Study of Behaviour of n-in-p Silicon Sensor Structures Before and After Irradiation

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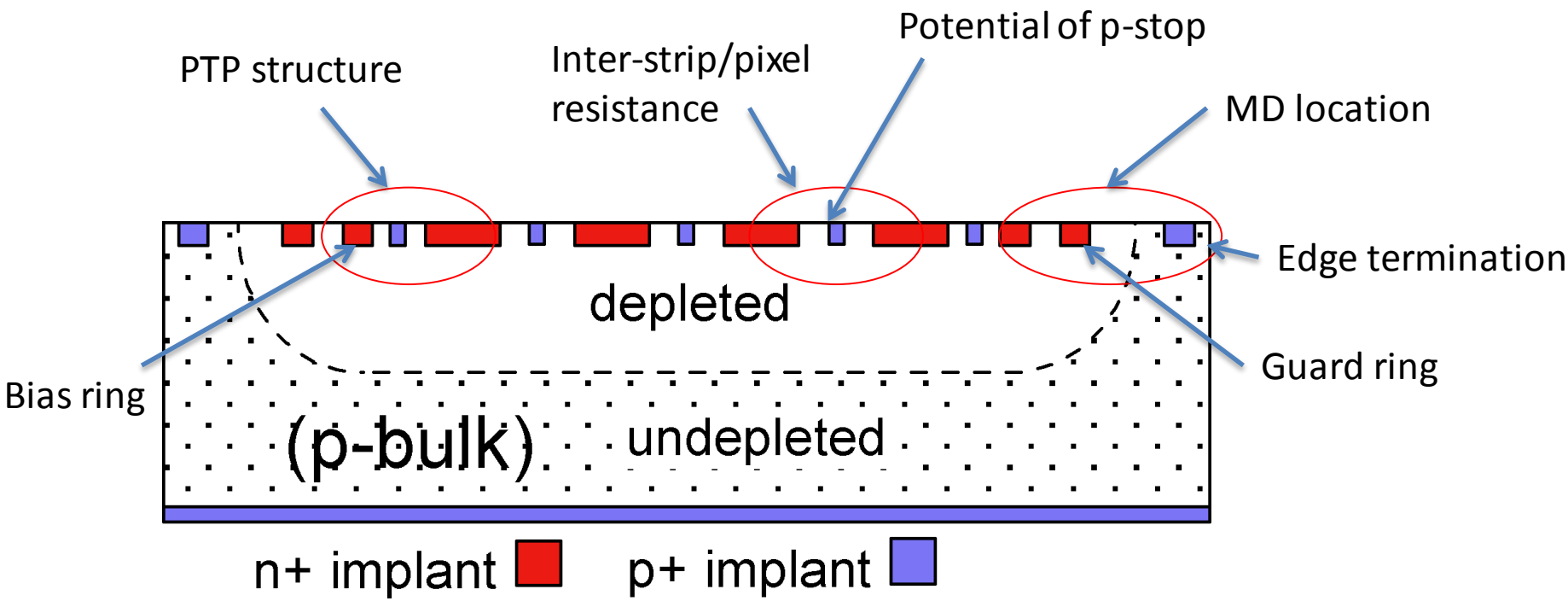
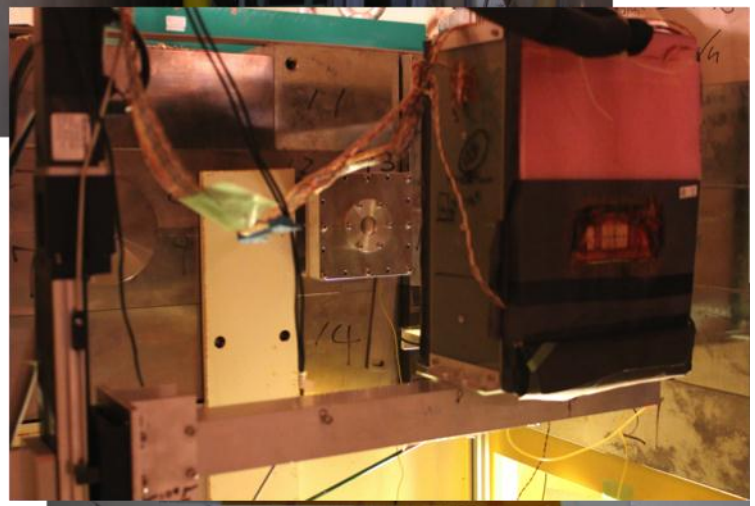
O. Jinnouchi, T. Kubota, K. Motohashi (Tokyo Tech.), et. al.

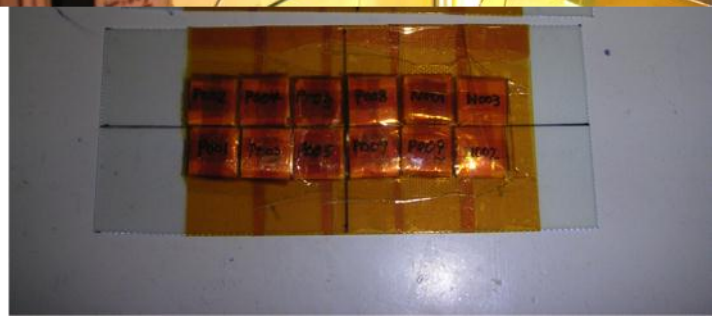
n-in-p Structures and Measurements



- In case of n-in-p sensor with p-stop isolation
- Inter-strip/pixel resistance between two readout implants
- Electric potential of p-stop structures
- Onset voltages of Punch-Through Protection (PTP) structures
- Location of microdischarge (MD) at high voltages

Proton Irradiations at CYRIC

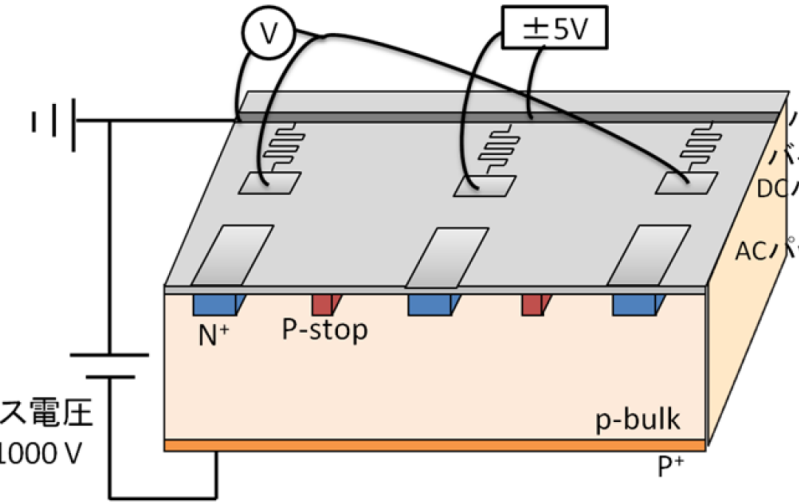


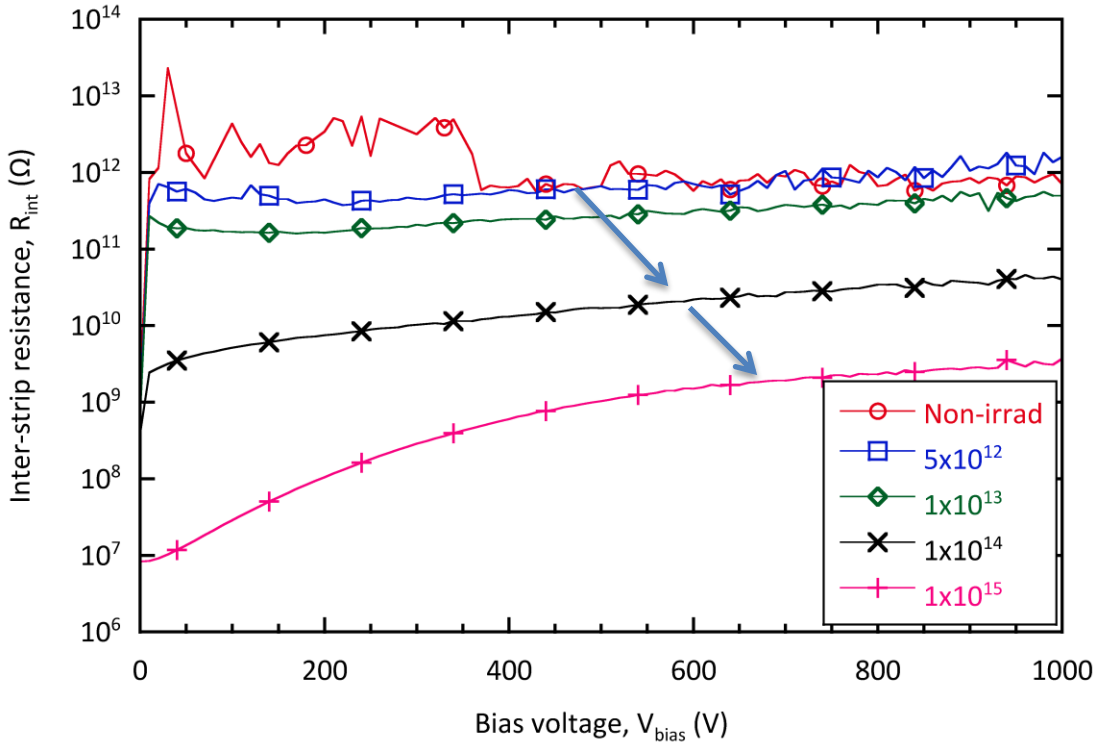


- Tohoku University, Sendai, Japan
- 70 MeV protons from 930AVF Cyclotron
- Irradiation setup in the 32 course
  - CYRIC exp. no. 9214
- Fluences:
  - 5.2×10^{12}, 1.1×10^{13}, 1.2×10^{14}, 1.2×10^{15} n_{eq}/cm^2

