Simulation of Irradiated Si Detectors

Ranjeet Dalal, Kirti Ranjan, Ashutosh Bhardwaj, Geetika Jain, Kavita Lalwani

Department of Physics and Astrophysics,

University of Delhi, INDIA

Contents

Simulation approaches for irradiated sensors : Up to now !

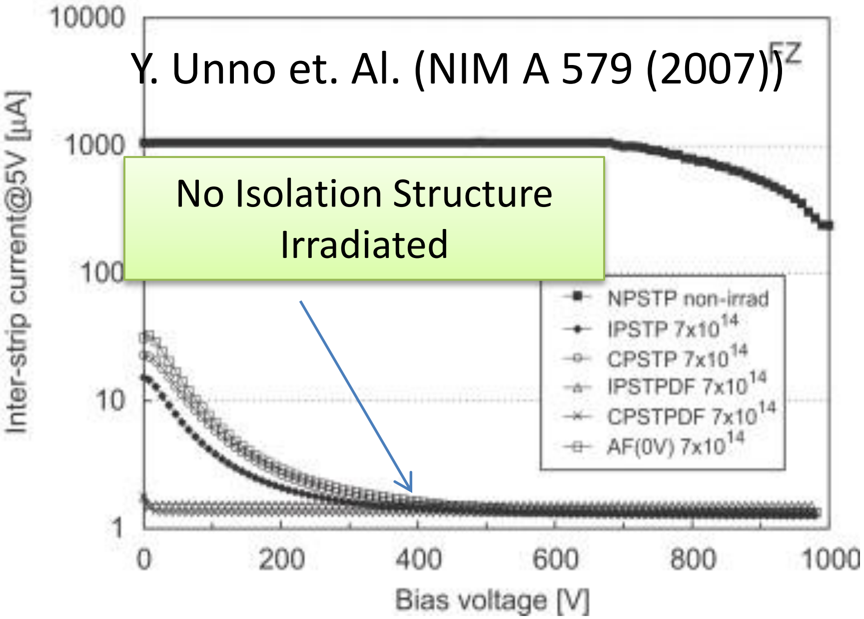
-Either considered Surface damage only or considered Bulk damage only
- Only Oxide charge density (Q_F) variation was taken into account for Surface damage; **No interface trap state included!**

No simulation study which incorporate Bulk + Surface damage simultaneously !

Simulation using Surface damage only	Simulations using Bulk damage only
1. G. Verzellesi & G.F. Dalla Betta **Nucl. Sci. Symp., 2000 IEEE (Vol.-1)** Compact modeling of n-side interstrip resistance in p-stop and p-spray isolated double-sided silicon microstrip detectors	1. V. Eremin et al. NIM A 476 (2002) 556–564 The origin of double peak electric field distribution in heavily irradiated silicon detectors
2. P. Claudio (2006) IEEE Trans. ON Nucl. Sci., VOL. 53, NO. 3 Device Simulations of Isolation Techniques for Silicon Microstrip Detectors	2. M. Petasecca *et al.* NIM A 563 (2006) 192–195 Numerical simulation of radiation damage effects in p-type silicon detectors
3. Y Unno et al. NIM A 636 (2011) S118–S124 Optimization of surface structures in n-in-p silicon sensors using TCAD simulation	3. V. Chiochia et al., IEEE Trans. Nucl. Sci. NS-52 (2005) 1067 Simulation of Heavily Irradiated Silicon Pixel Sensors and Comparison With Test Beam

Some puzzling observations !

➢ Very good interstrip resistance values (Rint) are observed for n-on-p Si sensor with very low p-stop (~ $5x10^{15}cm^{-3}$) and p-spray doping densities (~$1x10^{15}cm^{-2}$) even after very high proton fluences (~$1x10^{15}cm^{-2}neq$) (CMS-HPK tracker phase-II upgrade study)
➢ Good Rint was reported [see right] for n-on-p strip sensors, irradiate with high proton fluences, having no insulation structures !



Oxide charge density (Q_F) appears to be suppressed in the hadron irradiated sensors!

