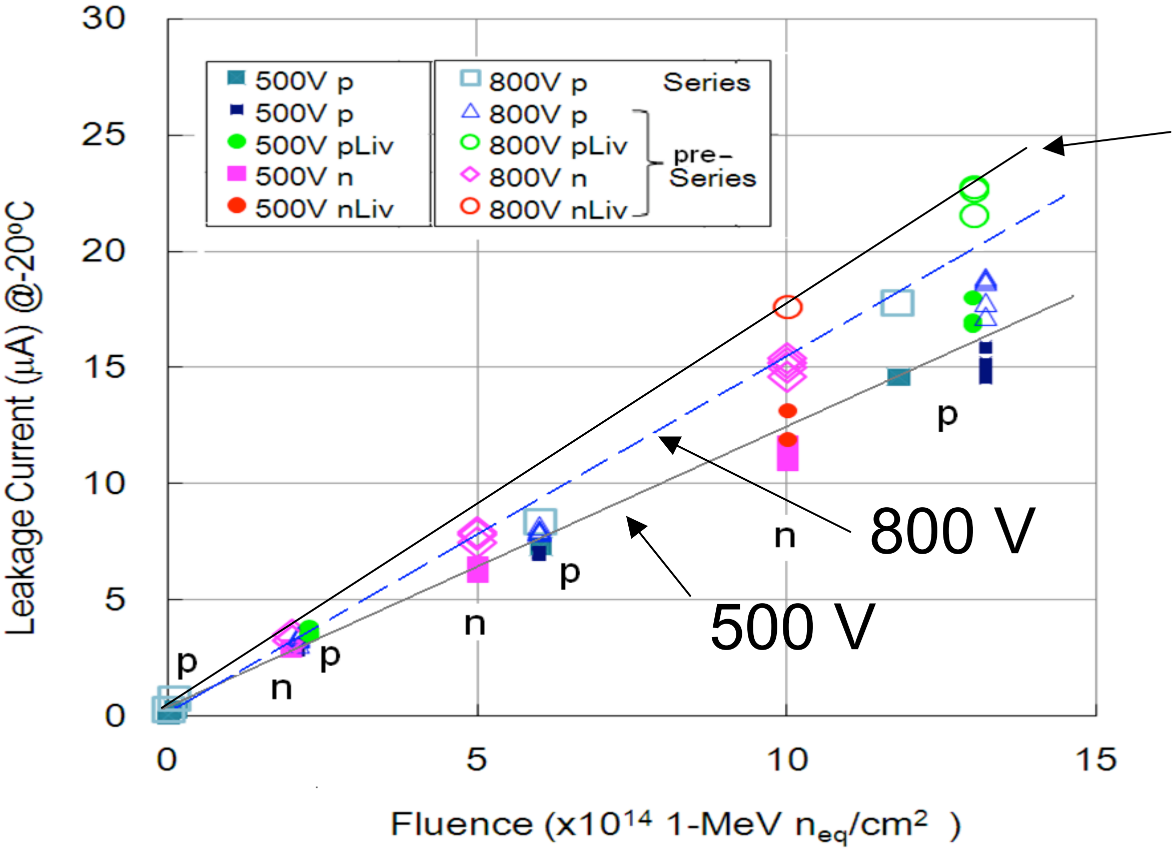


U. Tsukuba KEK

miniatures:10x10x0.32 mm^3
(strip=8 mm long)
measured at -20^{o}C

Temp-dependence does not support avalanche (μ-discharge).