Let’s first go through measurements

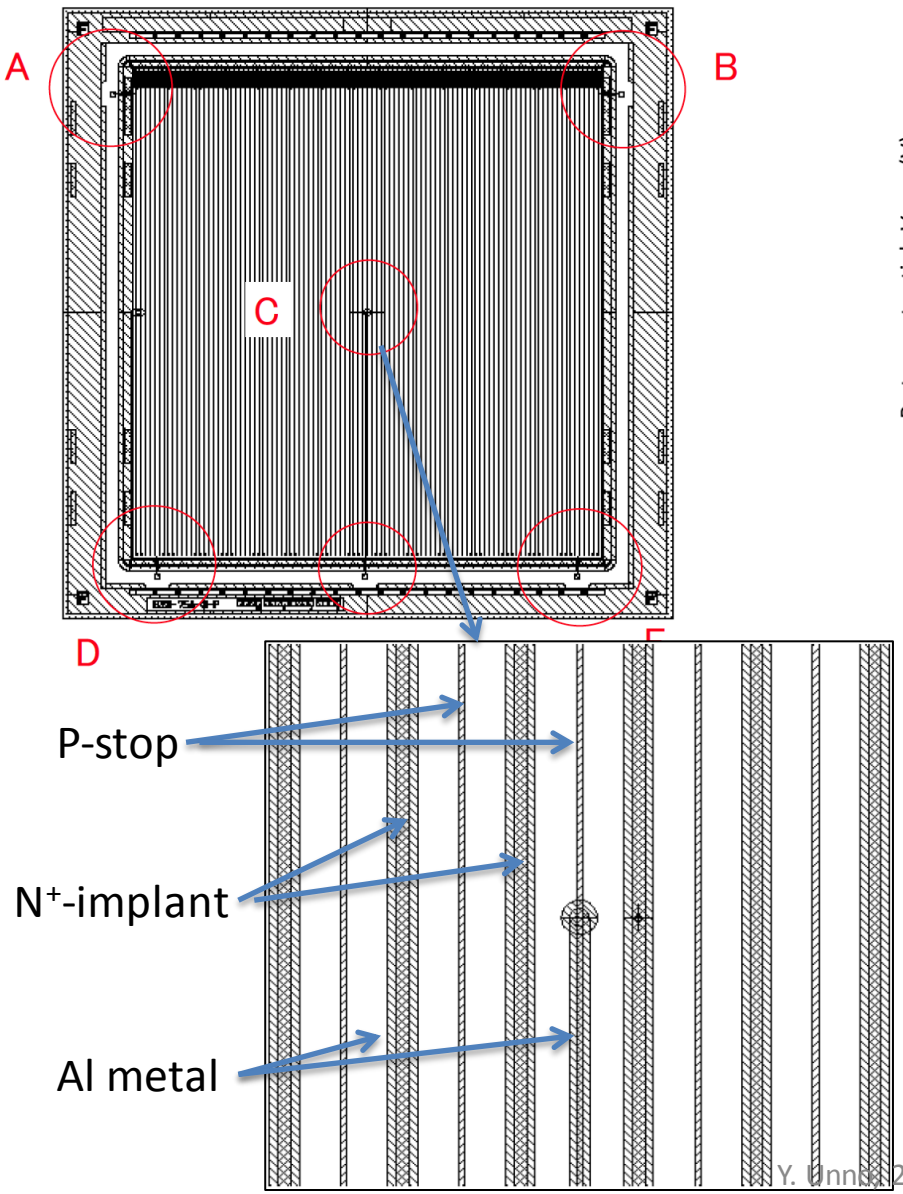
Inter-strip Resistance

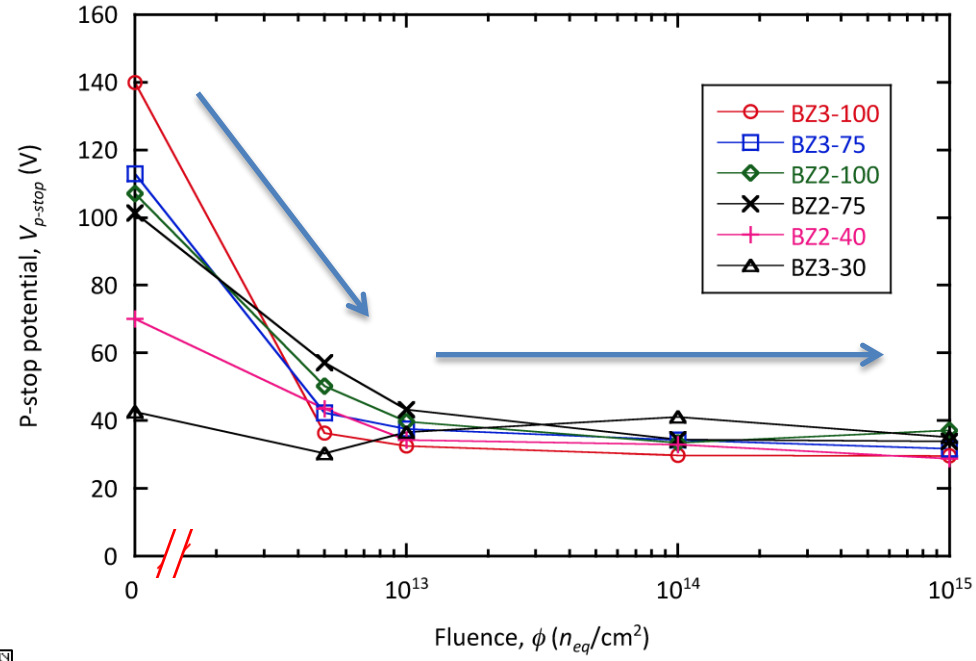




- Inter strip resistance decreased as accumulating the fluence
  - It is due to the "radiation damage", but which damage?

