Study of Behaviour of Silicon Sensor Structures, Before and After Irradiation

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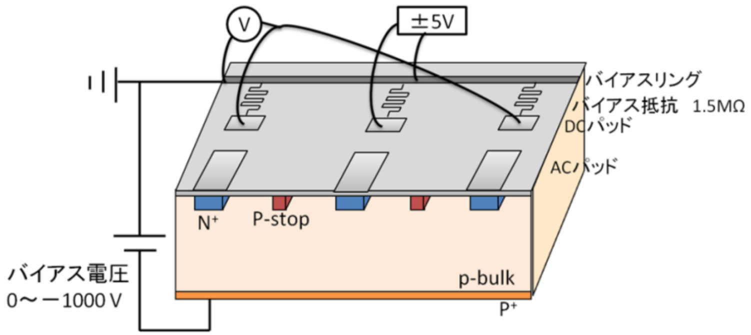
Proton Irradiations at CYRIC

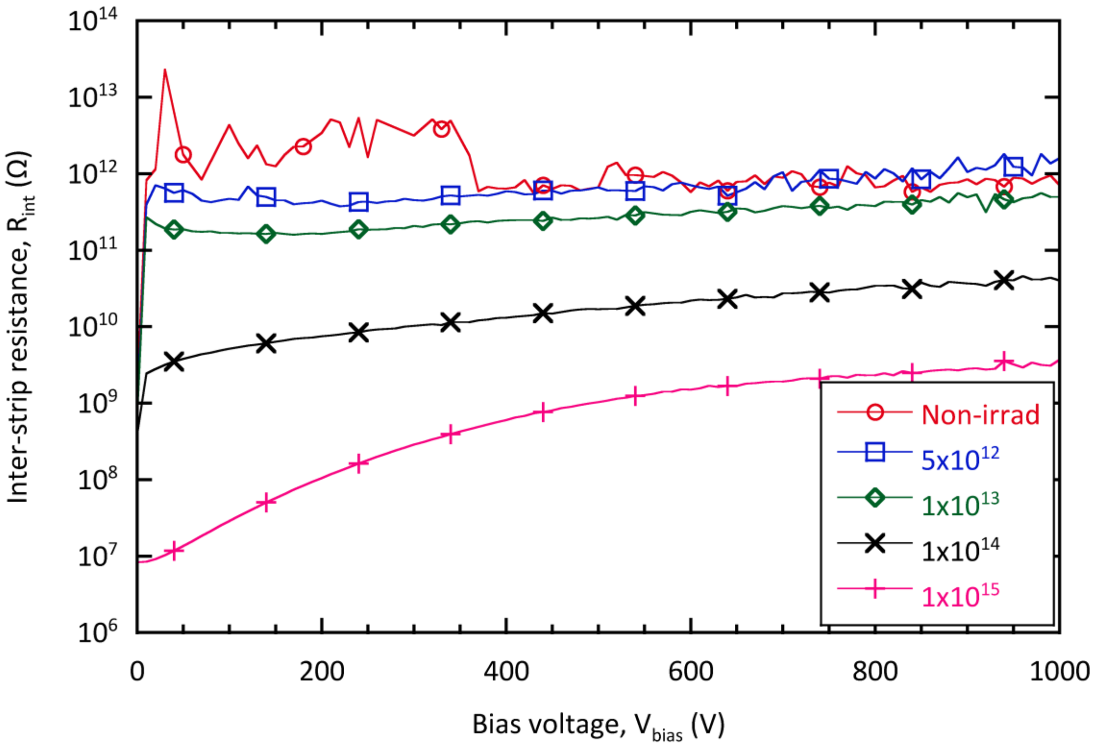
- 70 MeV protons from 930AVF Cyclotron
- Irradiation setup in the 32 course
  - CYRIC exp. no. 9214
- Fluences:
  - 5.2×10^{12}, 1.1×10^{13}, 1.2×10^{14}, 1.2×10^{15}

Structures and Measurements

- Inter-strip resistance between two strips,
- Electric potential of p-stop structures,
- Onset voltages of Punch-Through Protection (PTP) structures,
  - as a function of fluence