Leakage Currents

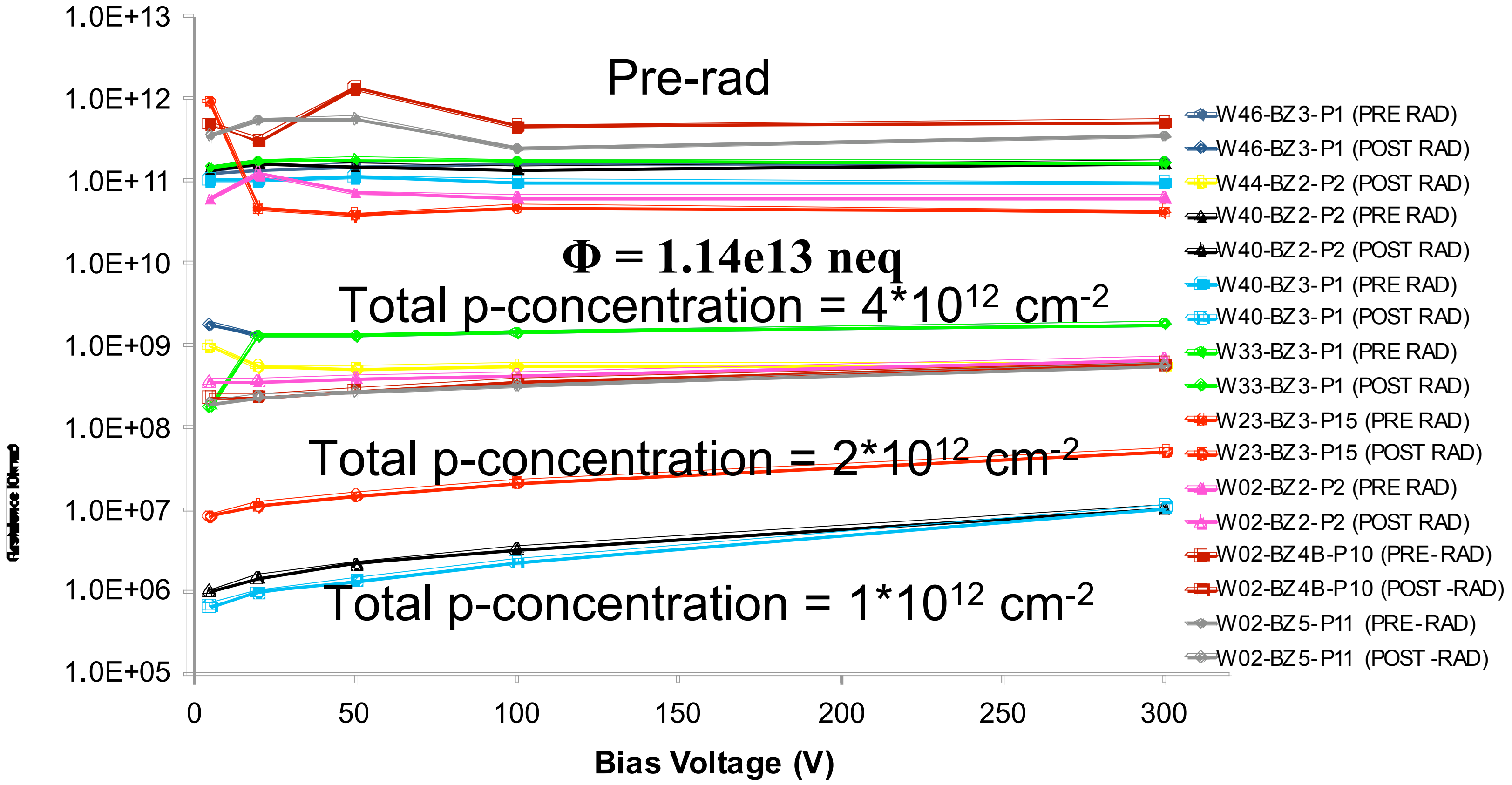


The damage constant for n-bulk, (3.99+/-0.03) x10^{-17} A/cm, can be translated to 18.0 μA at 10^{15} 1-MeV n_{eq}/cm^2 for effective area of 83 mm^2 and 0.32 mm thickness. The energy gap energy of 1.21 eV is taken in the temperature correlation.

- Damage constants to neutrons and protons are the same.
- Damage constants of p-bulk is similar to the n-bulk.

Strip Isolation

Interstrip Resistance for Detectors from the 3rd Series

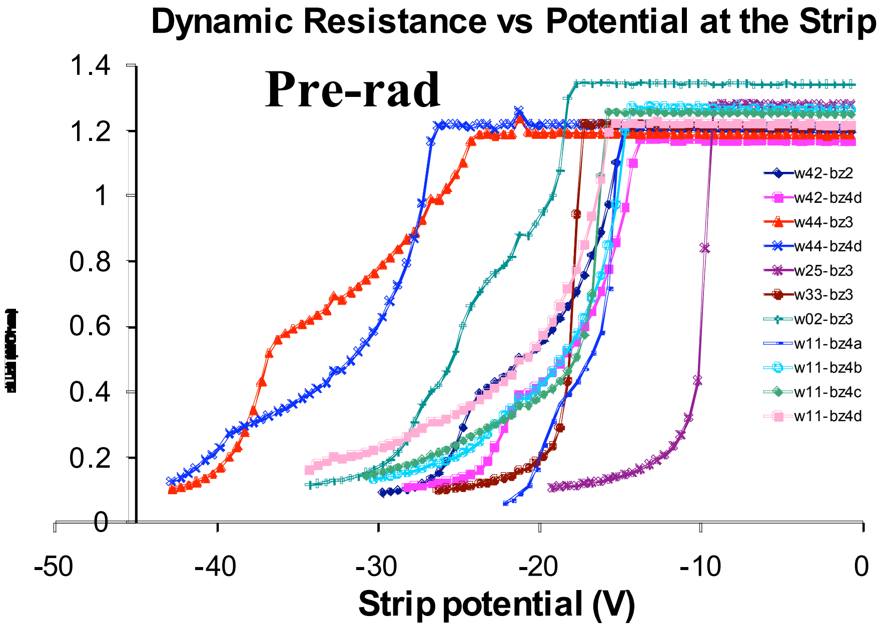


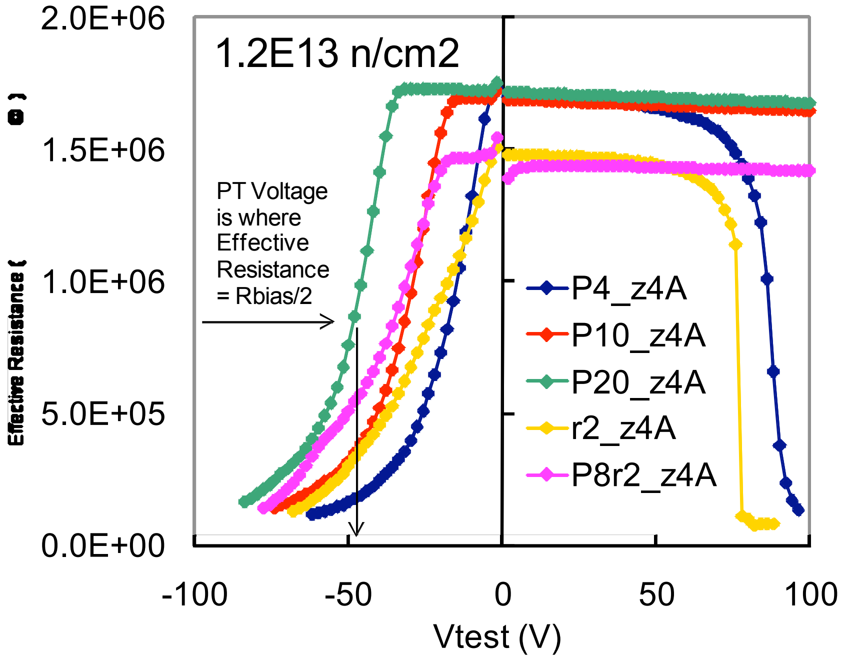
- ❑ Total p-concentration of ≥$4x10^{12}$ ions/cm^2 is desirable

S. Lindgren et al., "Testing of surface properties pre-rad and post rad of n-in-p silicon sensor for very high radiation environment", HSTD7 presentation