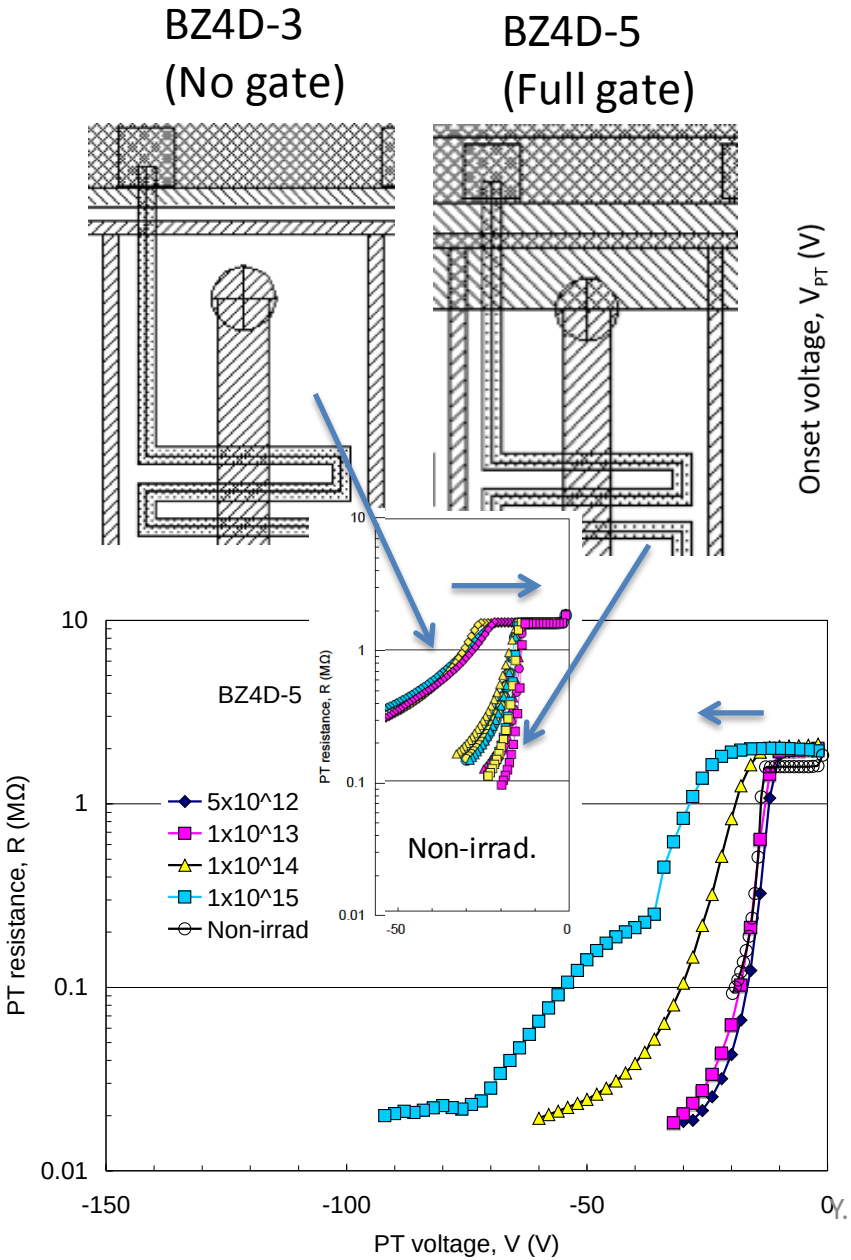
Potential of P-stop Structure

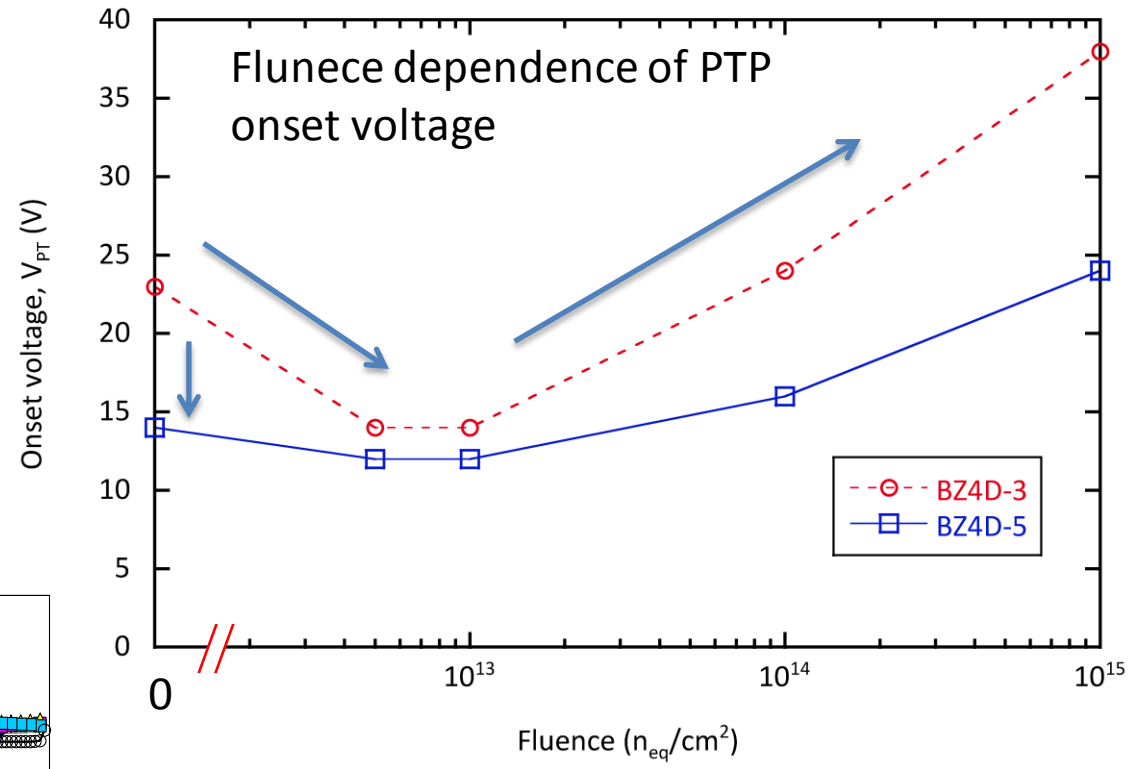




- Electric potential of p-stop implant decreased first (around 1×10^{13}) and then saturated.
  - It sounds familier…

Punch-Through Protection (PTP) Structure





- "Full gate" induced PTP onset in lower voltages than "No gate".
- Onset voltage went down first and then started to increase.
  - What causes the transitions?

Microdischarge After γ Irradiation

Y. Takahasi et al., http://dx.doi.org/10.1016/j.nima.2012.04.031

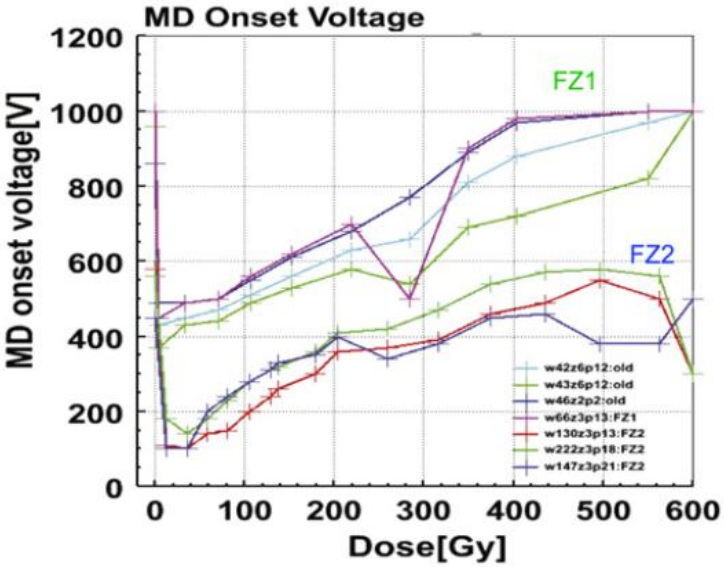


Fig. 4. Micro-discharge onset voltage vs. accumulated dose, measured at 200 V bias and 200 Gy/h. The two clusters of the curves correspond to FZ1 and FZ2 wafers.

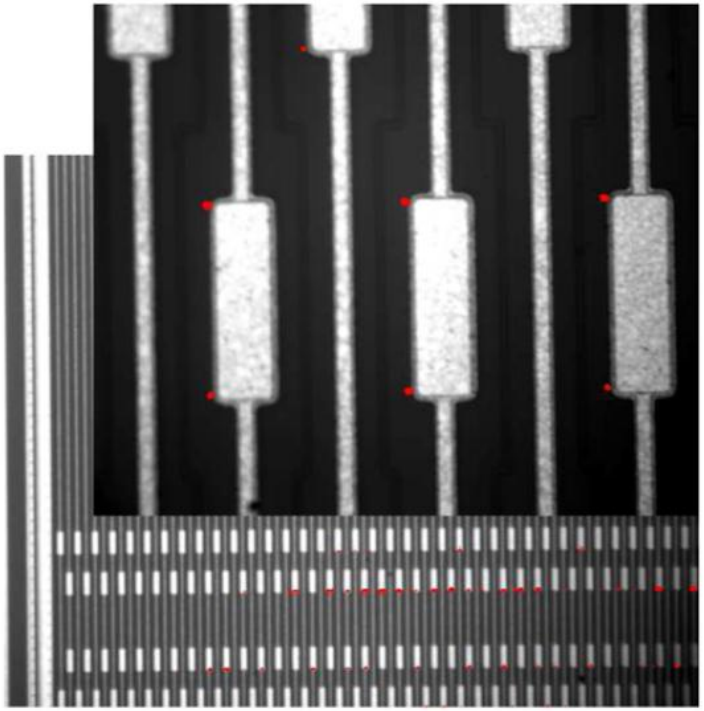
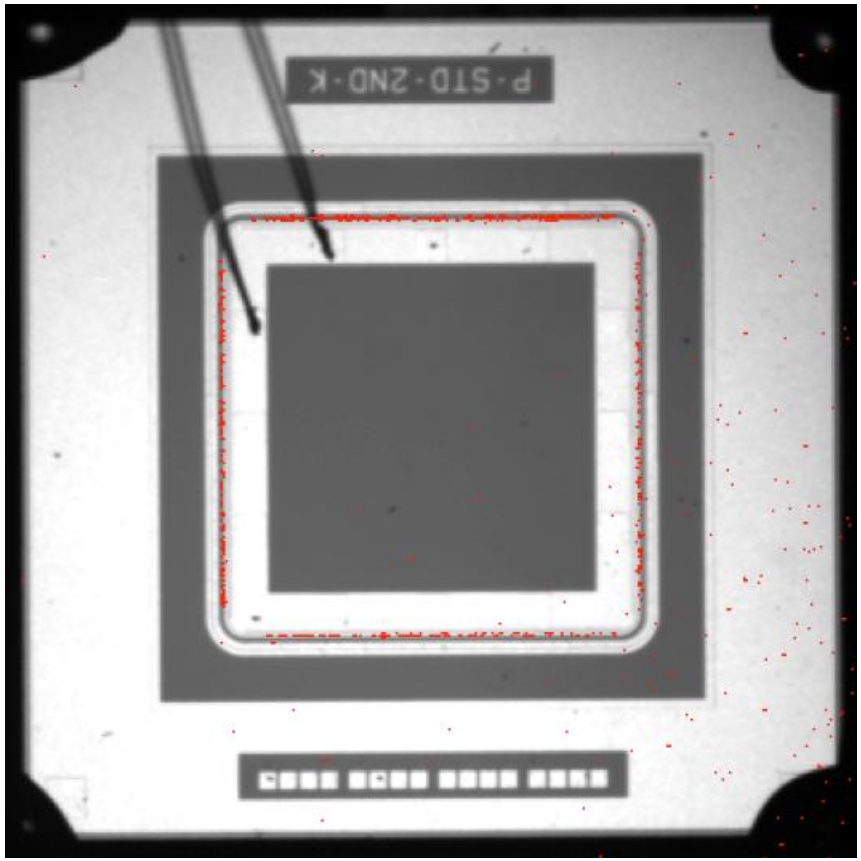


Fig. 9. Hot spots observed at AC pad corners. The AC pad is 60 μm wide and 200 μm long.