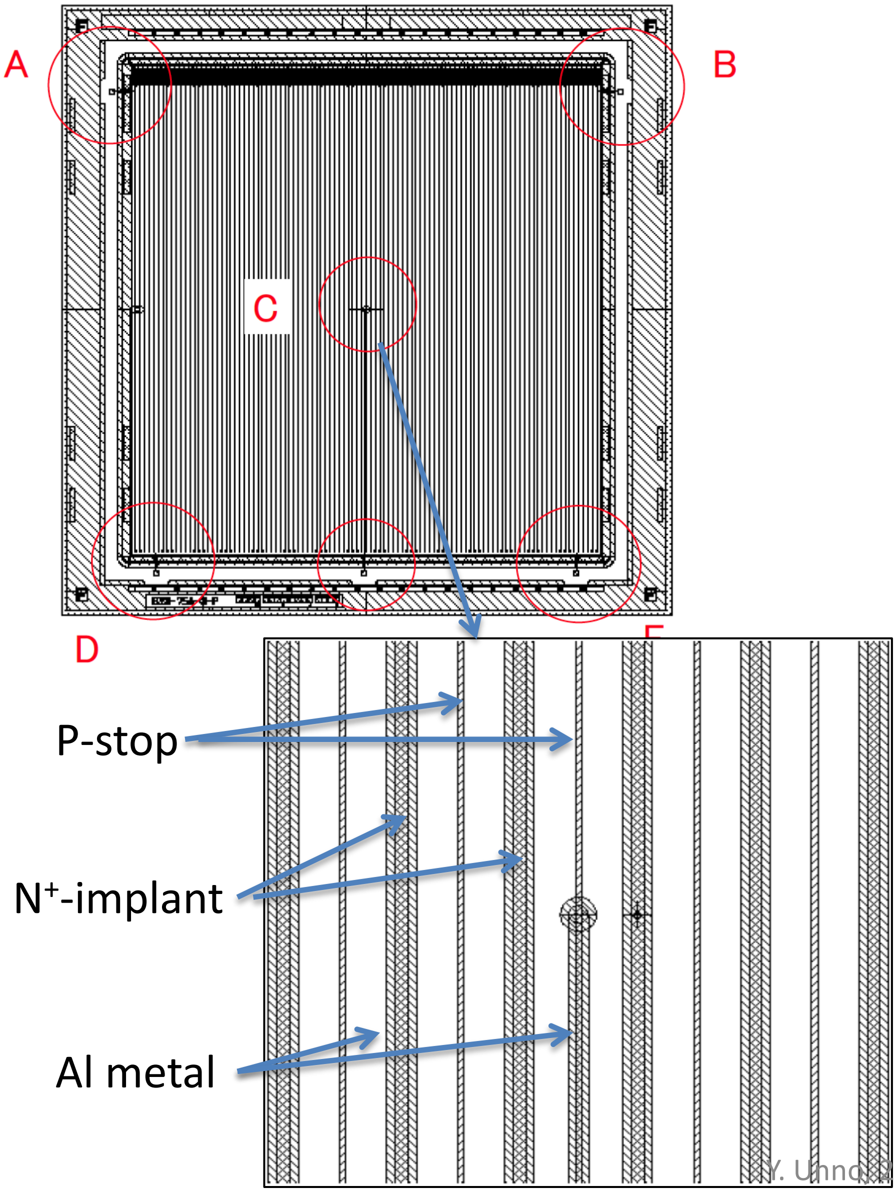
Inter-strip Resistance

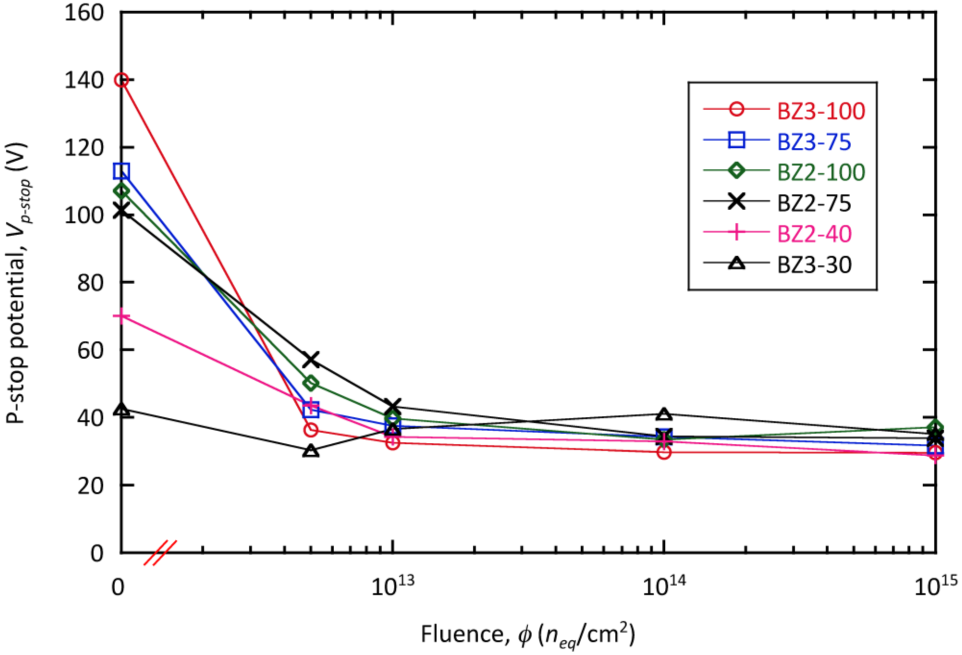




- Inter strip resistance decreased as the fluence was accumulated.
  - It is due to the “radiation damage”, but which factor?

Potential of P-stop Structure

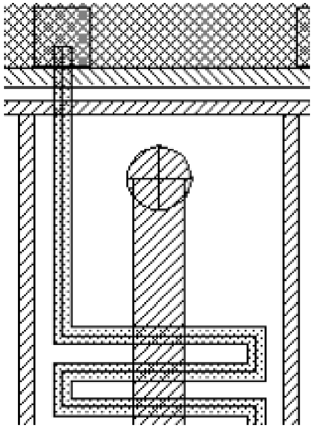




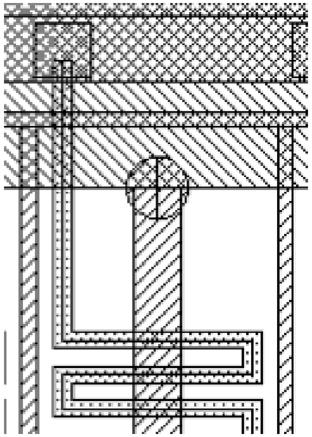
- Electric potential of p-stop implant decreased first (around 1×10^{13}) and then saturated.
  - It sounds familier…

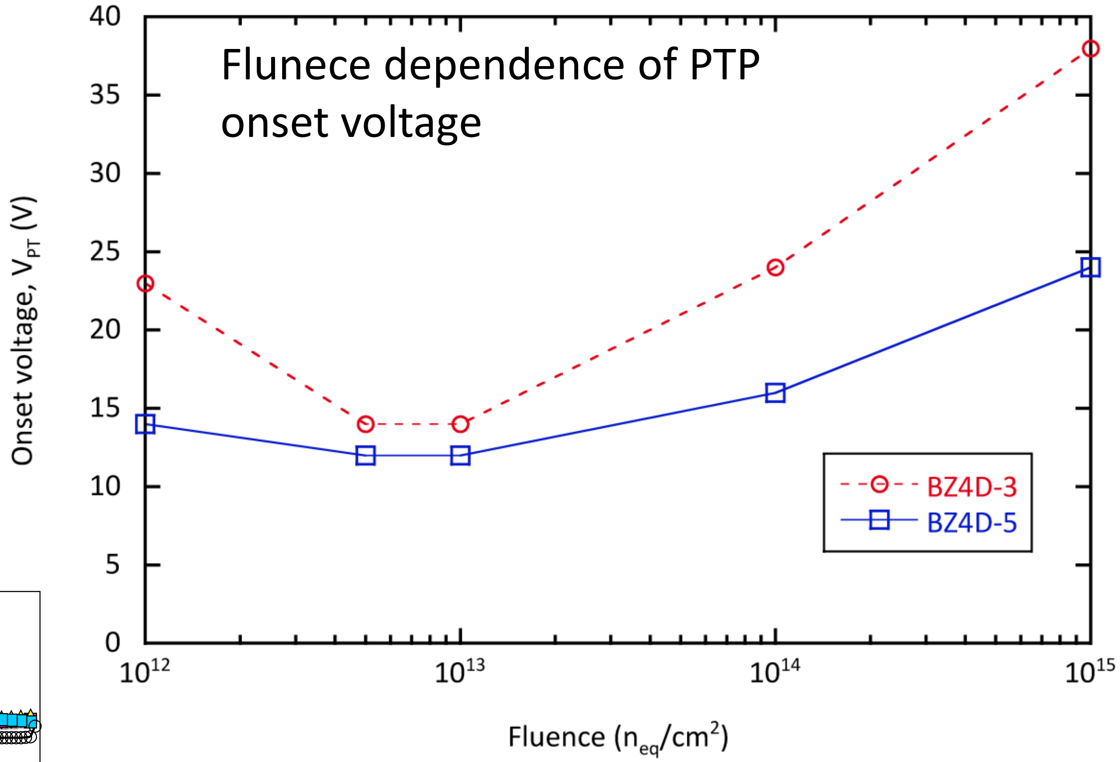
Punch-Through Protection (PTP) Structure