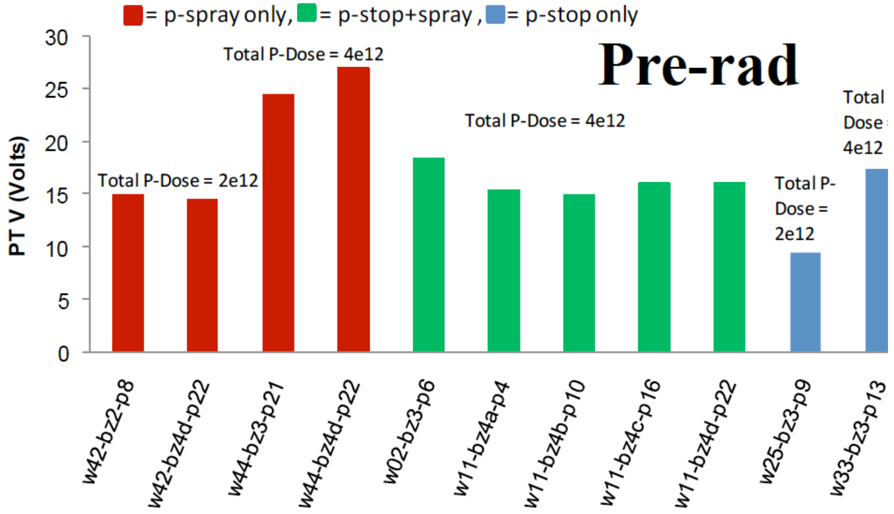
Protection against Accidents

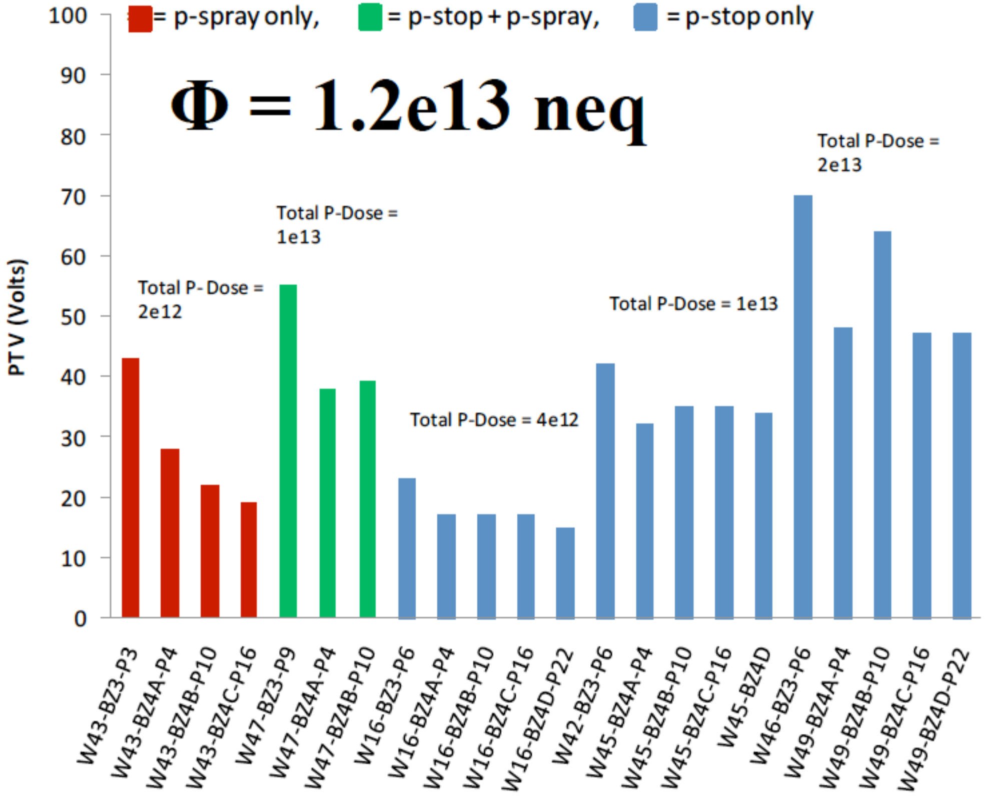
- ❑ Splash of beam, e.g.
  - ❑ Voltage drop in n+-strips
  - ❑ Voltage across the AC coupling insulator
- ❑ Punch-Through Protection structure
  - ❑ Narrow gap between the end of strip and the bias rail, n-n gap
    - ❑ Z1, Z4: 20 μm; Z2, Z3, Z5, Z6: 70 μm
    - ❑ p-stop between the n-n gap