- After γ irradiation, onset of microdischarge occured at the n-implat, instead of p-stop edges, and "annealed" along the accumulation of dose.
- MD at n-implant edge could be a "corner" effect, but …
- (A warning: Be prepaired for a large drop of MD onset voltage initially.)

Microdischarge After Irradiation



CYRIC proton irradiated
1×10^{14} n_{eq}/cm^2
10 uA at 2000 V
-15 ° C

S. Mitsui et al.,
Nucl. Instr. Meth. A699 (203) 36-40

- Hot electron images confirm that
  - hot spots were observed first at the edge of the bias ring, and then at the inside of the edge metal.
  - the highest electric field is at the bias ring (n^+ implant), not at the edge ring (p^+ implant).

How can we explain these measurements with TCAD simulations?

(The summary of my last year's presentation was)

- Performance before and after irradiation has been accumulated.
  - We have had a number of evidences that require a fundamental explanation.
    - The explanation must be simple if understood (my guess).
  - If you have already had the explanation, let's have a dinner together.
  - We hope to have a quantitative explanation by the next workshop.

TCAD Simulation

- Semiconductor Technology Computer-Aided Design (TCAD) tool
  - ENEXSS 5.5, developed by SELETE in Japan
  - Device simulation part: HyDeLEOS
- N-in-p strip sensor
  - 75 μm pitch, p-stop 4×10^{12} cm^{-2}
  - 150 μm thickness
  - p-type bulk, N_{eff}=4.7×10^{12} cm^{-3}, V_{FDV}=80 V at 150 μm
- Radiation damage approximation:
  - Increase of acceptor-like state ← Effective doping concentration
  - Increase of leakage current ← SRH model
  - Increase of interface charge ← Fixed oxide charge

Simulation of the bulk current

- After irradiation, the current increases as a function of fluence as
  - $\Delta I / V \sim 4 \times 10^{-17}$ (A/cm) $\times$ ϕ (n_{eq}/cm^2)
  - E.g.,
    - Volume = 75 μm x 1 μm x 150 μm = 1.13 x 10^{-8} cm^3
    - ϕ=1x10^{15} n_{eq}/cm^2
    - ΔI ~45 nA
- Community has a view that
  - the leakage current increases with an introduction of levels near the middle of the forbidden band,
  - with the energy of band gap being half (of the full gap), the leakage current flows order of magnitude larger…
- Unfortunately, we have no freedom to change/add a program to the ENEXSS, but
  - we can tune the leakage current by modifying the model parameters to an unrealistic world…

Shockley-Reed-Hall (SRH) Model

- Leakage current: SRH model
  - Generation-recombination of carriers (electrons and holes)
  - A_n, A_p, etc. are model parameters.

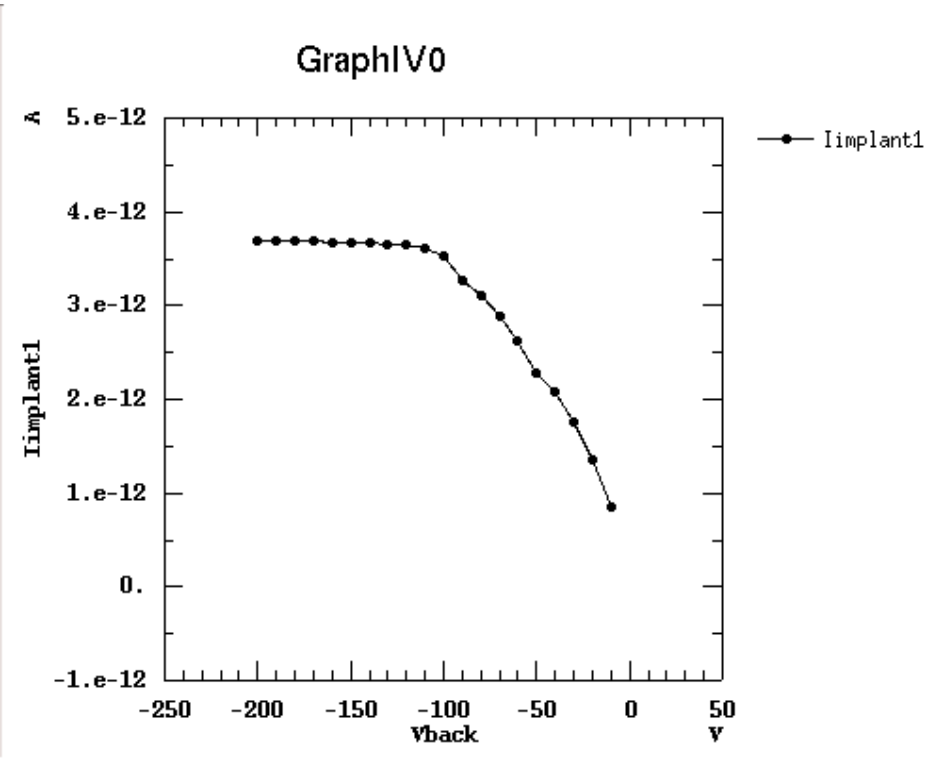
$$U_{SRH} = \frac{n_i^2 - pn}{\tau_p\left(n + n_i\right) + \tau_n\left(p + n_i\right)}$$

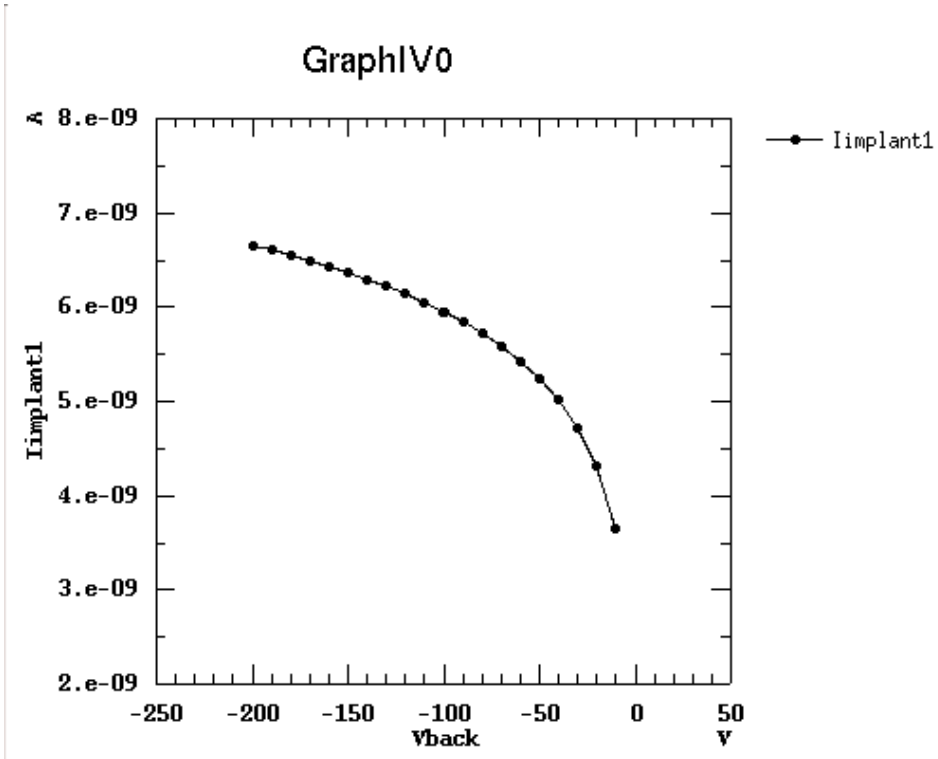
$$\tau_{n,p} = A_{n,p}\left(\tau_{\min}^{n,p} + \frac{\tau_{\max}^{n,p} - \tau_{\min}^{n,p}}{1 + \left(N / N_t^{n,p}\right)^{B_{n,p}}}\right)$$