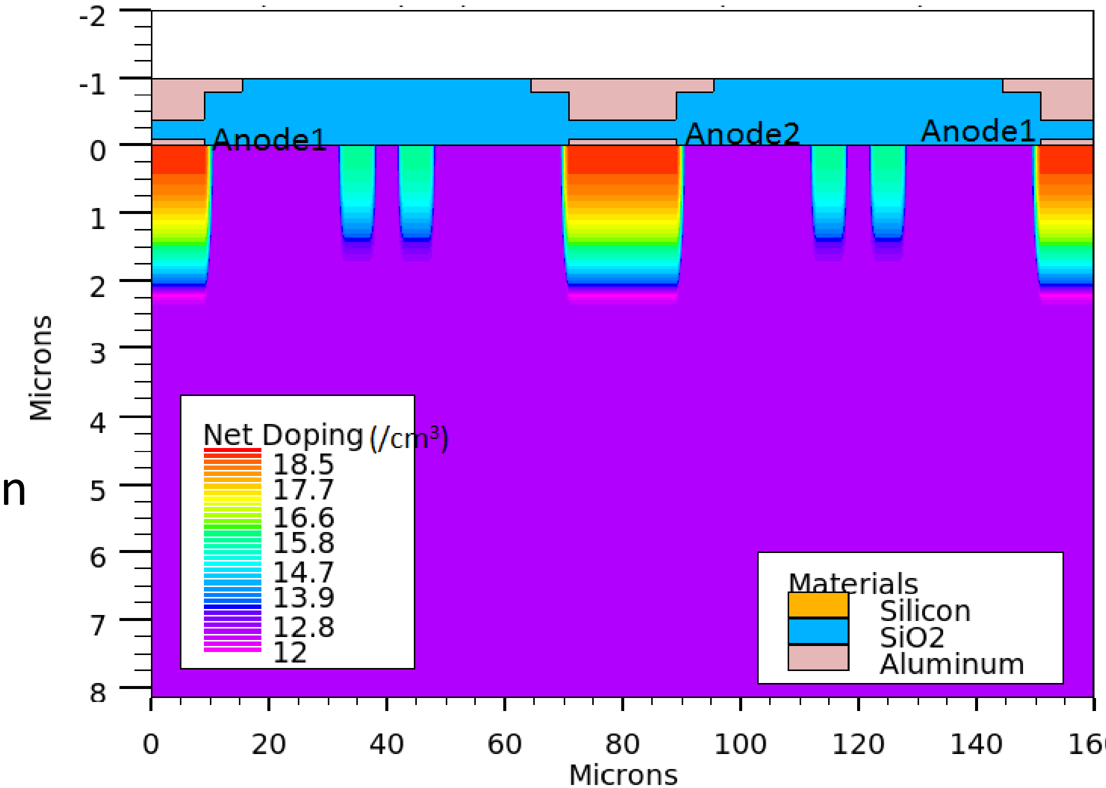
➢ From eTCT measurements and earlier Bulk damage simulations, higher electric fields are expected near n^+ strips compare to p^+ strip; so n-on-p strip sensors should show lower breakdowns at higher fluences

But p-on-n type strip sensors are found to be much more prone to microdischarge!

These observations (and many others) can be understood as combine effects of Bulk and Surface damage (Q_F and N_{it} both) !

Simulation structure

- Bulk doping = $3x10^{12}cm^{-3}$
- 2-D simulations
- Double p-stops
- Each 4µm wide separated by 6µm
- P-stop doping = $5x10^{15}cm^{-2}$
  P-stop doping depth = 1.6um
- CMS HPK tracker upgrade campaign
  parameters



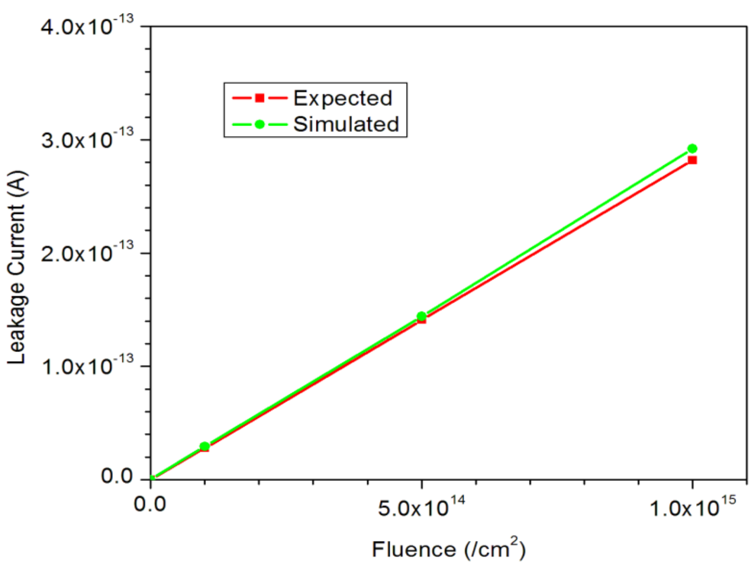
❑ <u>*Three strips structure*</u> was used for R_{int} simulations in which bias of 0.2V is given to Central DC Anode while two neighboring Anodes are shorted together. Reverse bias is provided from backside contact (not shown here)

❑ Simulations are carried out using Silvaco TCAD tool. (For details on meshing, boundary conditions, models etc., see last vertex talk by Mathieu Benoit)