Dynamic Resistance vs Potential at the Strip



Punch-Through Voltage



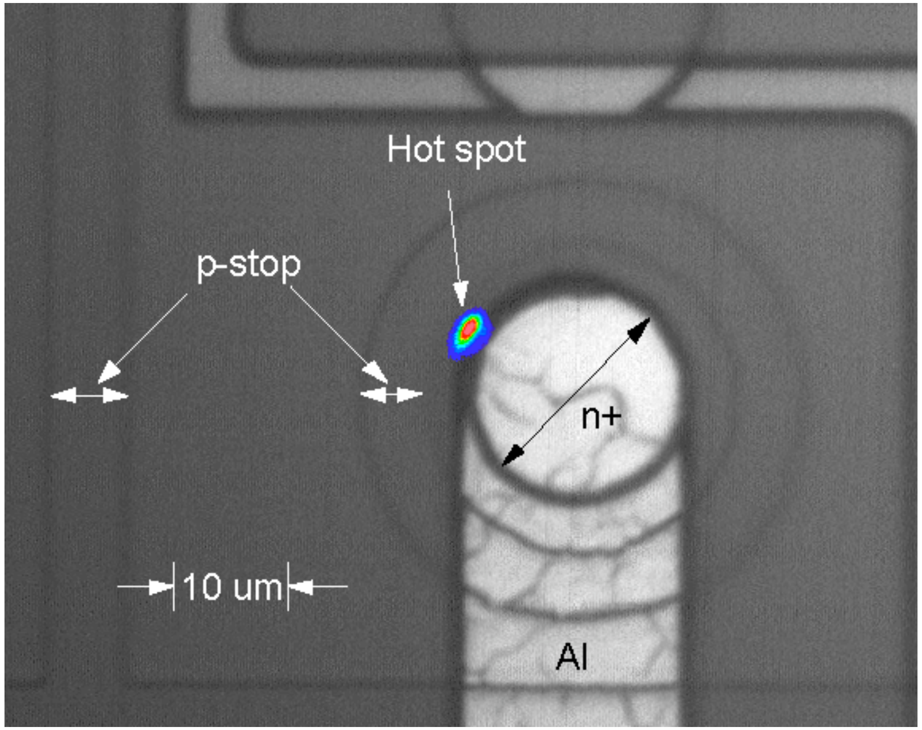


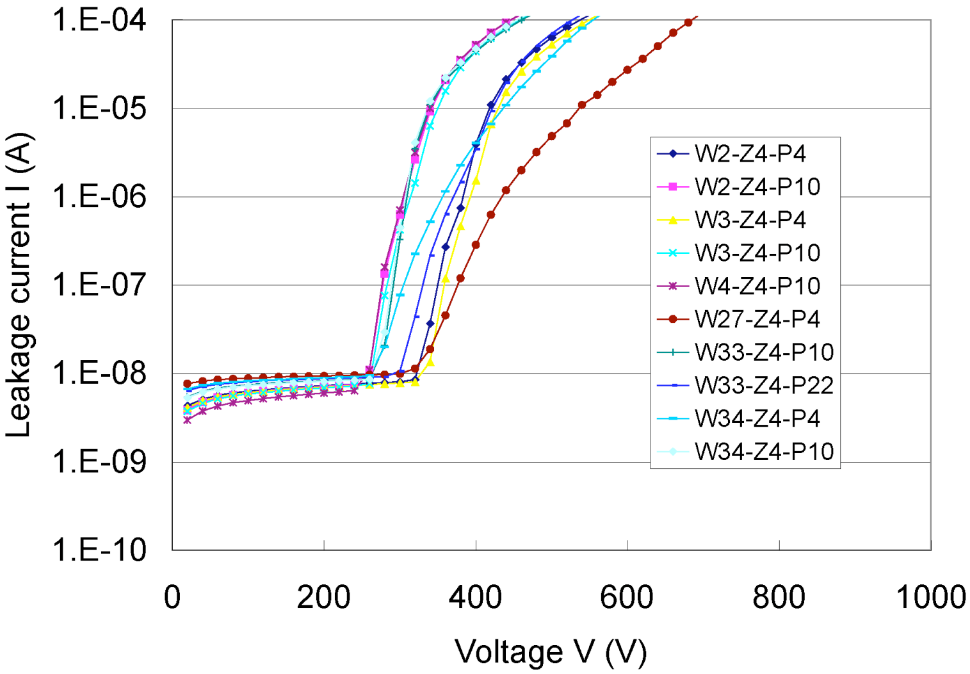
- Within the different configurations (p-spray only, p-stop only, p-stop + p-spray) there is a dependence on the total p-concentration, i.e. the sum of the two.
- After irradiation the punch-through voltage exhibits a dependence on the total p-concentration for detectors with the same configuration.
- Although similar, PTV in Z3 (n-n gap 70 μm) is higher than Z4 (n-n gap 20 μm)

Mask Design Improvement

- Observation of microdischarges
  - 300 - 400 V
  - Onset of leakage current in I-V
  - Hot spots with Hot-electron visualization
- Understanding of the causes
  - with TCAD simulations
- Mask modification from X1 to X2
  - Miniature sensors
  - Main sensors

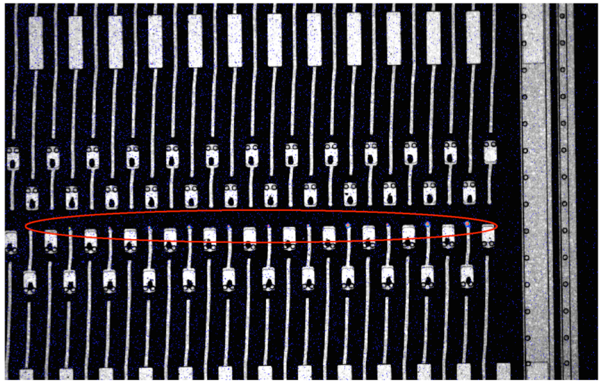
Microdischarge - Mini Sensors



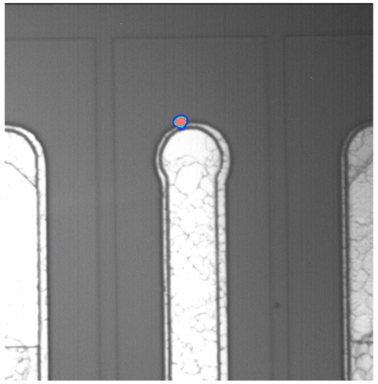


- ❑ PTP miniatures (X1FZ1Z4)
  - ❑ Onset of Microdischarge ~300V
  - ❑ Hot spot identified