n_i: intrinsic carrier density,

n, p: electron, hole carrier density

Increase of Leakage Current

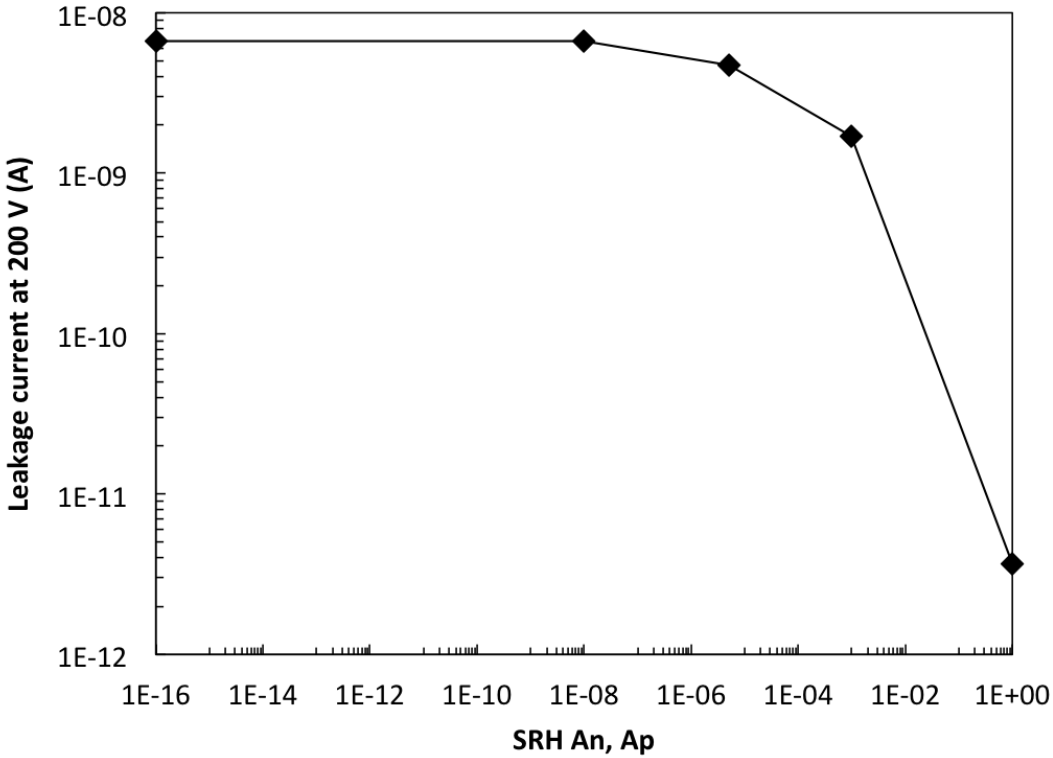




- SRH A_n, A_p = 1.0 (default)
- Saturated current ~3.7 pA

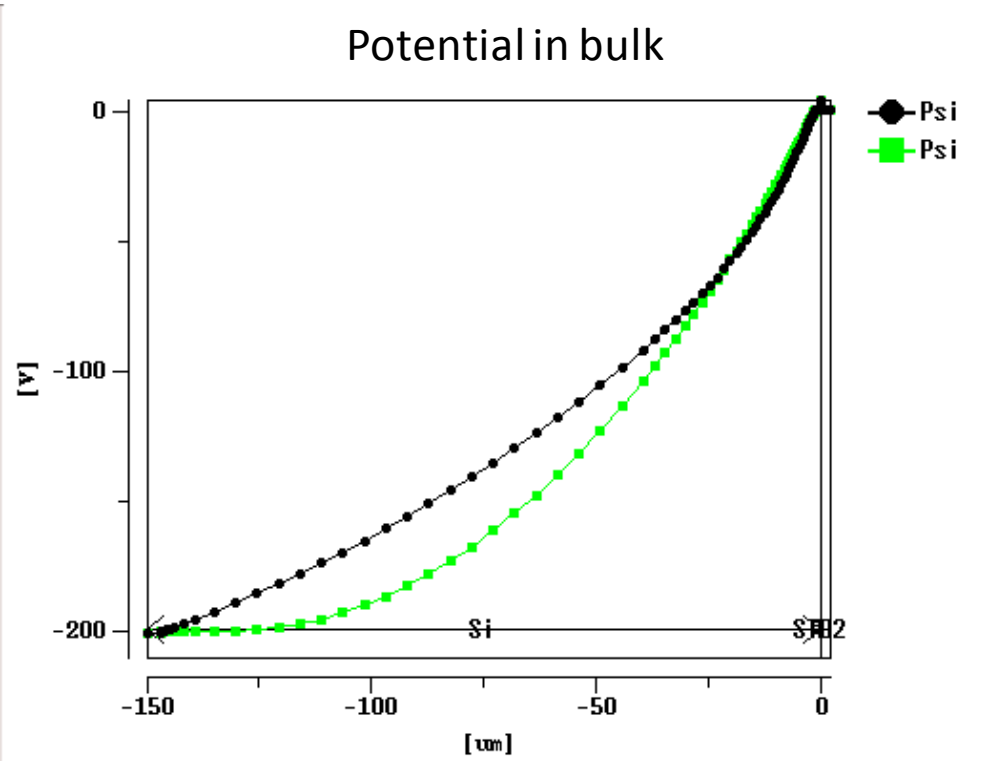
- SRH A_n, A_p = 1×10^{-8}
- Current ~ 6.7 nA (at 200 V)
  - 3 orders of magnitude increase

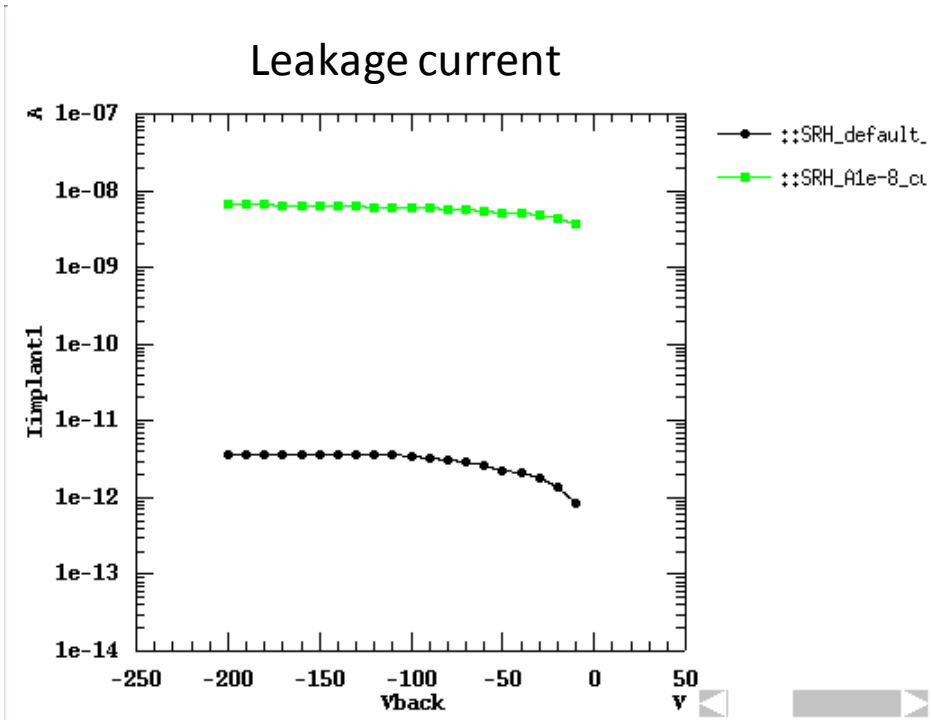
Leakage Current at 200 V



- Leakage current can be increased by 3 orders of magnitude by varying the SRH modeling parameter, A_n and A_p.
  - Current saturates when A_n, $A_p < 1 \times 10^{-8}$
  - Current can be tuned by a factor between 1 and 10^3