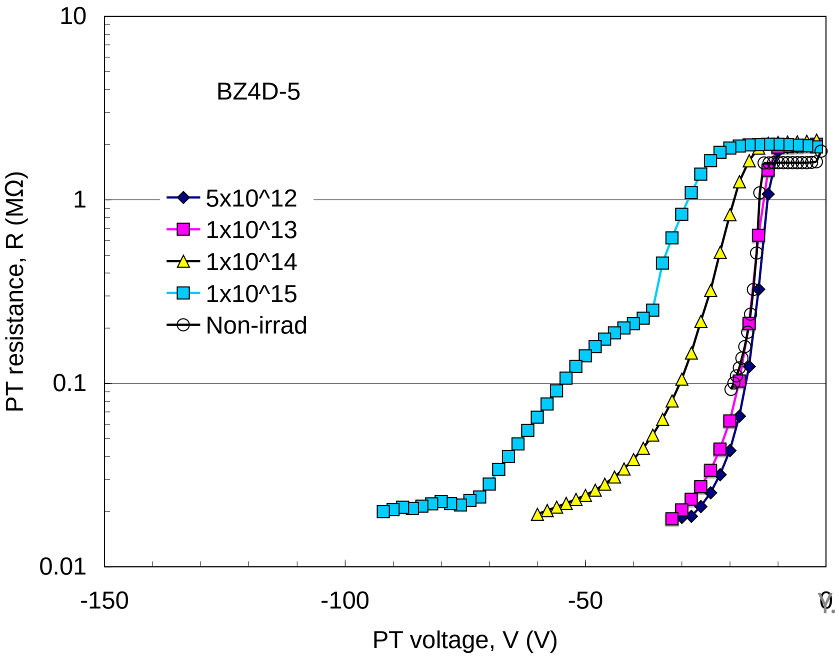
BZ4D-3
(No gate)



BZ4D-5
(Full gate)







- "Full gate" induced PTP onset in lower voltages than "no gate".
- Onset voltage went down first and then started increase.
    - Why/how?

TCAD Simulation

- Semiconductor Technology Computer-Aided Design (TCAD) tool
  - ENEXSS 5.2, developed by SELETE in Japan
  - Device simulation part: HyDeLEOS
- N-in-p strip sensor
  - 75 µm pitch, p-stop $4\text{x}10^{12}$ cm^{-2}
  - 150 µm thickness
  - p-type bulk, $N_{eff}=4.7\times10^{12}$ cm^{-3}, $V_{FDV}=80$ V at 150 µm
- Radiation damage approximation:
  - Increase of acceptor-like state → Bulk resistivity
  - Increase of leakage current → SRH model tuning
  - Increase of interface charge → Fixed oxide charge

Shockley-Reed-Hall (SRH) Model

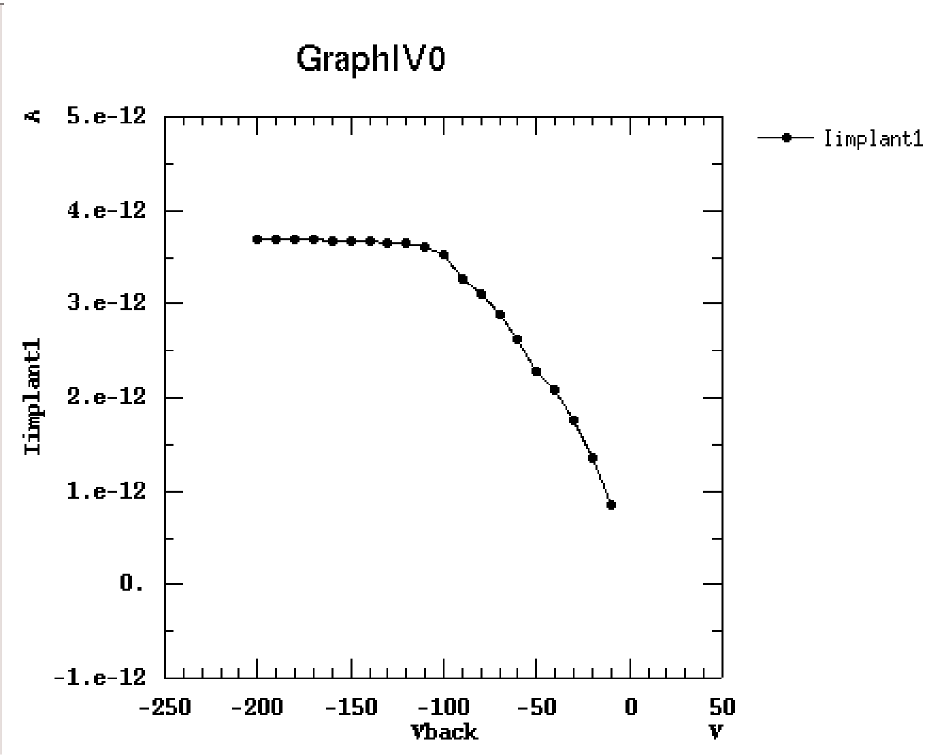
- After irradiation, the current increases as a function of fluence as
  - $\Delta I / V \sim 4 \times 10^{-17}$ (A/cm) × ϕ (n_{eq}/cm^2)
  - E.g.,
    - Volume = 75 µm x 1 µm x 150 µm = 1.13×10^{-8} cm^3
    - $\phi = 1 \times 10^{15}$ n_{eq}/cm^2
    - $\Delta I \sim 45$ nA
- Leakage current: SRH model

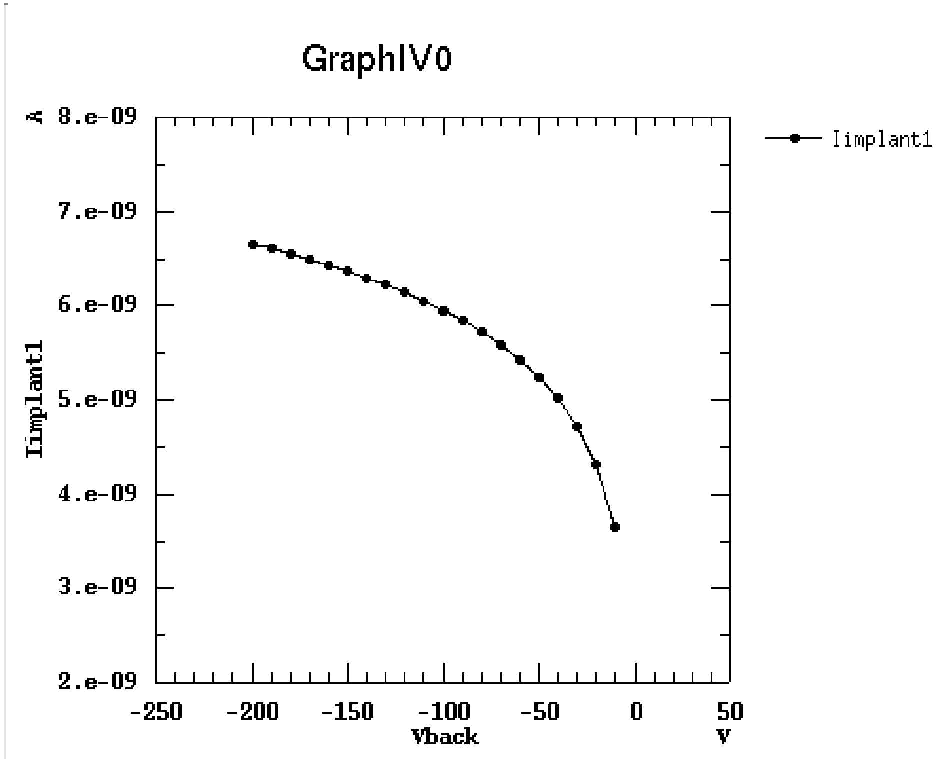
$$U_{SRH} = \frac{n_i^2 - pn}{\tau_p\left(n + n_i\right) + \tau_n\left(p + n_i\right)}$$

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

  - A_n, A_p, etc. are model parameters.