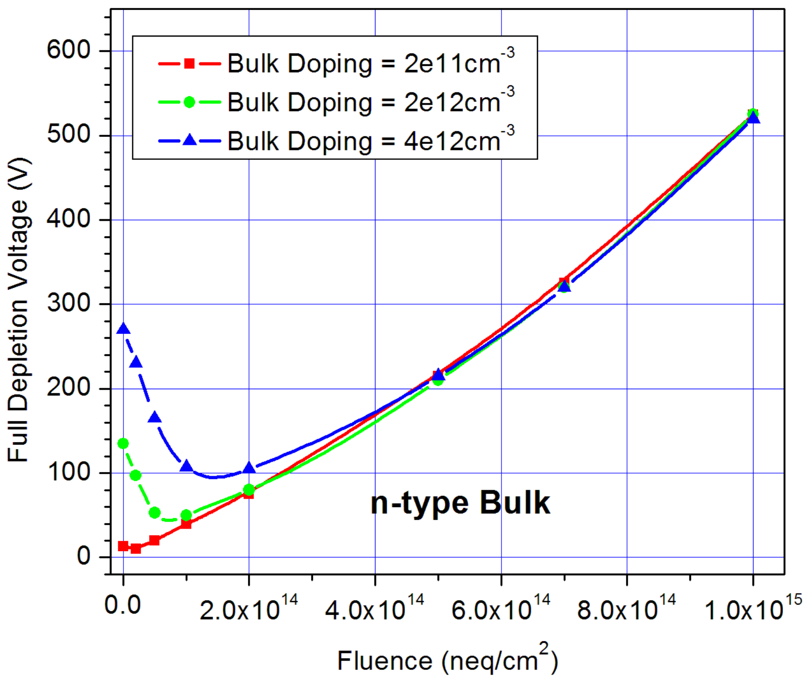
Bulk + Surface damage model

Bulk damage model (for proton irradiation)
-Produce experimentally measured currents for irradiated diodes
- Correct full depletion voltages (say, ~500V for 1e15neq/cm2 fluence of proton irradiation)
- Produces electric fields from both sides
 (See Kramberger's eTCT measurements for charged hadrons, presented in last Vertex)

Trap	Energy Level (eV)	Intro.	σ_e (cm^{-2})	σ_h (cm^{-2})
Acceptor	E_C - 0.51eV	4	2x10^{-14}	2.6x10^{-14}
Donor	E_V + 0.48eV	3	2x10^{-14}	2x10^{-14}



Leakage current comparison (@253K) for 1x1x300µm diode

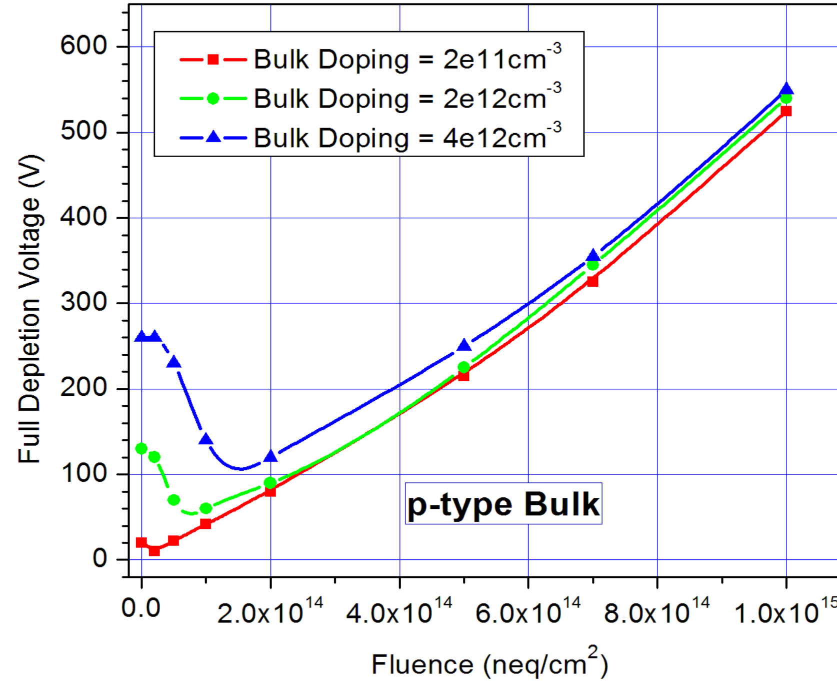


Simulated V_{FD} for different fluences for three n-type different bulk doping

Double junction effect on V_{FD}

- Initial V_{FD} drop for all of the three bulk doping
- V_{FD} minimum for bulk doping 2e11cm^{-3} happen at very low fluence but for higher bulk doping, V_{FD} minimum is at higher fluence

One is tempted to attribute this effect as "Donor Removal" and "Acceptor Removal" but we have not used any donor/acceptor removal term in the simulations !