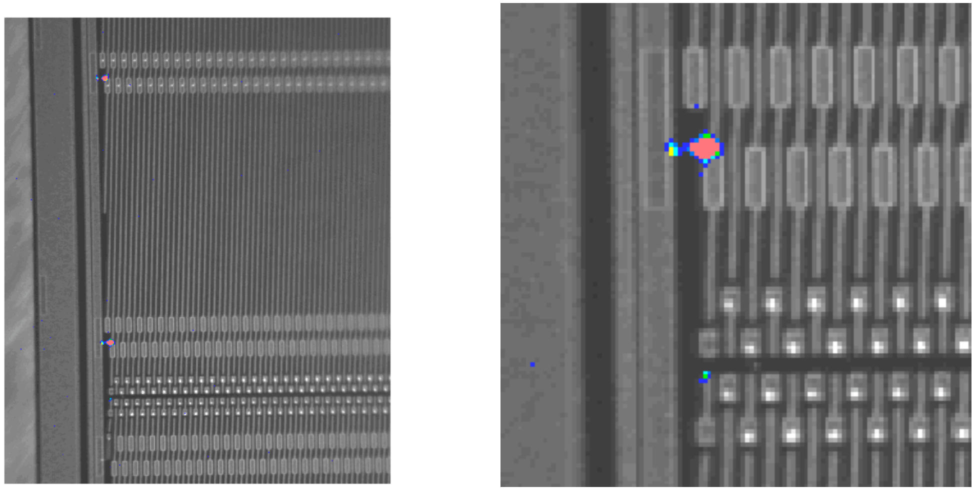
Microdischarge - Main Sensor



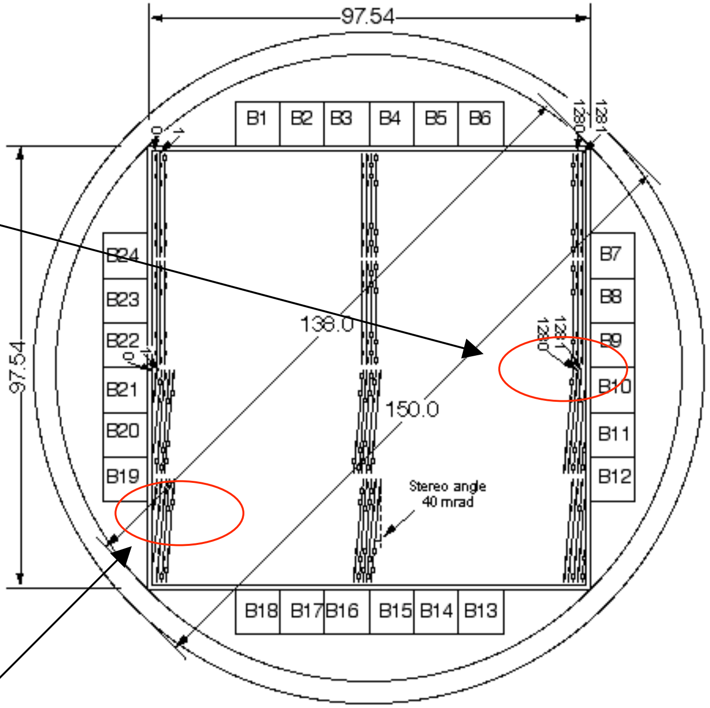
Seg4 の DC PAD ｽﾄﾗｲﾌﾟ 先端で発光（×5）



Seg4 の DC PAD ｽﾄﾗｲﾌﾟ 先端で発光（×100

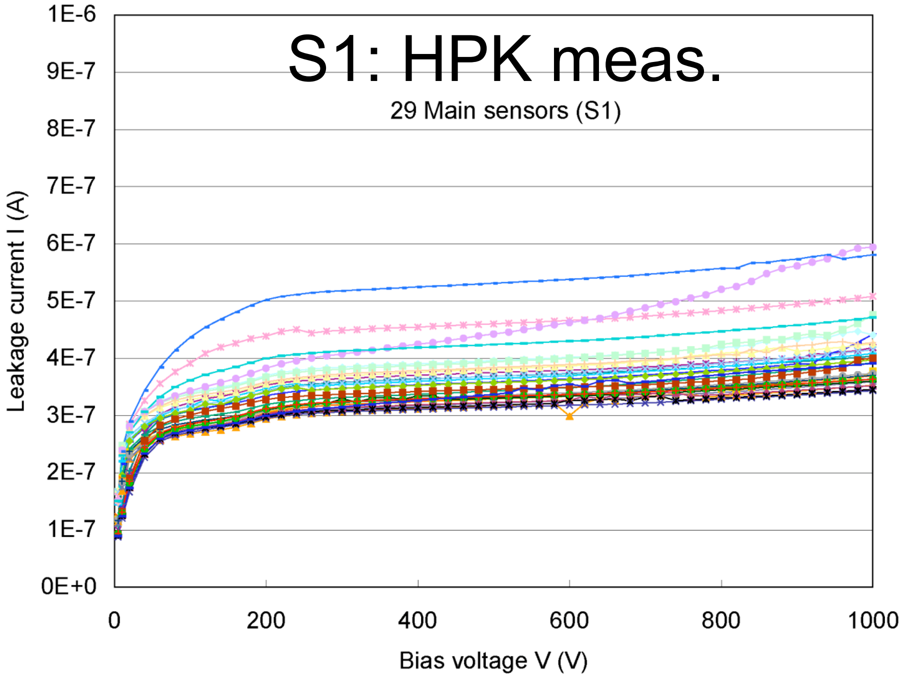


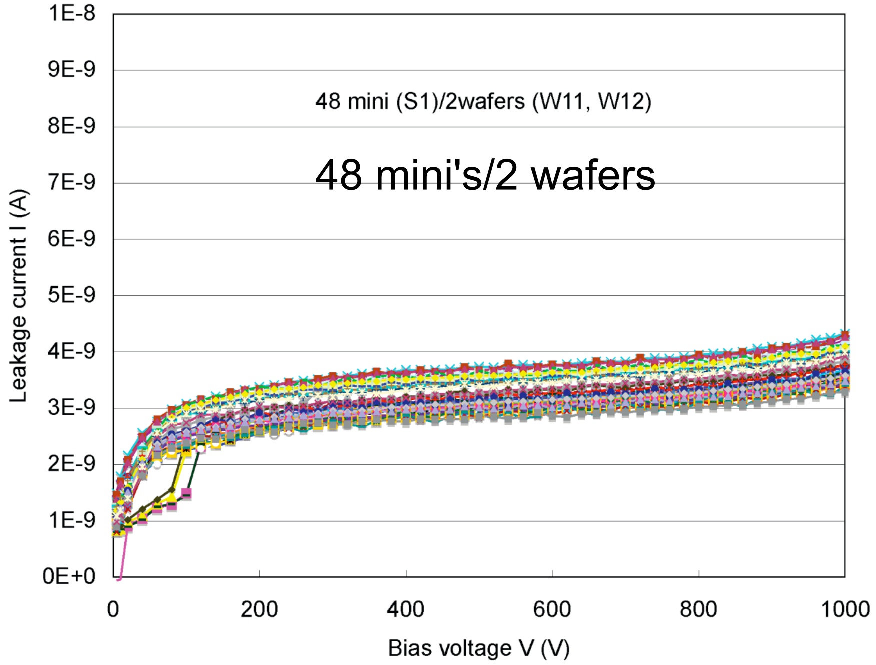
Seg3 の AC PAD 角と Seg4 の DC PAD ｽﾄﾗｲﾌﾟ 先端で発光（×0.8）