Increase of Leakage Current

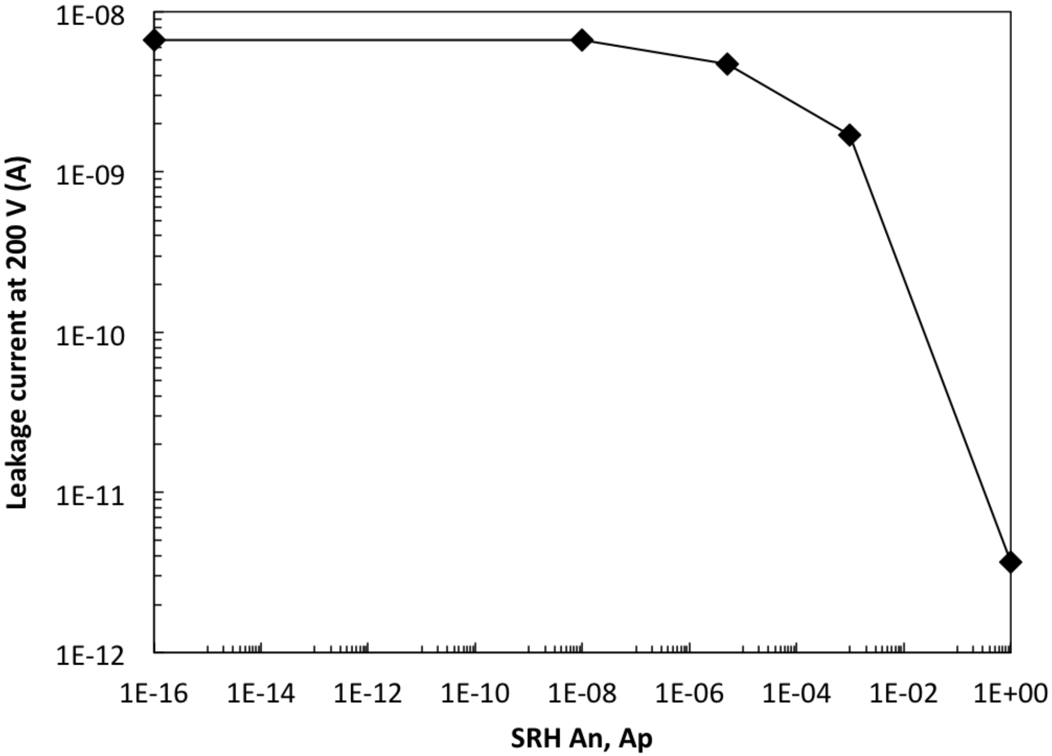




- SRH A_n, A_p = 1.0 (default)
- Saturated current ~3.7 pA

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

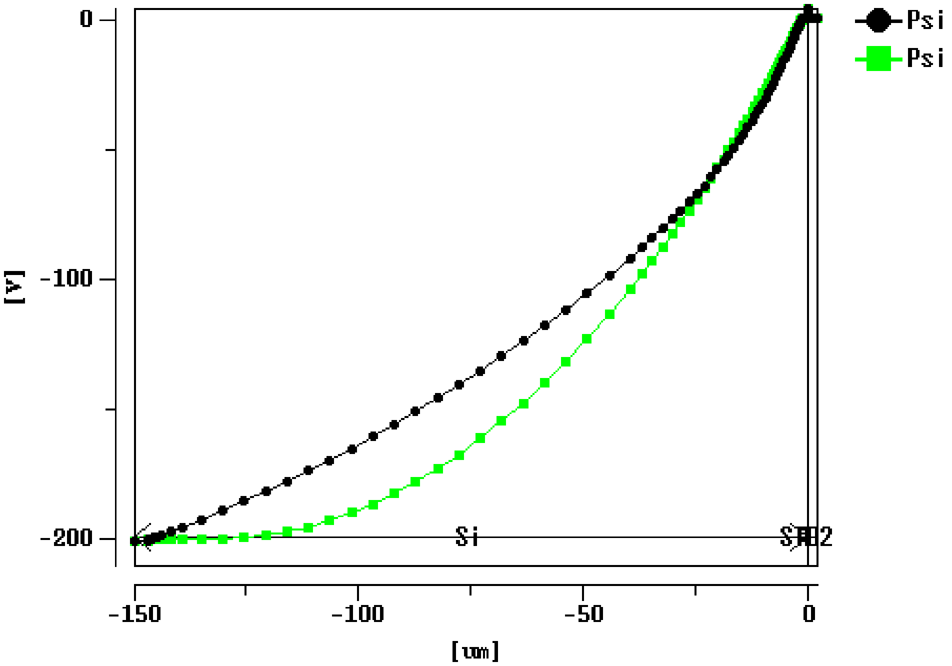
Leakage Current at 200 V



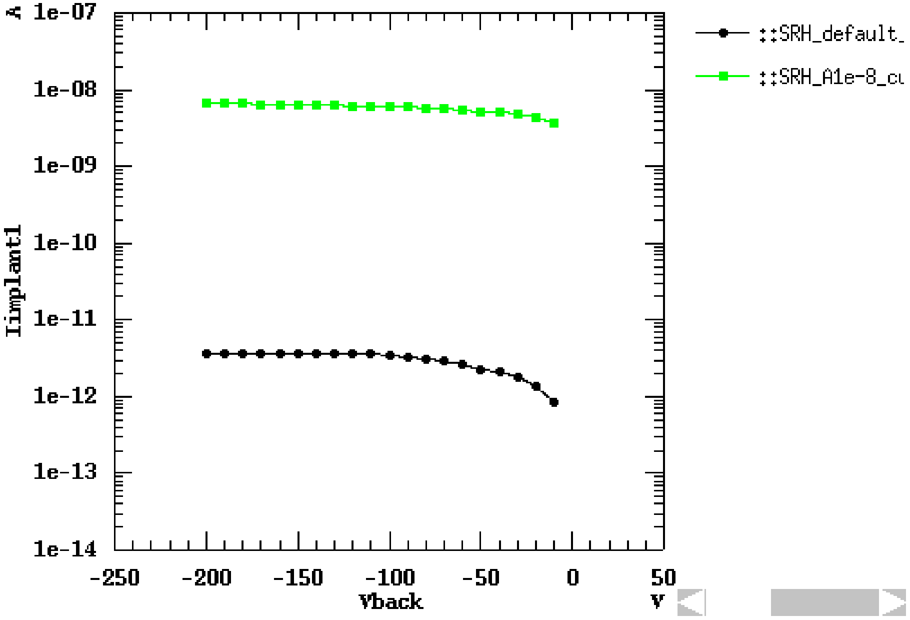
- Leakage current can be increased by 3 orders of magnitude by varying the SRH modeling parameter, A_n and A_p.
  - Current saturates when A_n, $A_p < 1 \times 10^{-8}$
  - Current can be tuned by a factor between 1 and 10^3