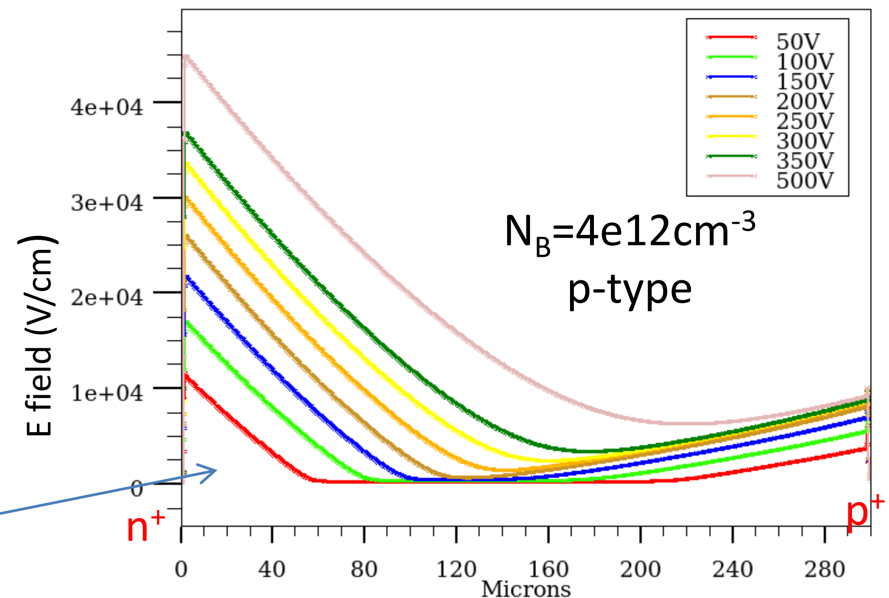


The initial lowering of V_{FD} is simply due to the double junction effect in irradiated Si

- Due to the double junction effect, depletion of charge carriers starts from both sides of Si diode
- Due to depletion from the both ends, Si diodes is depleted at lower V_{FD} bias , for initial fluences.
- There may not be any need for the "Donor/Acceptor Removal" terms.

- See my 24th RD-50, talk for further discussions!

E field across the diode bulk for different bias for Fluence=5e14neq/cm^2

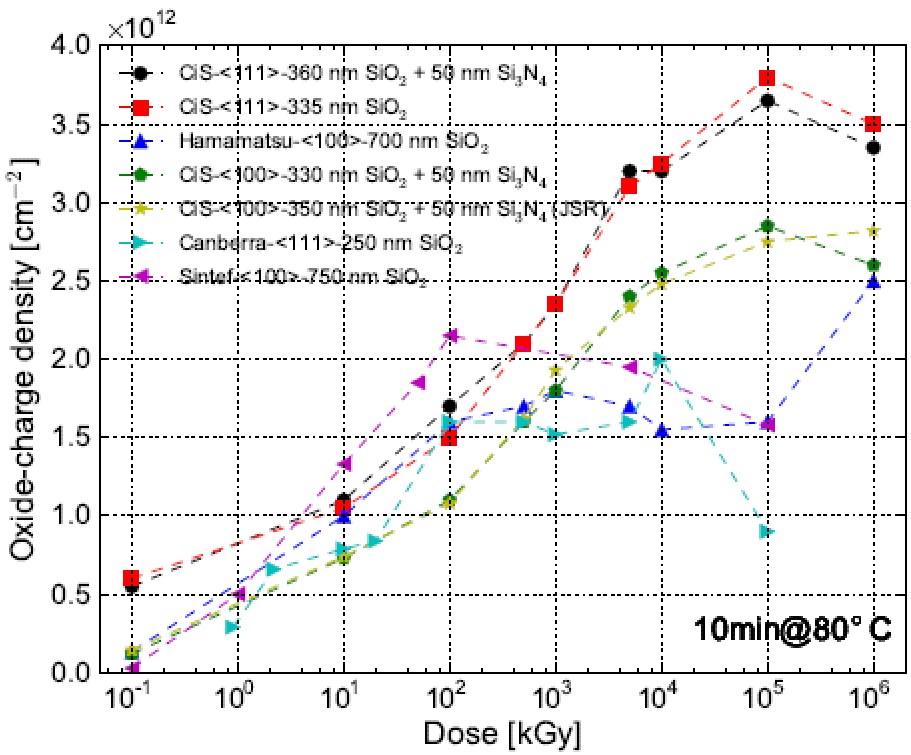


Surface damage- Oxide charge density (Q_F)

- Surface damage is incorporated using the Oxide charge density (Q_F) and Interface state density (N_{it})
- Oxide charge density (Q_F) is a complex function of fabrication process, annealing steps, humidity etc.
- Hence, instead of taking one value of Q_F, Oxide charge density is incorporated in simulations by considering range of Q_F for a given fluence.