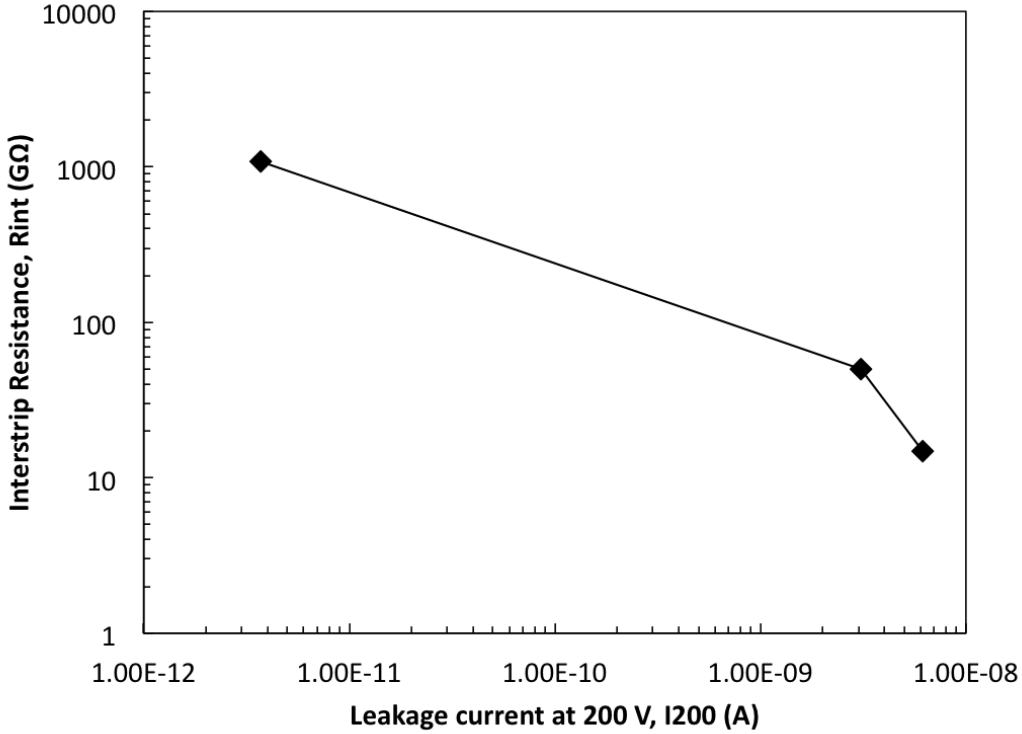
Radiation Damage Approximation





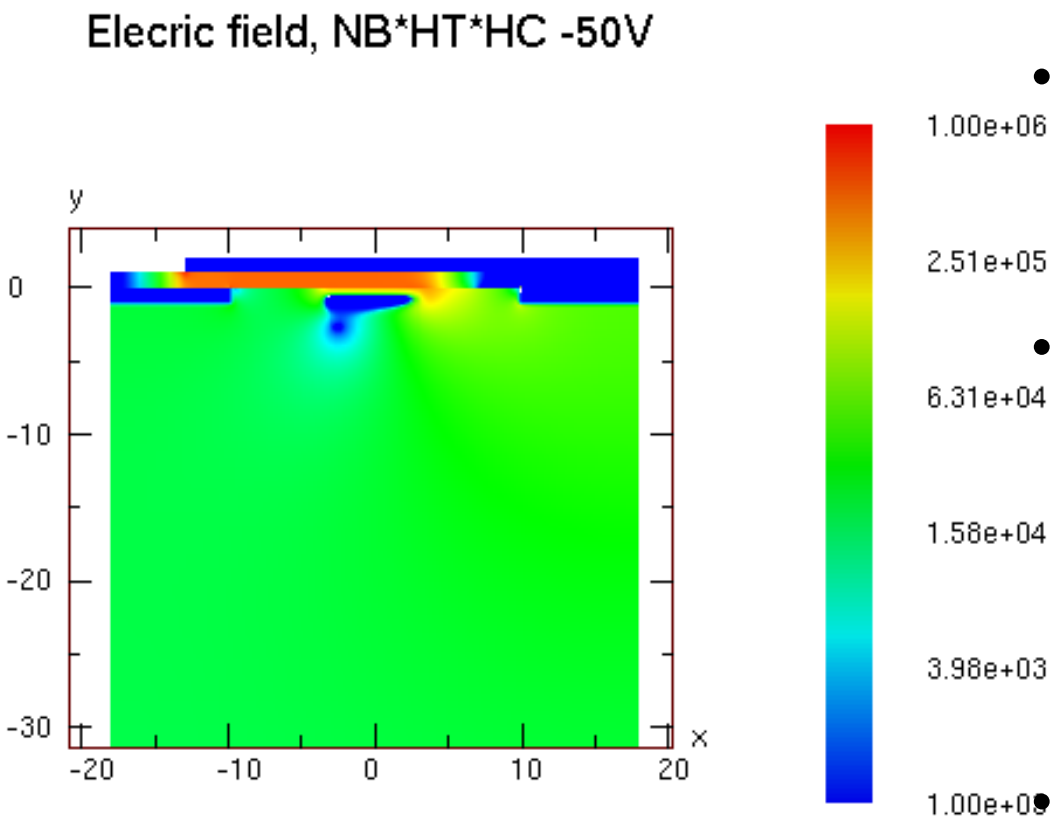
- Green: Irrad.
  - Increase of full depletion voltage, N_{eff}=1.5 × 10^{13} cm^{-3}
  - Increase of leakage current, A_n, A_p = 1 × 10^{-8}
- Black: non-irrad.
  - N_{eff}=4.7 × 10^{12} cm^{-3}, A_n, A_p = 1.0
- Potential in bulk, Leakage currents
  - Backplane at 200 V

Interstrip Resistance, R_{int}



- Decrease of interstrip resistance is qualitatively explained by the increase of leakage current (after irradiation).
  - Other factors, the effective doping concentration nor the oxide interface charge, do not change the interstrip resistance.
  - In retrospect, it is natural that the current is the other face of the resistance.

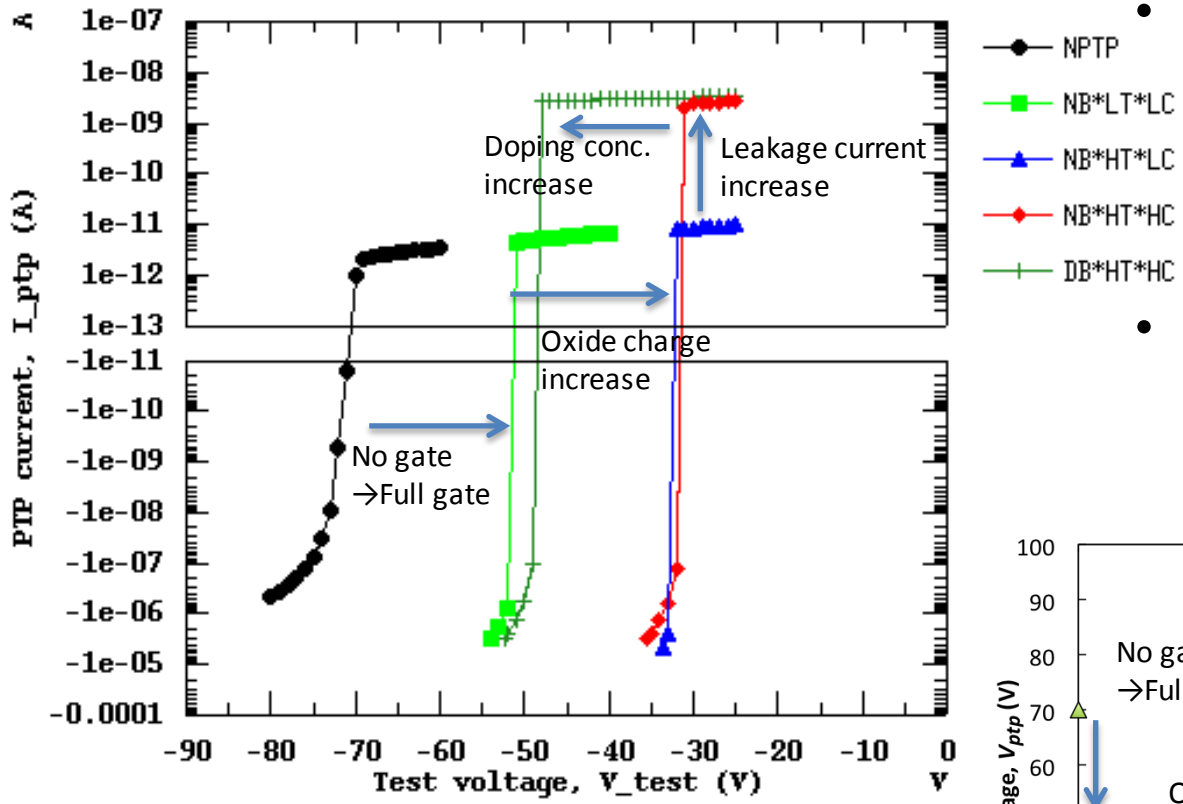
PTP Simulations



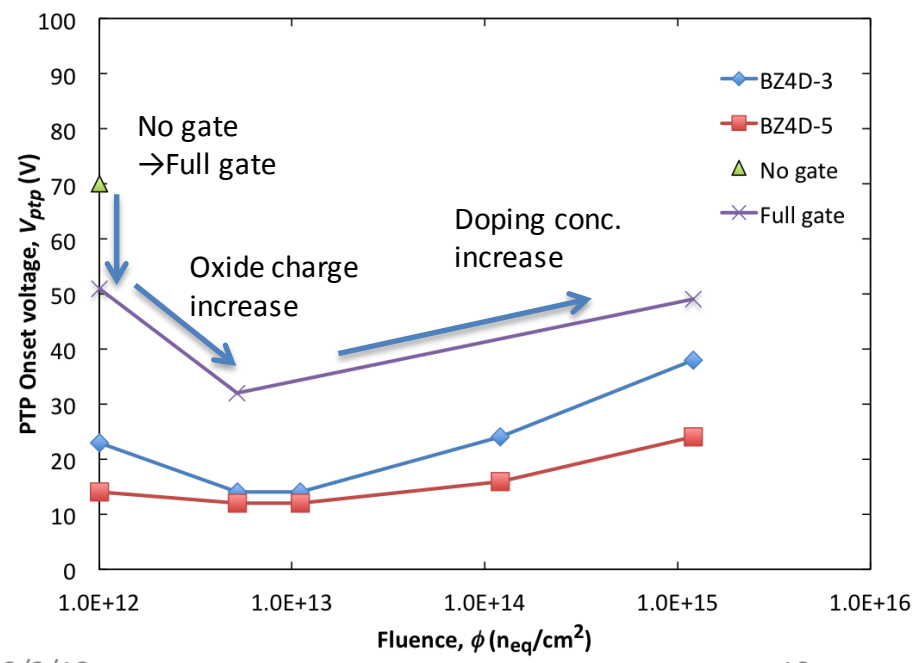
- TCAD
  - no bias resister in parallel
  - NPTP:“No gate”
  - Others: “Full gate”
- Parameters:
  - NB/DB: non/damaged bulk
  - LT/HT: lo/hi interface charge
  - LC/HC: lo/hi current
  - Non irrad: NB*LT*LC
  - Irrad: DB*HT*HC
- Irrad. simulation
  - Damaged bulk,
  - hi interface charge,
  - hi leakage current