- ❑ Main sensors
  - ❑ MD onset ~400 V

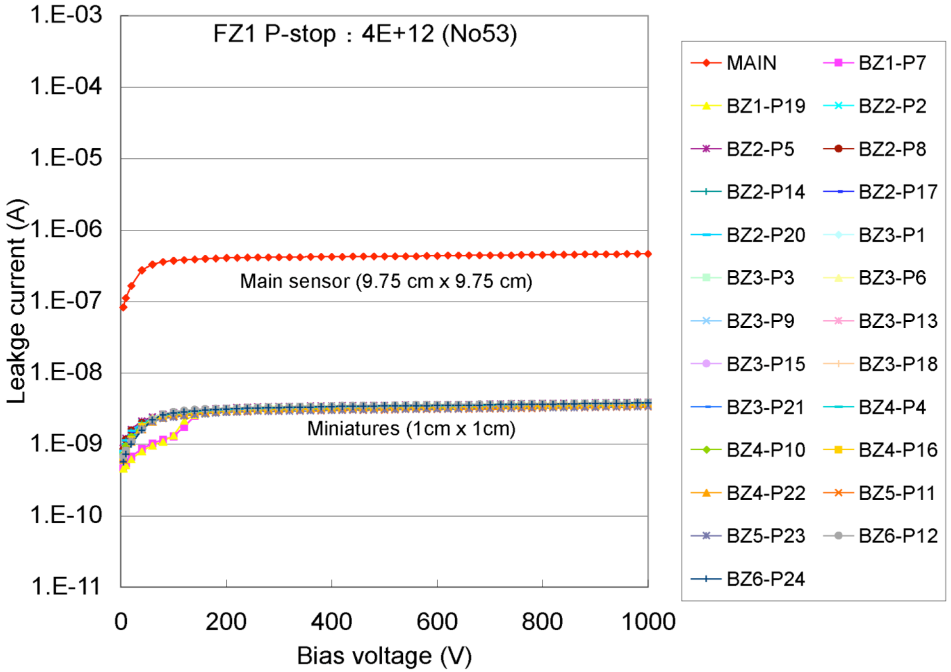
I-V with Modified Masks

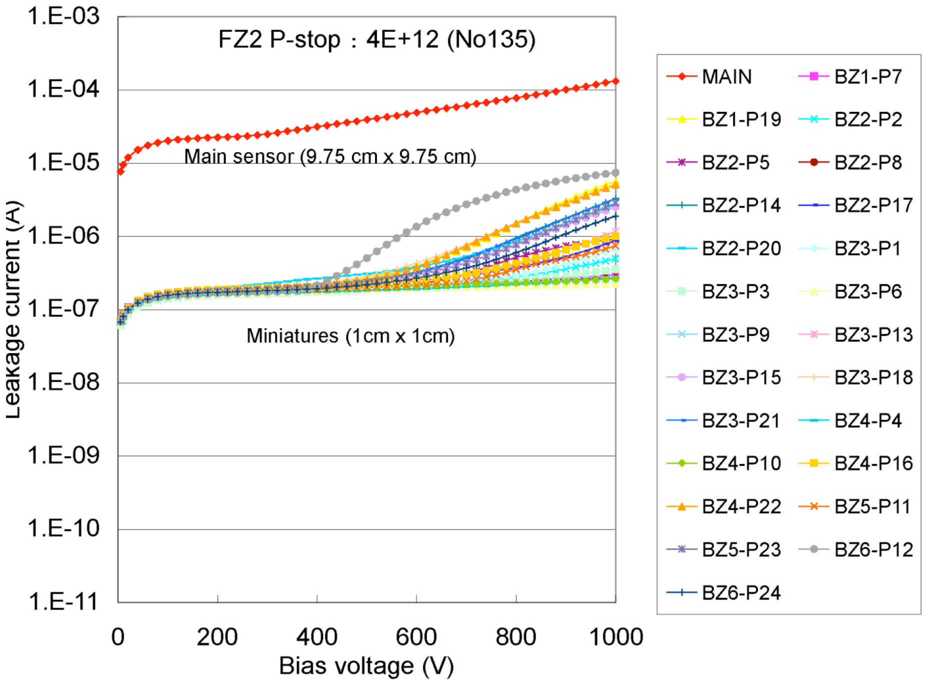




- ❑ Sources of onset have been understood by TCAD simulations, then the masks were modified (X1 to X2 and after)
- ❑ Onset of Microdischarge ≥1,000V
  - ❑ Main and all miniatures
  - ❑ P-stop concentration 4x10^{12} ions/cm^{2}
- ❑ Established basic technology of radiation tolerant n-in-p sensor
  - ❑ ~1,000V operation even in the non-irradiated sensors
- ❑ Good yield for >50 (FZ1 p-stop 4x10^{12} cm^{-2}) sensors