Irradiation fluence (neq/cm^2)	Range of Q_F (cm^{-2})
0	5e10 to 5e11
1x10^{14}	1e11 to 8e11cm-2
5x10^{14}	5e11 to 1.2e12
1x10^{15}	8e11 to 2e12

Ranges of Oxide charge density (Q_F) used for different fluences

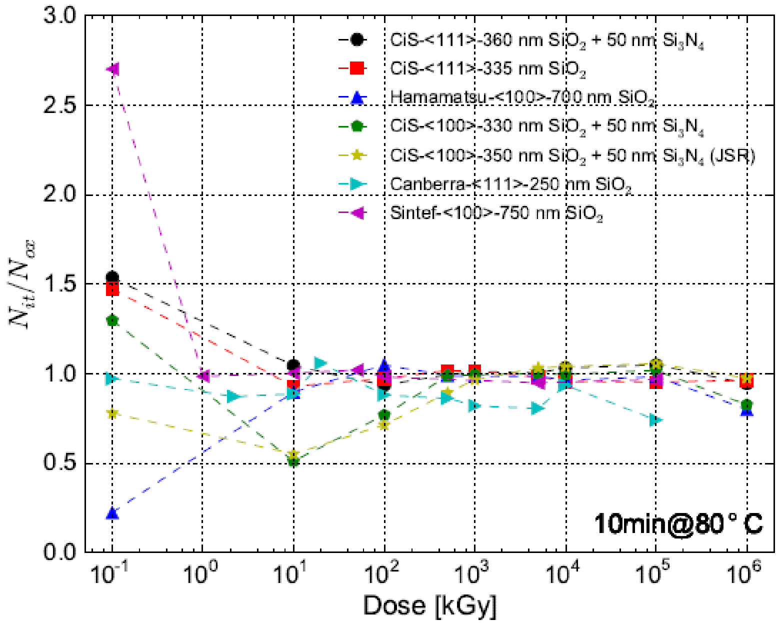


Robert Klanner, RESMDD-2013

Surface damage-Interface state density (N_{it})

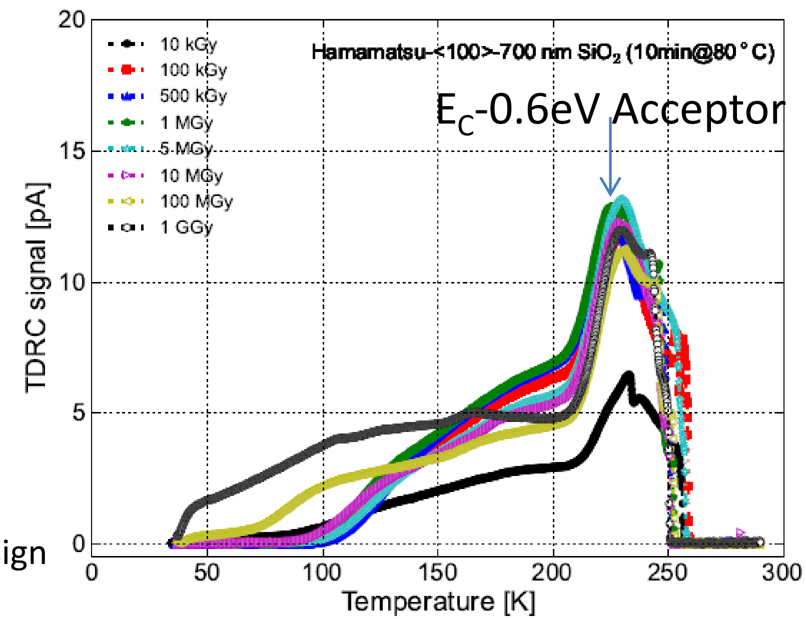
The interface trap states can play very important role in irradiated Si sensor, because,

- Its density (N_{it}) is comparable to the Oxide charge density (Q_F) as shown in the right side plot [1]
- A significant number of N_{it} states are deep trap states, thus capable of altering the space charge near interface (see the TDRC spectra, right below [1])
- Rint simulations indicates that these interface traps are acceptor type states