Radiation Damage Approximation

Potential in bulk

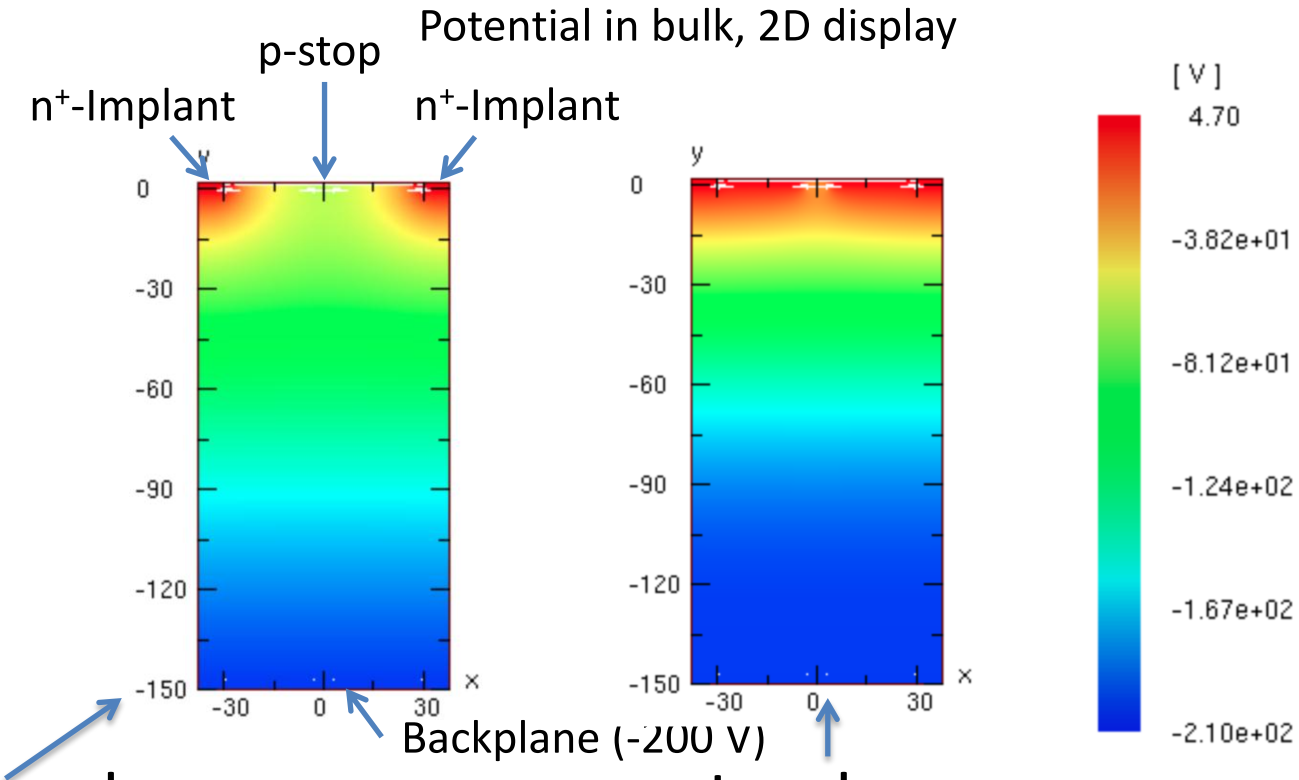


Leakage current



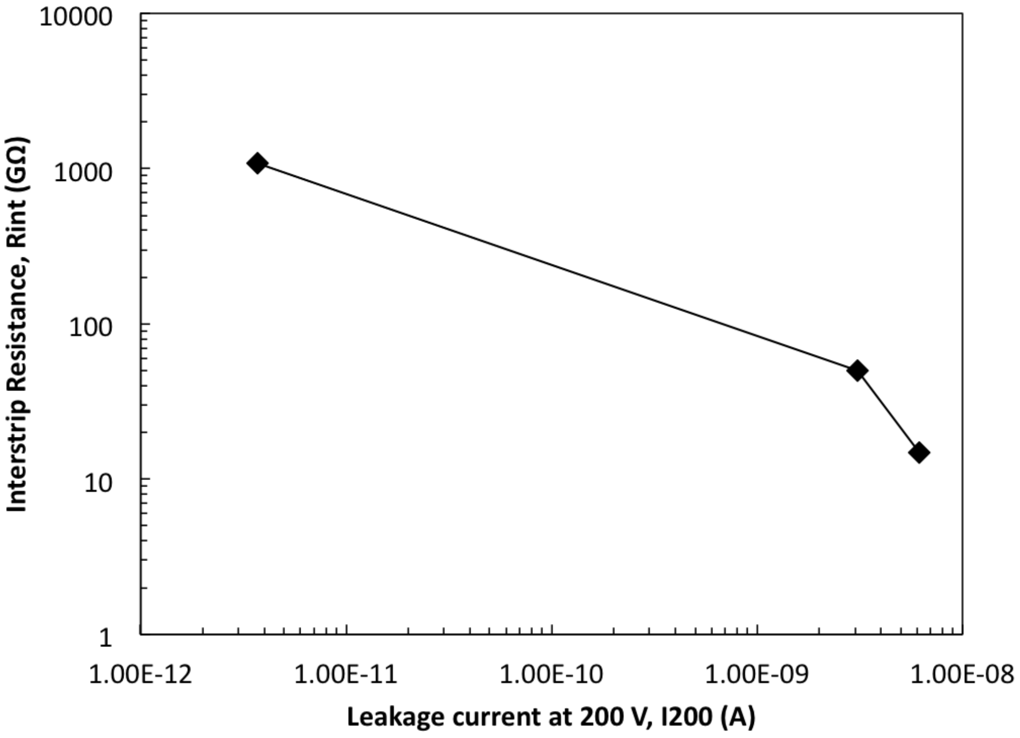
- Green: Irrad.
  - Increase of full depletion voltage, N_{eff}=1.5 × 10^{13} cm^{-3}
  - Increase of leakage current, A_n, A_p = 1 × 10^{-8}
- Black: non-irrad.
  - N_{eff}=4.7 × 10^{12} cm^{-3}, A_n, A_p = 1.0
- Potential in bulk, Leakage currents
  - Backplane at 200 V