TCAD simulation of
“Full gate” PTP, irradiated
Electric field at onset
when the backplane bias voltage at -200 V
V_{test} (left implant) at -50 V

PTP Simulations

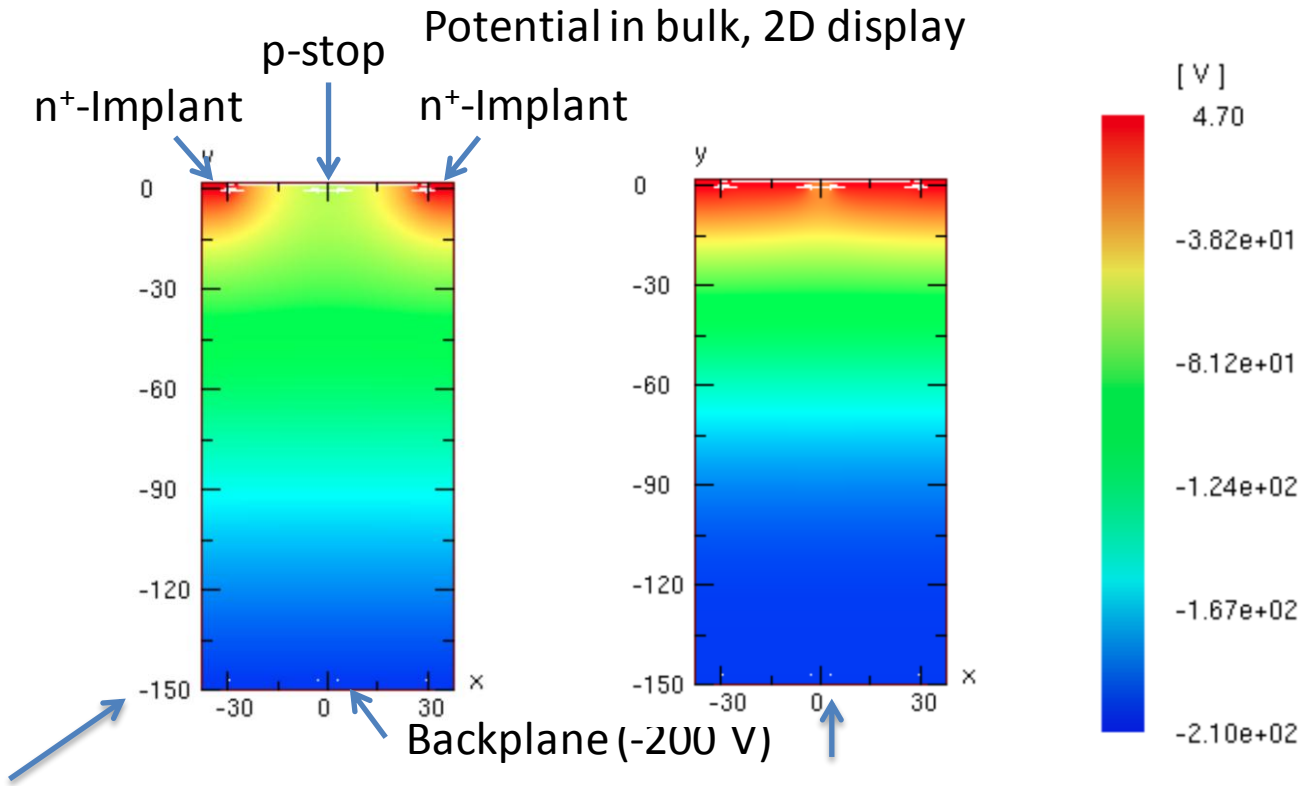


- The fluence dependence can be understood as the effect of
  - Build-up of the Interface charge and
  - Increase of acceptor-like levels.
- The systematic "offset"
  - difference between the 2D simulation and the 3D real.



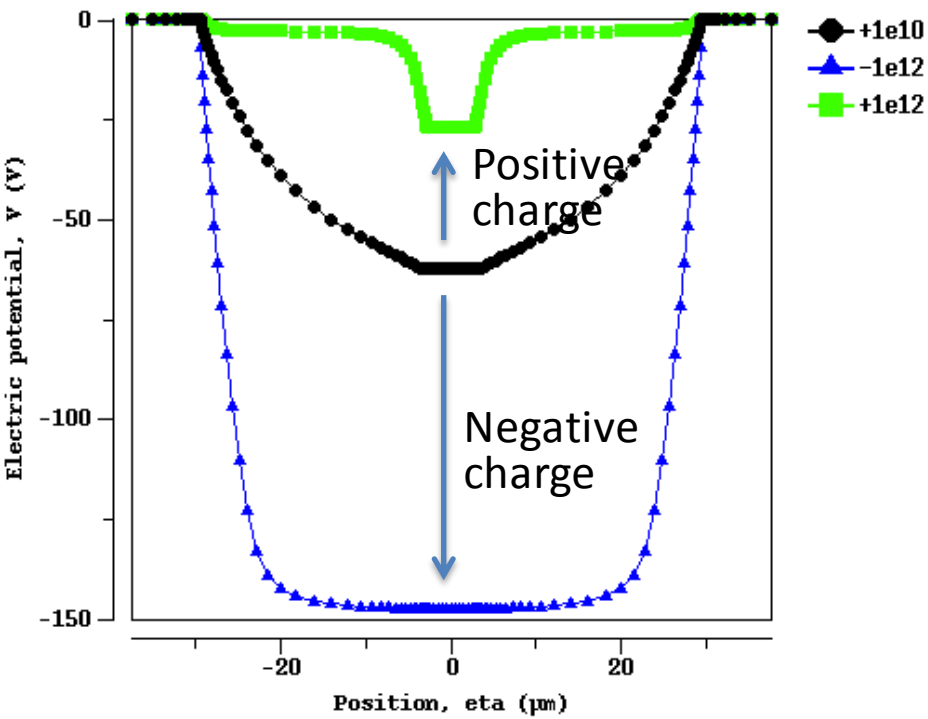
- Onset voltage decreased as
  - No gate (black) → Full gate (colored)
  - Interface charge increased
- Increased as
  - accepter-like state increased

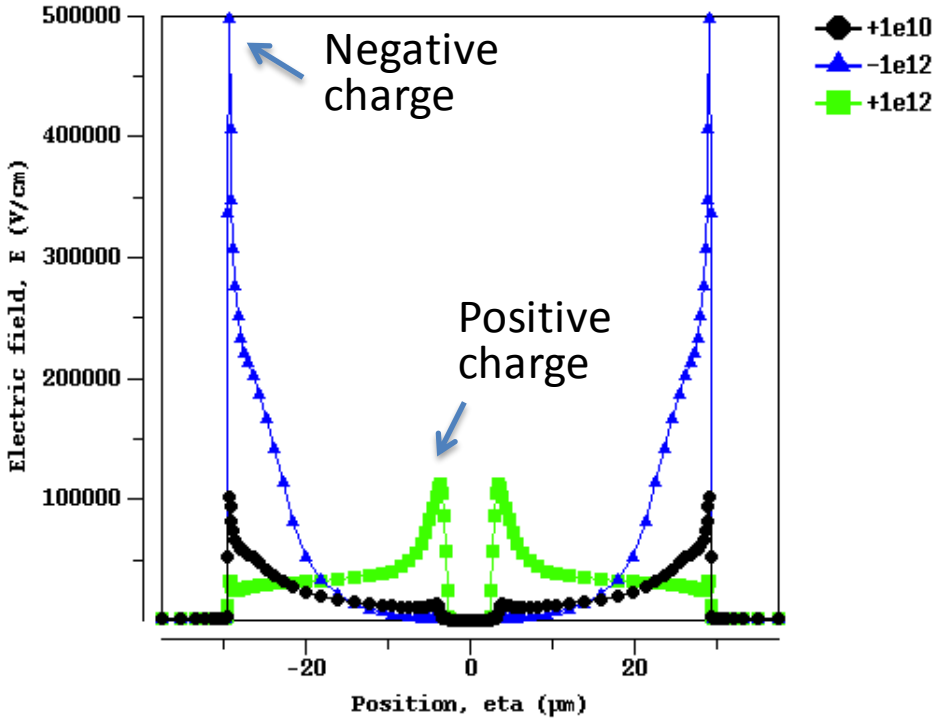
Electric potential of p-stop
- Introduction of Si-SiO_2 interface charge -



- Non-irrad:
  - N_{eff}=4.7 × 10^{12} cm^{-3},
  - SRH A_n, A_p=1.0,
  - Fixed Oxide Charge =1 × 10^{10} cm^{-2}
- Irrad:
  - N_{eff}=1.5 × 10^{13} cm^{-3},
  - SRH A_n, A_p=1 × 10^{-8} ,
  - Fixed Oxide Charge =1 × 10^{12} cm^{-2}