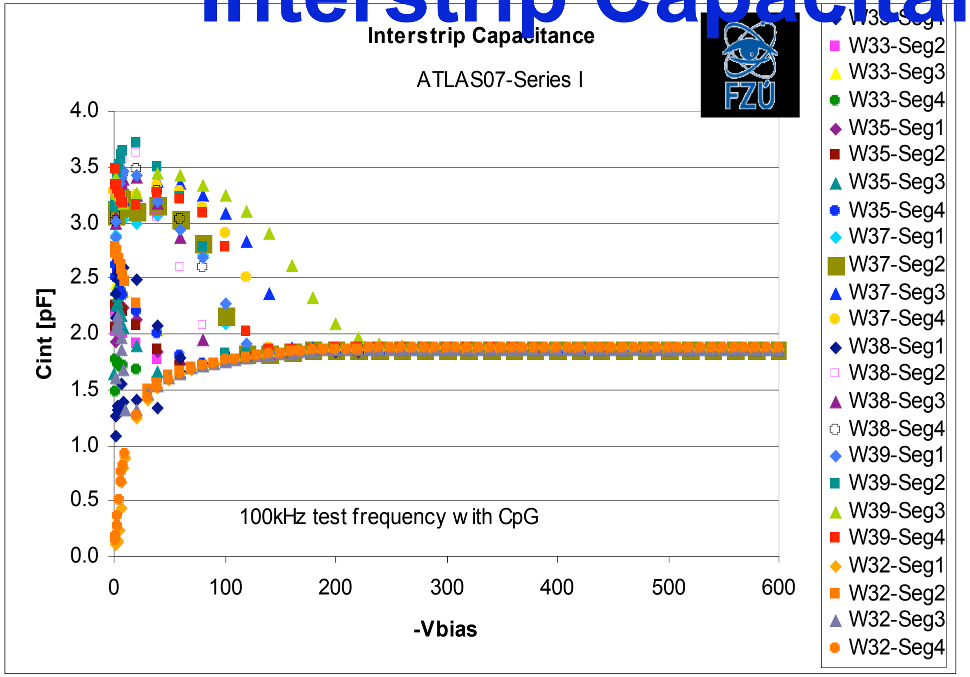
FZ1 and FZ2 wafers

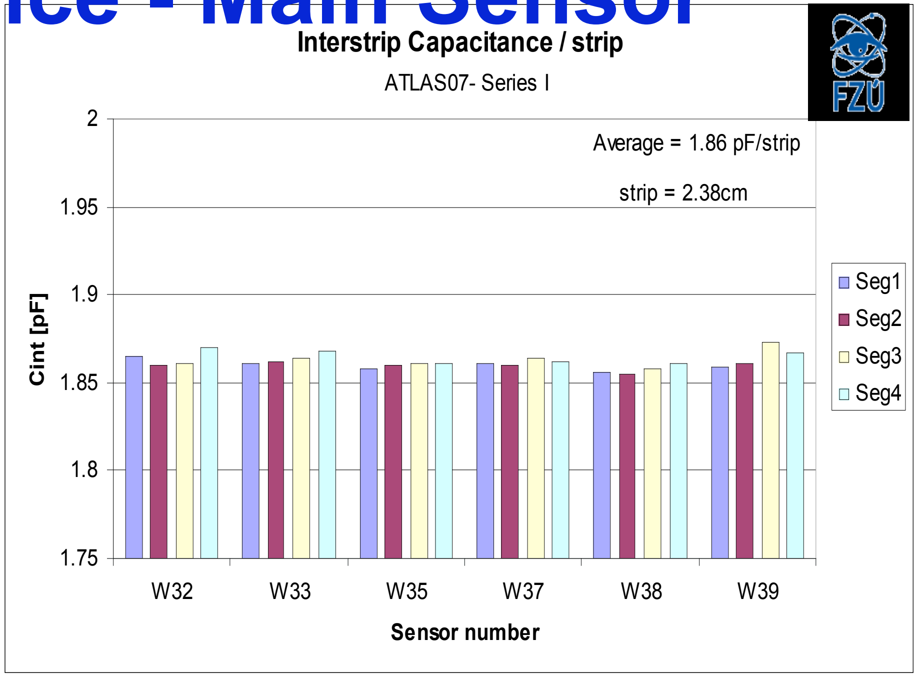




- FZ1 and FZ2 are float-zoning wafers
  - FZ2 is a lower grade wafer, but cheaper
- Typical I-V characteristics in the above
  - Same mask and same process
  - Leakage current of FZ2 is ~50 times larger than FZ1
    - This was known from earlier prototypes, but ...
  - Onset of microdischarge appeared to be 300 - 500 V range
    - Plausibly caused by the crystal defects

Interstrip Capacitance - Main Sensor





- Non-irradiated sensors (p-stop 4x10^{12} ions/cm^2)
- C$_{int}$/strip = 1.86 pF/2.38 cm @ 100 kHz
  - All tested sensors have Cint ~ 0.75-0.80 pF/cm
- Measurements taken on central strip with either neighbour grounded.
  - Including next-to-neighbours results in 10-15% higher readings.
- Cbulk = 3.25 nF at FDV for full area sensor
  - One strip capacitance is equal to ~0.6pF only.
  - It is 3 times smaller value than measured Cint = 1.86 pF/strip.

M. Mikestikova et al., Testing of large arean-in-p silicon sensors intended for a very high radiation environment, HSTD7 presentation

Finishing Touch - Next Steps

- Z4 - Punch-through protection structures
- Prototyping wedge sensors
- Irradiations of main sensors
  - Together with ASICs on hybrids

Summary

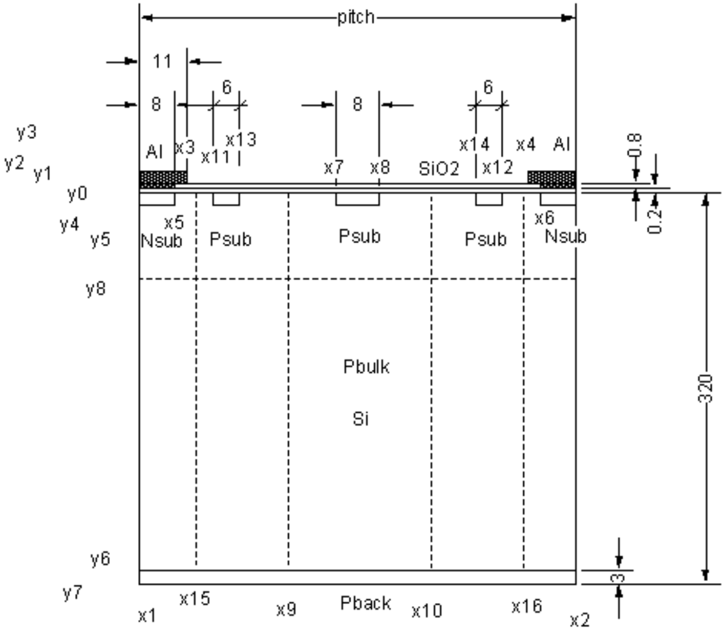
- Basic technology of a radiation tolerant n-in-p silicon microstrip sensor has been developed to hold
  - $V_{MD} \geq 1{,}000$ V
    - 10 cm x 10 cm large area sensors
    - 1 cm x 1cm miniature sensors
- Radiation damage studies have shown
  - Evolution of the full depletion voltage as a function of fluence
    - Protons: ~700 V@1×10^{15}, Neutrons: ~800V@5×10^{14} neq/cm^2
  - Isolation resistances of n-strips
    - of candidate isolation structures
      - p density $\geq 4\times10^{12}$ cm^{-2}
      - Wafer orientation <100>
  - Onset voltages of PTP protection
    - <<100 V
      - even with p-stop 4×10^{12} cm^{-2}
- Good yield has been obtained with the wafer material of p-FZ1
    - Out of >50 large area sensor and x24 miniatures per wafer

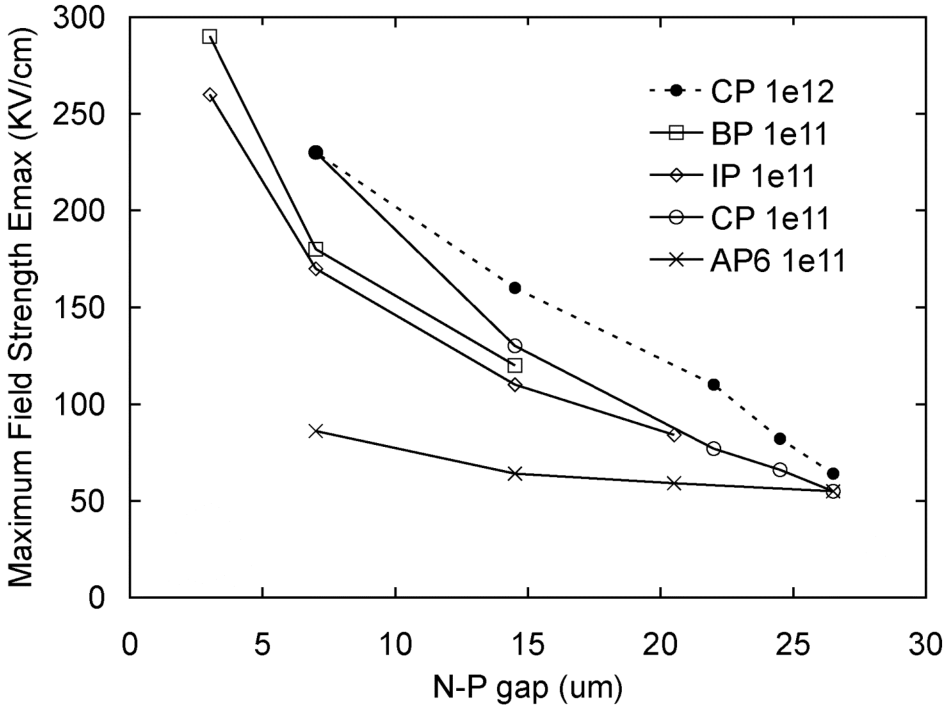
Backup Slides

What is the issues?