Si-SiO_2 Interface Charge Approximation



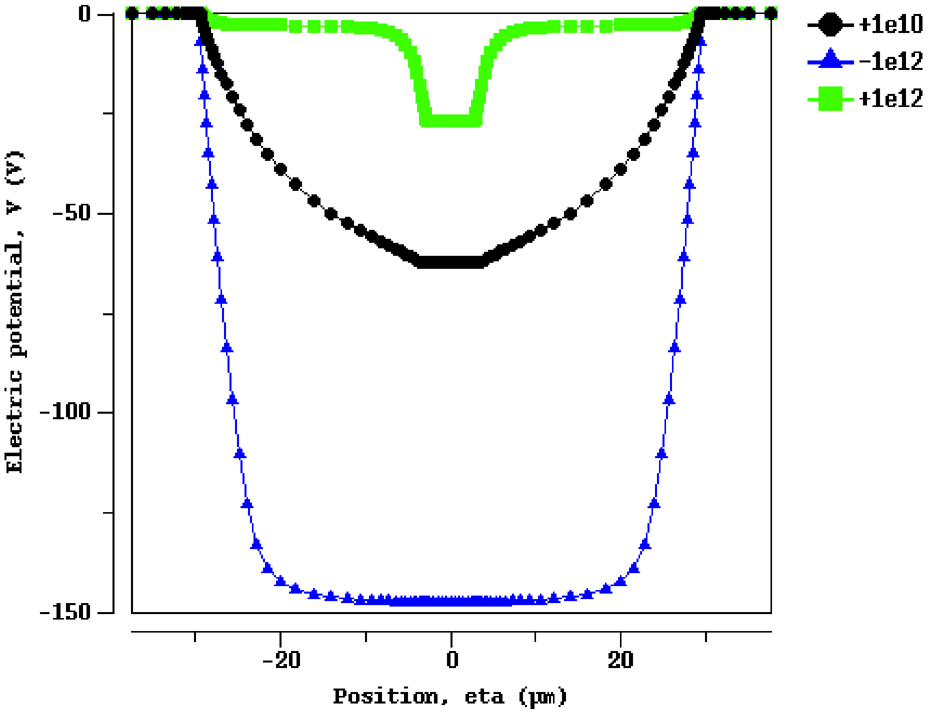
- Non-irrad:
  - N_{eff}=4.7 × 10^{12} cm^{-3}, SRH A_n, A_p=1.0
  - Fixed Oxide Charge (FOC)=1 × 10^{10} cm^{-2},
- Irrad:
  - N_{eff}=1.5 × 10^{13} cm^{-3}, SRH A_n, A_p=1 × 10^{-8}
  - Fixed Oxide Charge (FOC)=1 × 10^{12} cm^{-2},

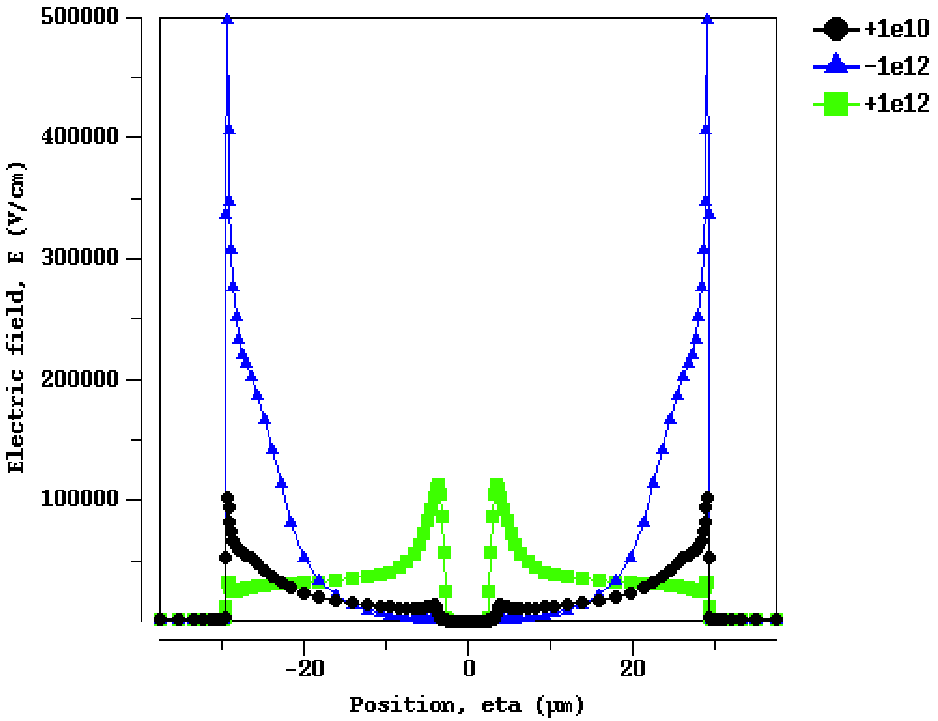
Interstrip Resistance, R_{int}



- Decrease of interstrip resistance can be qualitatively explained by the increase of leakage current (after irradiation)

Electric Potential between Strips





- Electric potential of p-stop decreases or increases as the interface charge increases positively or negatively, respectively.
- Location of the largest electric field is at n-implant side with the positive interface charge of +1x10^{10} cm^{-2}, moves at the p-stop side with +1x10^{12}. The field is enhanced if the interface charge is negative, e.g., -1x10^{12}.

Microdischarge After γ Irradiation

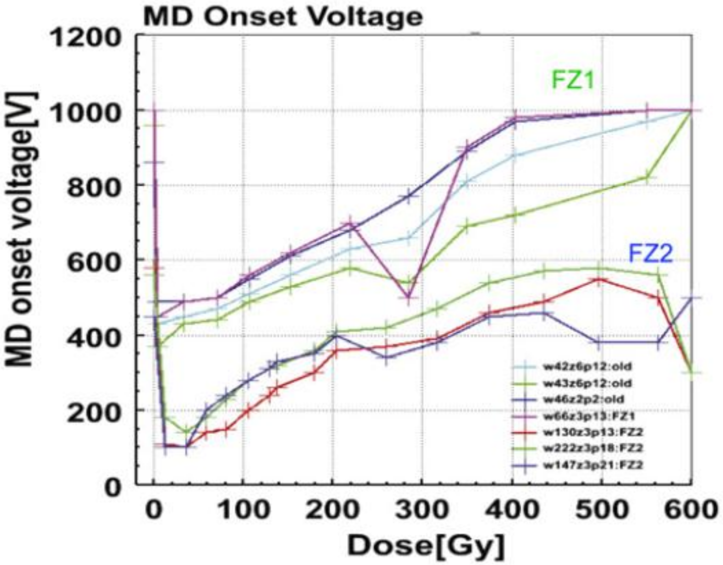


Fig. 4. Micro-discharge onset voltage vs. accumulated dose, measured at 200 V bias and 200 Gy/h. The two clusters of the curves correspond to FZ1 and FZ2 wafers.