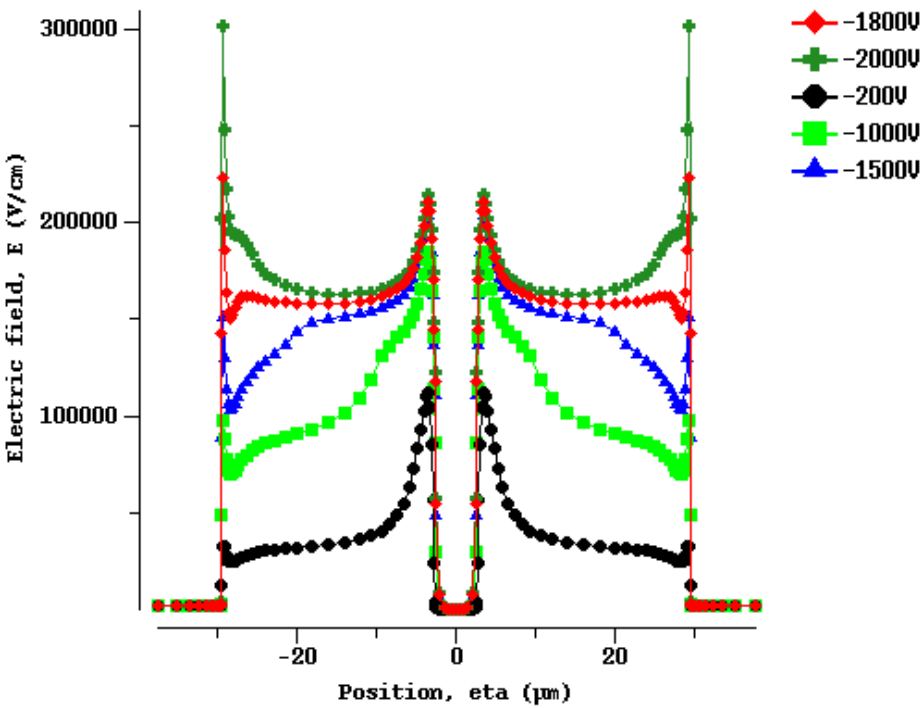
Electric Potential between Strips

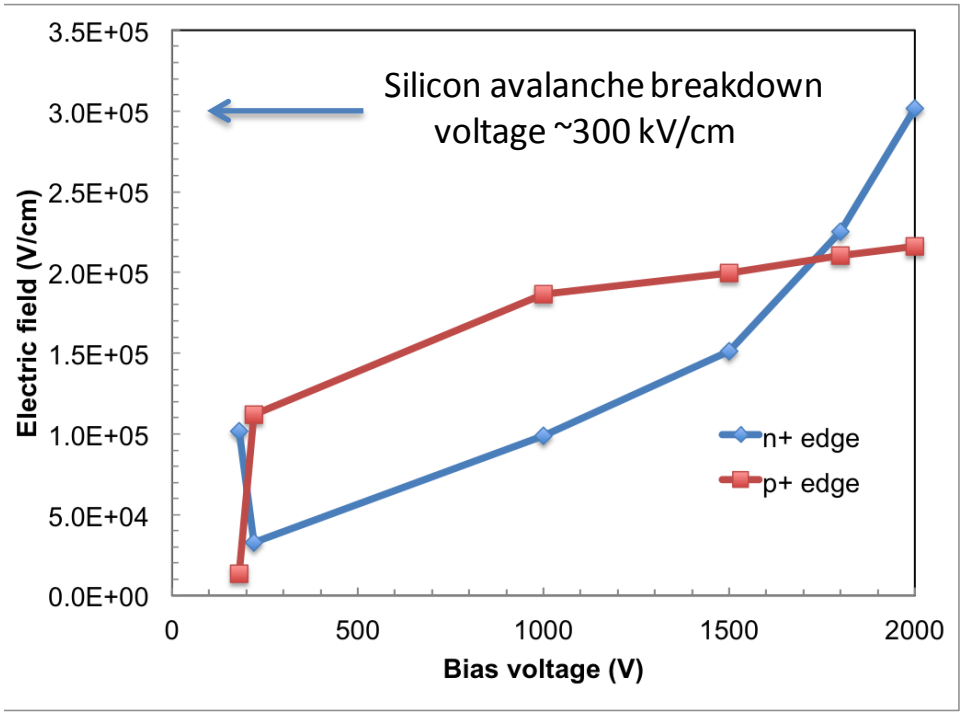




- Electric potential of p-stop
  - decreases as the interface charge increases positively,
  - increases as the interface charge increases negatively.
  - Measurement confirms that the built-up interface charge is positive.
- Location of the largest electric field is
  - at n-implant side with the positive interface charge of $+1\times10^{10}$ cm^{-2},
  - moves at the p-stop side with $+1\times10^{12}$.
  - The field is enhanced if the interface charge is negative, e.g., -1×10^{12}.

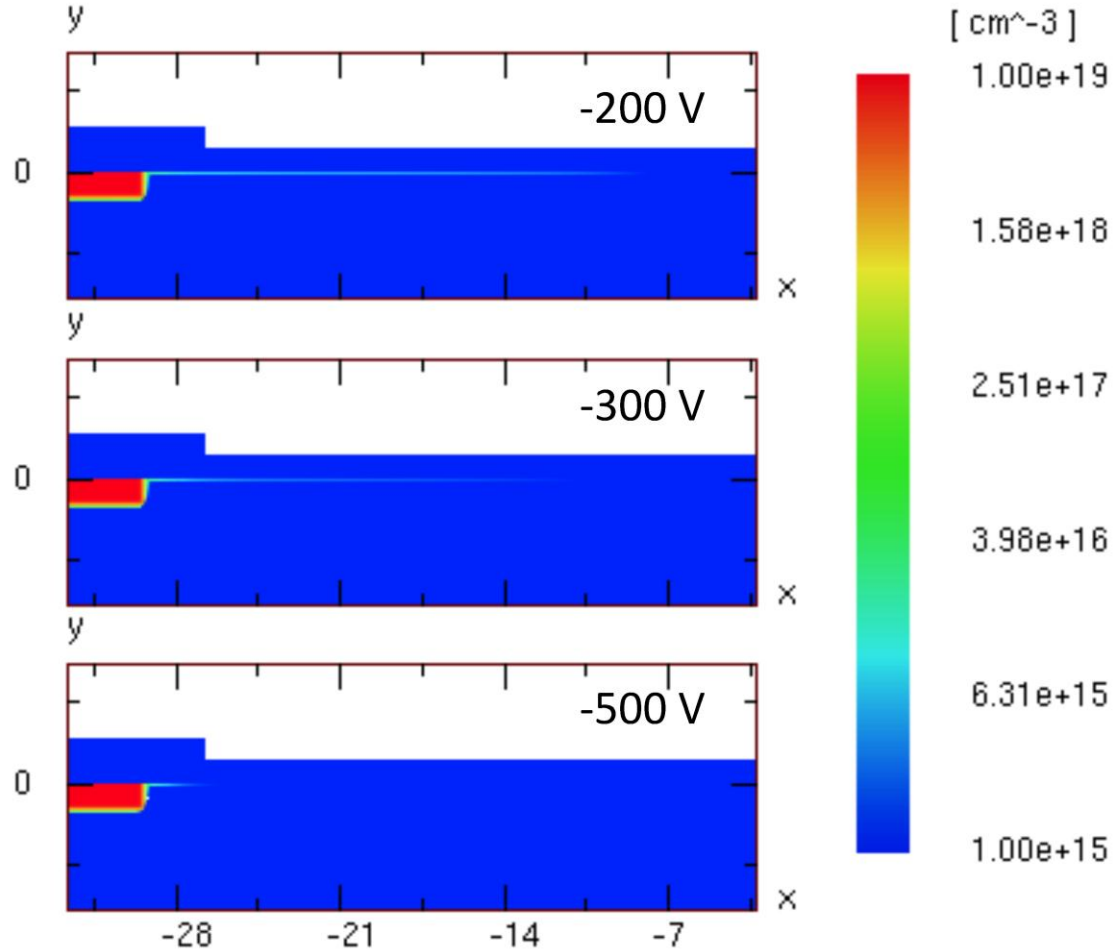
Breakdown at High Voltages





- Under the "Irradiated" condition, increasing the bias voltage to the limit.
- Breakdown occurs at high voltage at the n^+ edge, although the p-stop edge was the highest electric field at lower bias voltages.
- The rate to increase of the electric field at the p-stop edge is saturating at higher voltage.
- The p-n junction eventually overtakes the highest electric field by the time of breakdown.

Insight into what is happening



- Electron inversion layer is diminishing
  - as the bias voltage is being increased.
  - This also explains that in p-bulk the bias voltage helps to isolate the n^+ implants.
- A triumph of TCAD ☺/~

Summary

- Performance of various structures in the n-in-p silicon sensors, before and after irradiation, has been measured and understood.
- Fluence dependence is understood as:
  - Decrease of the interstrip resistance is the effect of radiation damage that leads to the increase of leakage current.
  - Decrease of electric potential of the p-stop structure is the build-up of the Si-SiO_2 interface charges that is positive.
  - Decrease and increase of PTP onset voltage is the build-up of the interface charges AND the increase of effective doping concentration by radiation damage.
- Location of microdischarge at high voltages is
  - at the n^+ edge, and not the p^+ edge, and
  - understood as the effect of diminishing electron inversion layer from the interstrip region and the faster increase of electric field at the p-n junction at the n^+ edge.