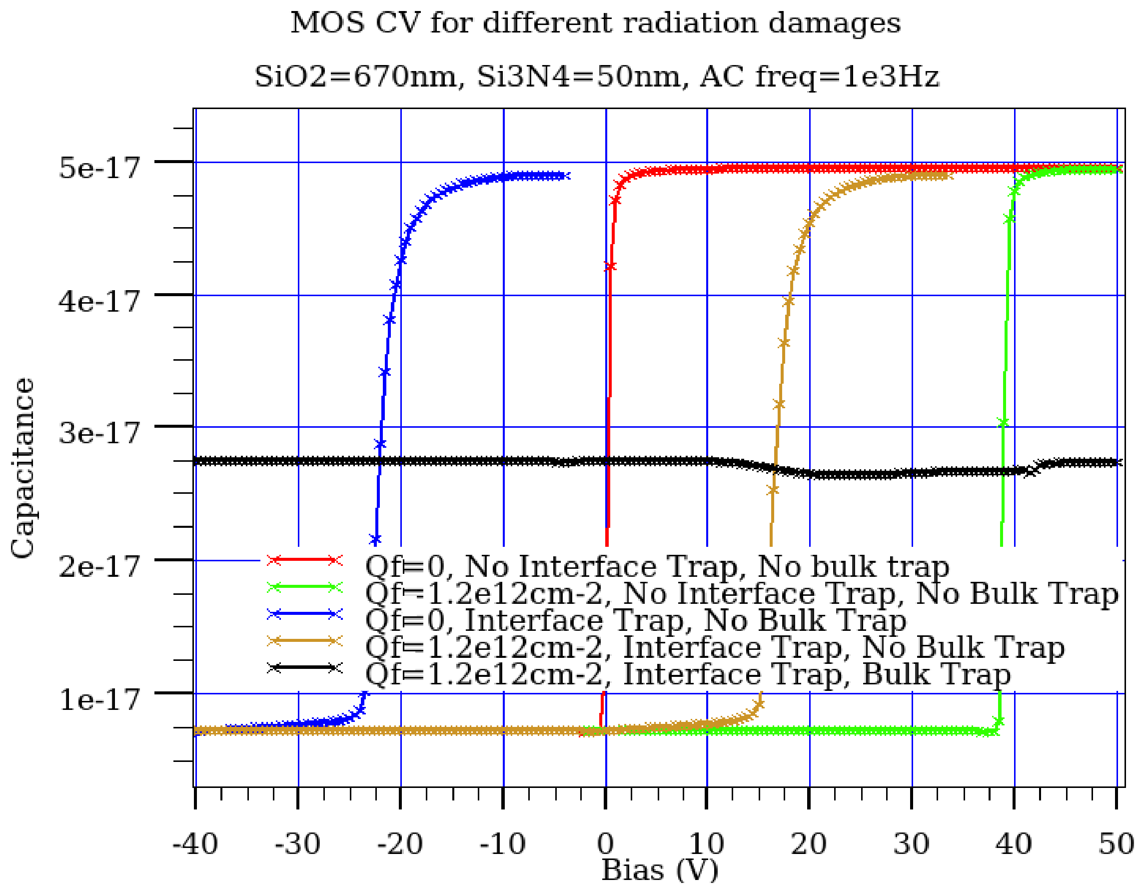
Assumptions;

1. We have assumed that N_{it} density is equal to Q_F density
2. For a given N_{it}, 60% of the states are deep traps (E_C-0.6eV) and 40% are shallow states (E_C-0.39eV) with $\sigma_n = \sigma_p$ = 1e-15cm^{-2} [1]



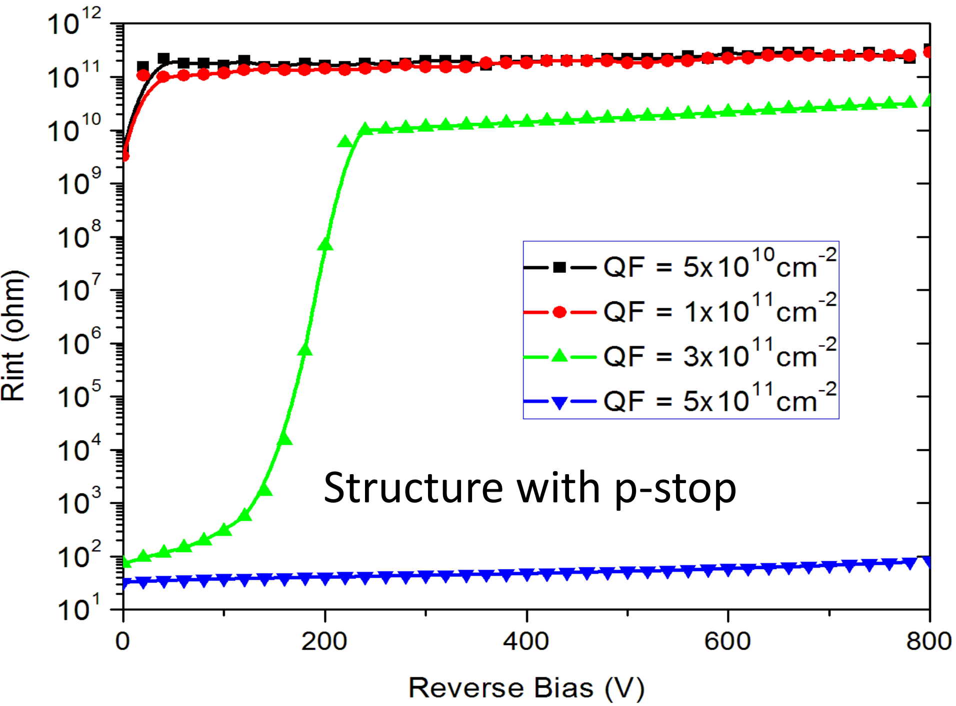
[1] J. Zhang, DESY Thesis-2013, “X-ray radiation damage studies and design of a Si Pixel sensor for different fluences for science at the XFEL”