- Bias voltage
  - What high voltage to get a reasonable amount of charges?
    - Full depletion voltage, charge trapping
    - A better wafer material?
  - Proof for the high voltage in non-irradiated sensors
    - QA of fabricated sensors, QA of system aspects
- Strip isolation, Onset of microdischarge
  - Coping with the inversion layer, enhanced by ionizing radiation
  - Microdischarge:
    - rapid increase of leakage current due to the avalanche breakdown in Silicon where electric field strength exceeds 300 kV/cm
    - Segmented electrodes and associated structures cause high electric field
  - Isolation technique / structures
- Other features?
  - AC coupling insulator protection
    - against an accidental splash of beam into the silicon wafer
- Robust design of the surface structures
  - Against high voltage operation

TCAD Simulation for Optimization

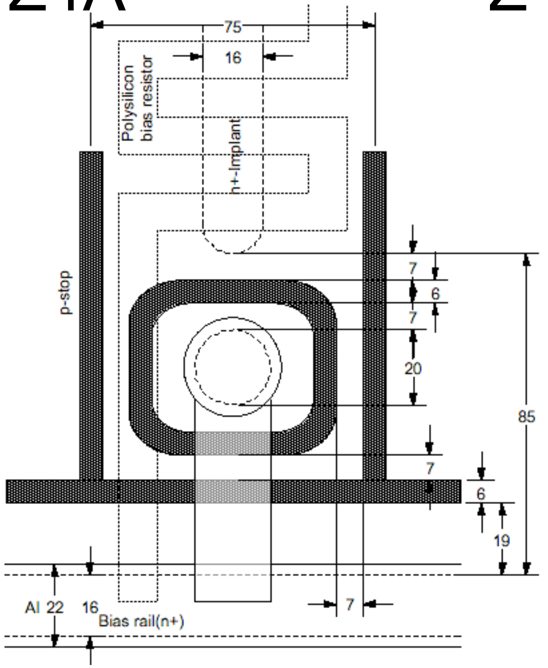




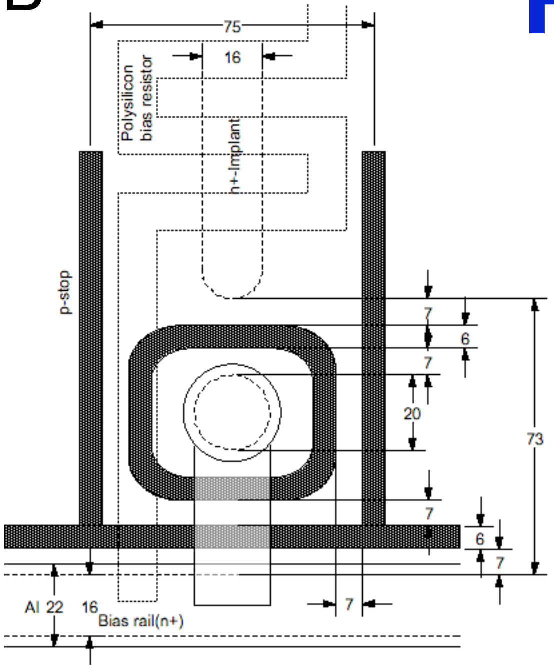
Y. Unno et al., "Optimization of surface structures in n-in-p silicon sensors using TCAD simulation", HSTD7 presentation

PT Protection

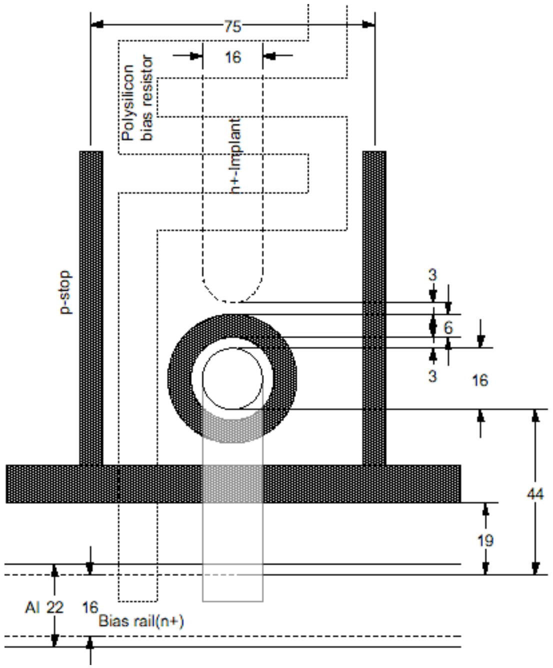
Z4A



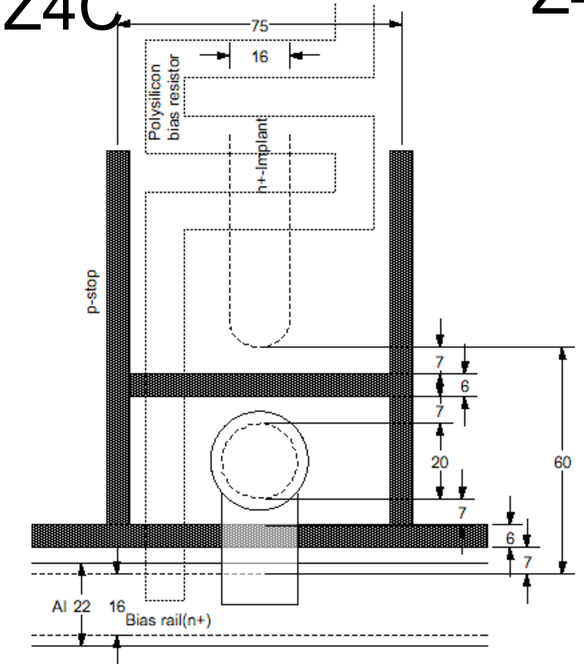
Z4B



X1Z4



Z4C



Z4D