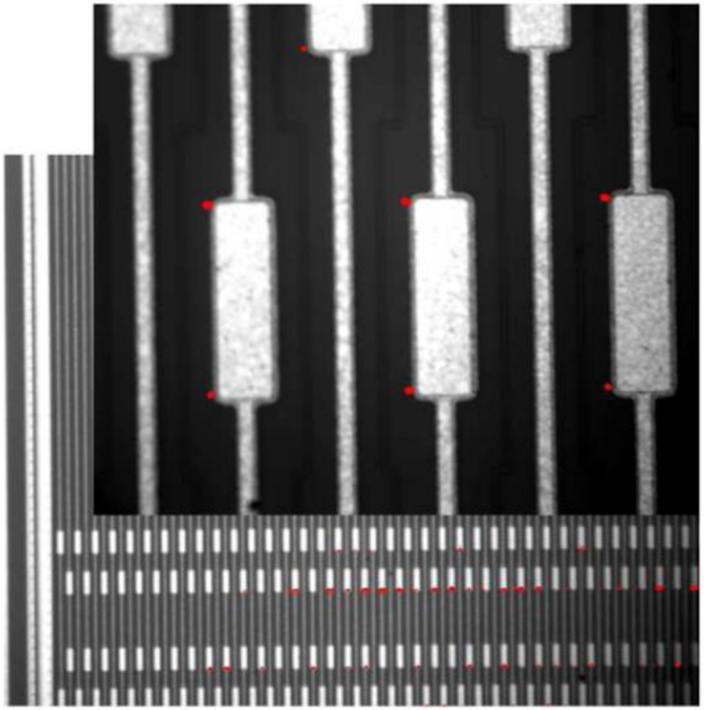
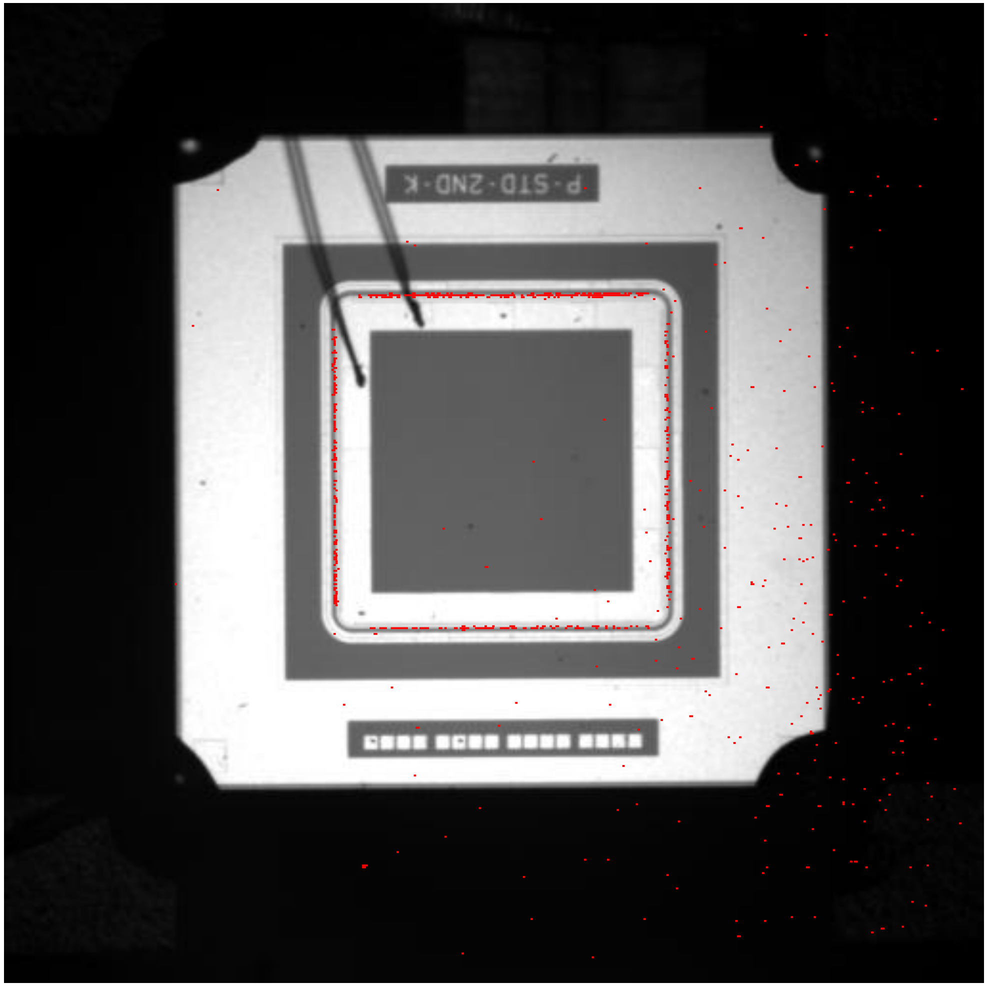


Fig. 9. Hot spots observed at AC pad corners. The AC pad is 60 μm wide and 200 μm long.

- After g irradiation, onset of microdischarge occured at the n-implat edges, instead of p-stop, and "annealed" along the accumulation of dose.
  - http://dx.doi.org/10.1016/j.nima.2012.04.031
- MD at n-implant edge could be a "corner" effect, but ...
- How can the "annealing" effect be understood with the TCAD...

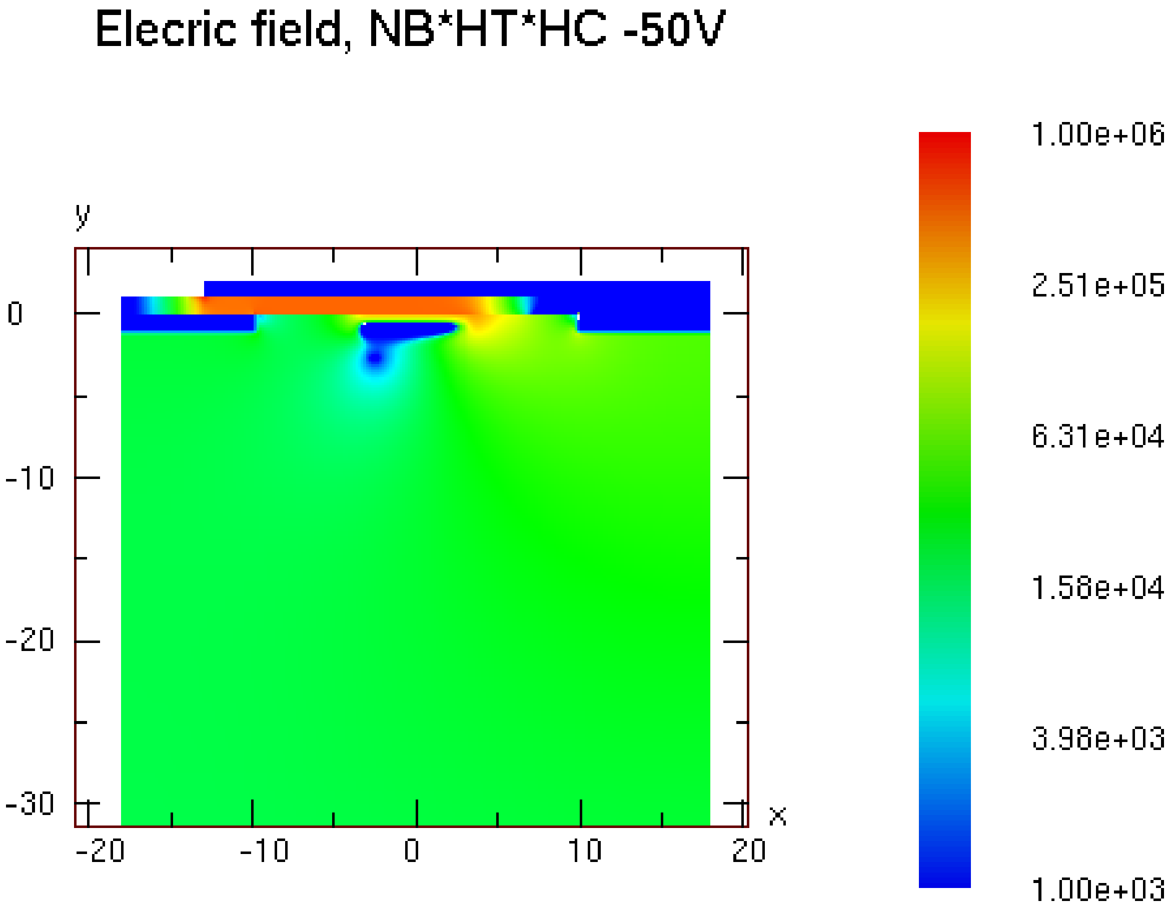
Microdischarge After Irradiation



CYRIC irradiation
$1\text{x}10^{14}$ neq/cm^2
10uA at 2000 V
-15 ° C

- Hot electron images confirm that
  - the highest electric field is
  - in the bias ring (n$^+$ implant)
  - not in the edge ring (p$^+$ implant)