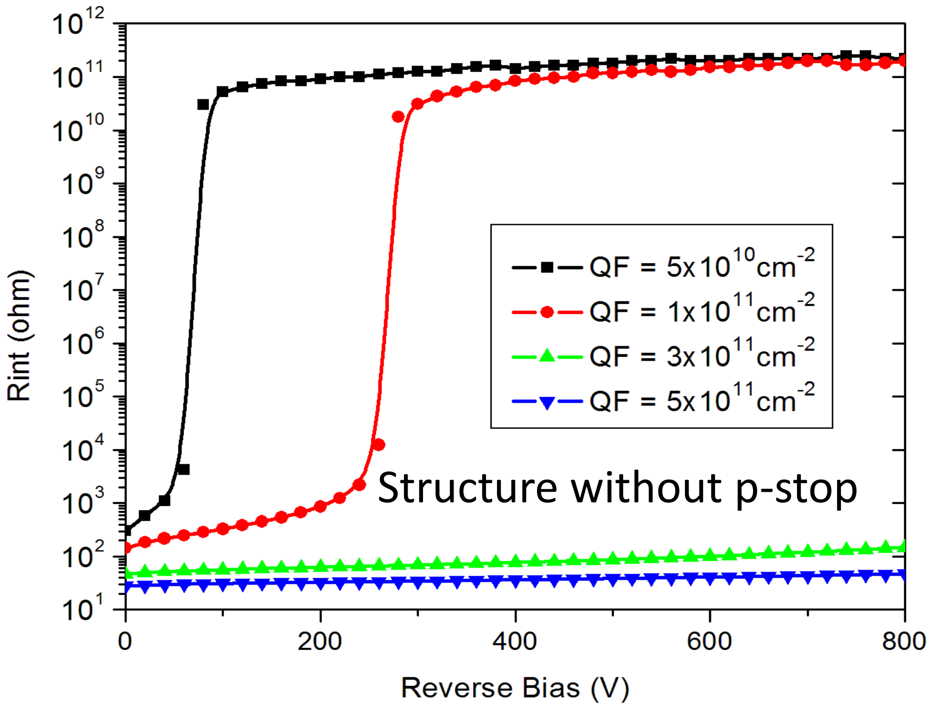
Effect of radiation damage - CV for MOS



- Interface states can significantly lower the flatband voltages for MOS
- It is not possible to extract any meaningful flatband voltage for hadron irradiated MOS (CV curve is almost flat for them, as shown by black curve, for fluence=1e15 neq/cm^2). A similar effect is reported in Maria Bernard-Schwarz's Deploma thesis, Vienna Uni., "Measurements and Irradiation Analysis of Silicon Structures for the CMS Upgrade"

Simulation of Rint without Bulk damage (Only Q_F variation)