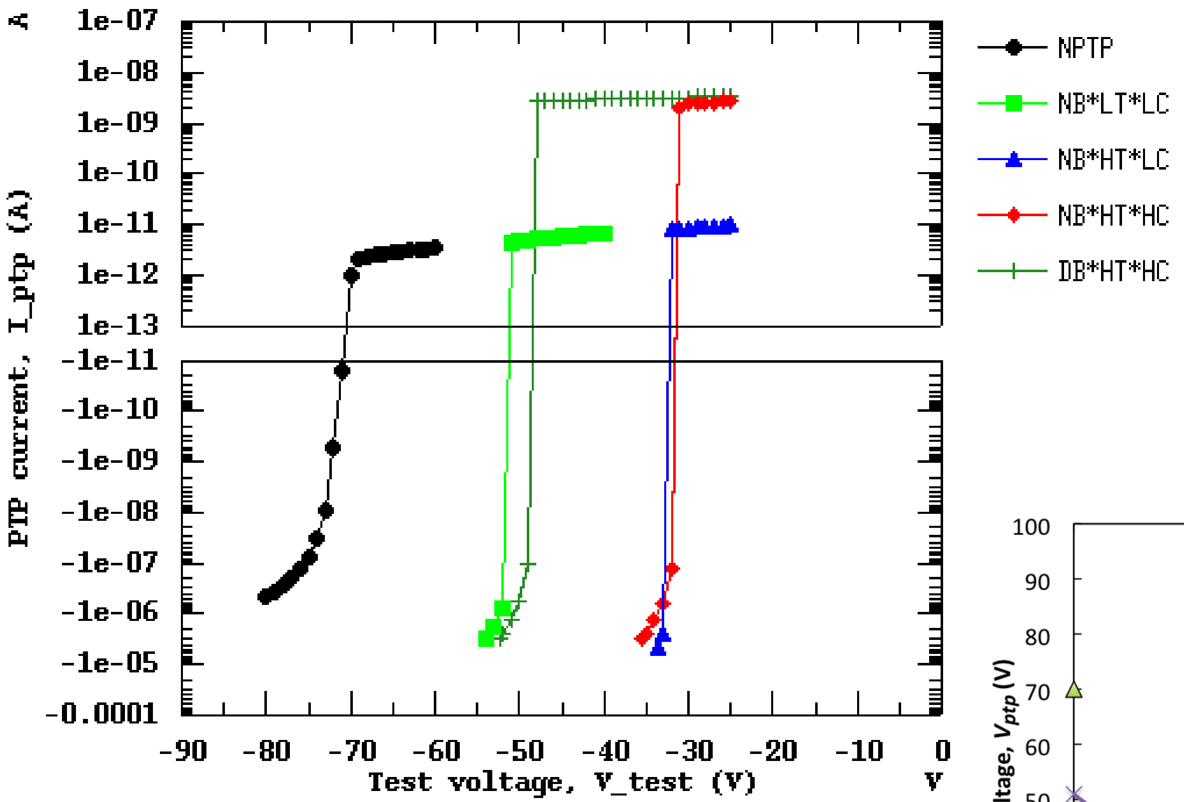
PTP Simulations



TCAD simulation of “Full gate” PTP, irradiated
Electric field at onset
Backplane -200 V
V_test (left implant) -50 V

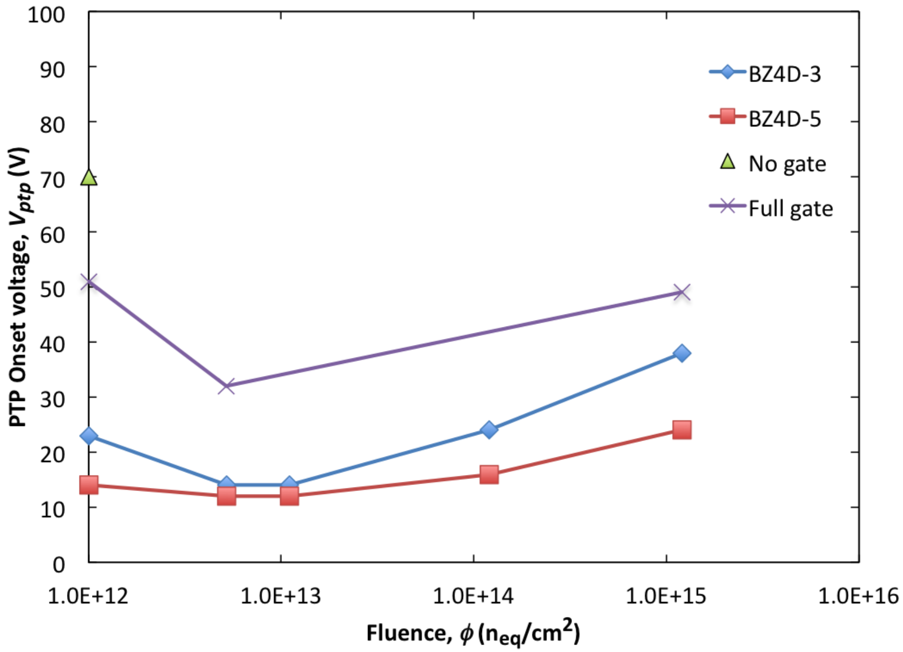
- TCAD
  - no bias resister in parallel
  - NPTP:“No gate”
  - Others: “Full gate”
- Parameters:
  - NB/DB: non/damaged bulk
  - LT/HT: lo/hi interface charge
  - LC/HC: lo/hi current
  - Non irrad: NB*LT*LC
  - Irrad: DB*HT*HC
- Irrad. simulation
  - Damaged bulk,
  - hi interface charge,
  - hi leakage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

PTP Simulations



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

- The fluence dependence can be understood as the effect of
  - Build-up of the Interface charge and decrease of bulk resistivity
- Understanding of the systematic "offset" is the remaining issue.



Summary

- Performance of various structures in the silicon sensors, especially of silicon microstrip sensors, have been studied, before and after irradiation.
- Fluence dependences are understood as:
  - Interstrip resistance as the effect of increase of leakage current.
  - Electric potential of the p-stop structures as the effect of the interface charge build-up.
  - PTP onset voltage as the effect of interface charge build-up and the increase of acceptor-like states in the silicon bulk.
- We still have remaining issues to understand, such as
  - the onset of microdischarge in the n-implant edge, instead of p-stop edge,
  - "annealing" of the onset voltages in the γ irradiation,
  - the systematic offset of the PTP onset voltage between the measurement and the TCAD simulations.