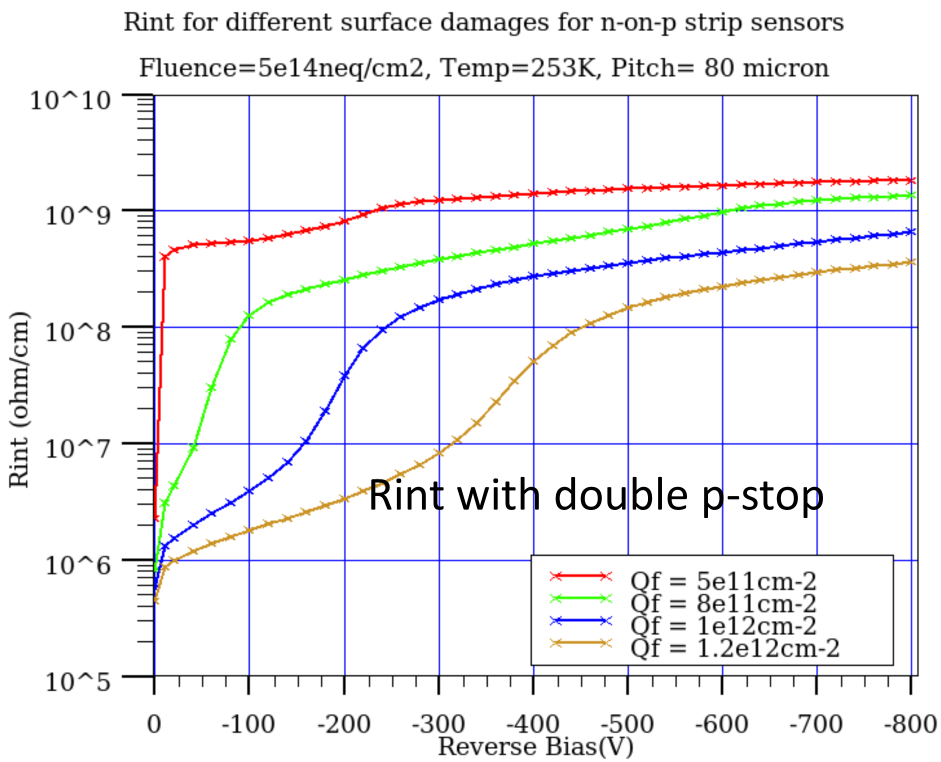


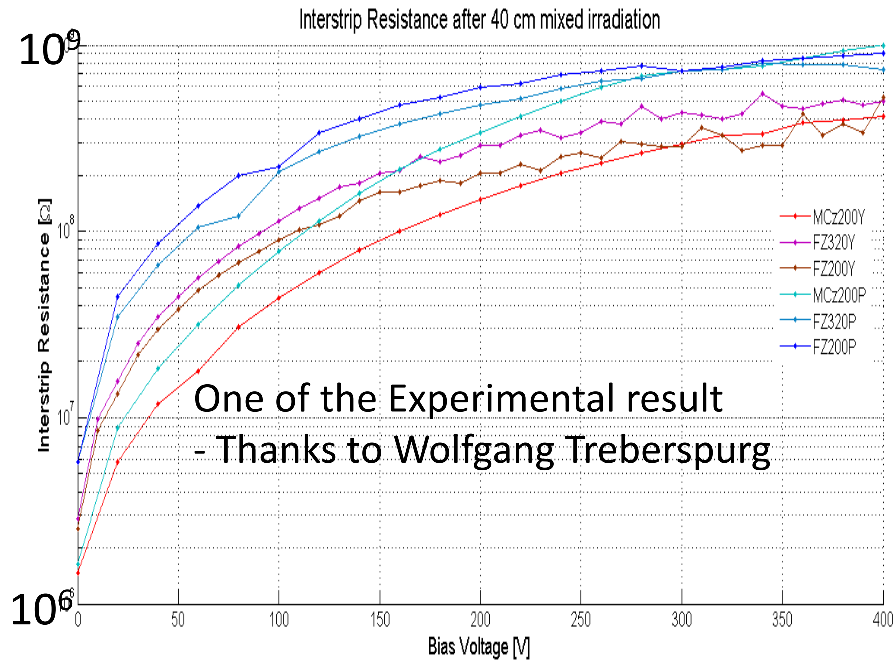


Three different Rint curves

1. For low values of Q_F, good strip insulation is obtained even for low bias voltages.
2. For intermediate values of Q_F, strip insulation is very poor for low voltages, but improves with higher reverse biases, as the electrons from accumulation layer are progressively removed, resulting in a higher Rint.
3. But for higher values of Q_F, R_{int} remains very low up to 800 V.
4. Rint values are lower for structure without pstop.

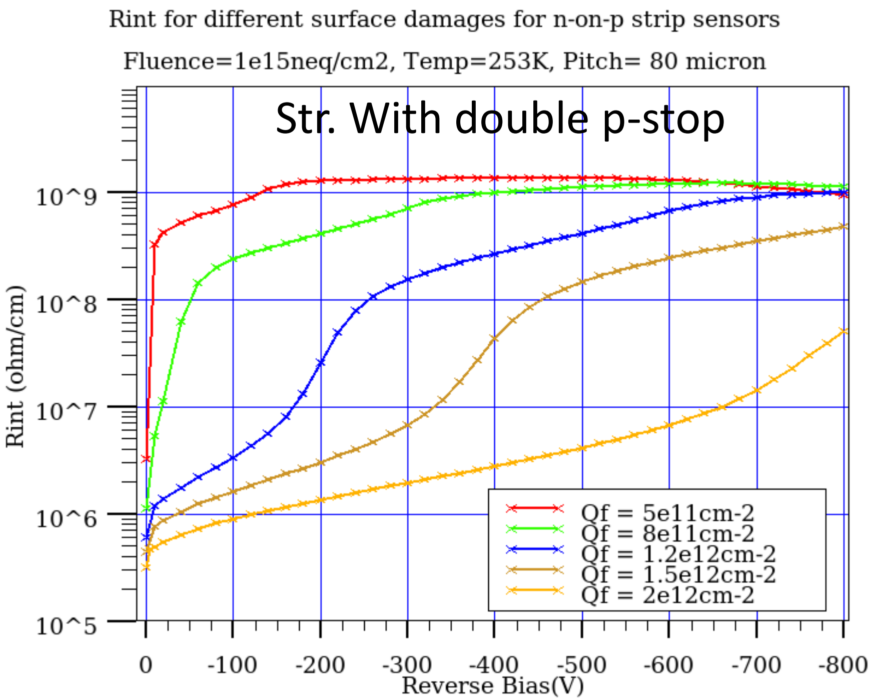
Simulations of Rint for Fluence = $5x10^{14}neq/cm^2$



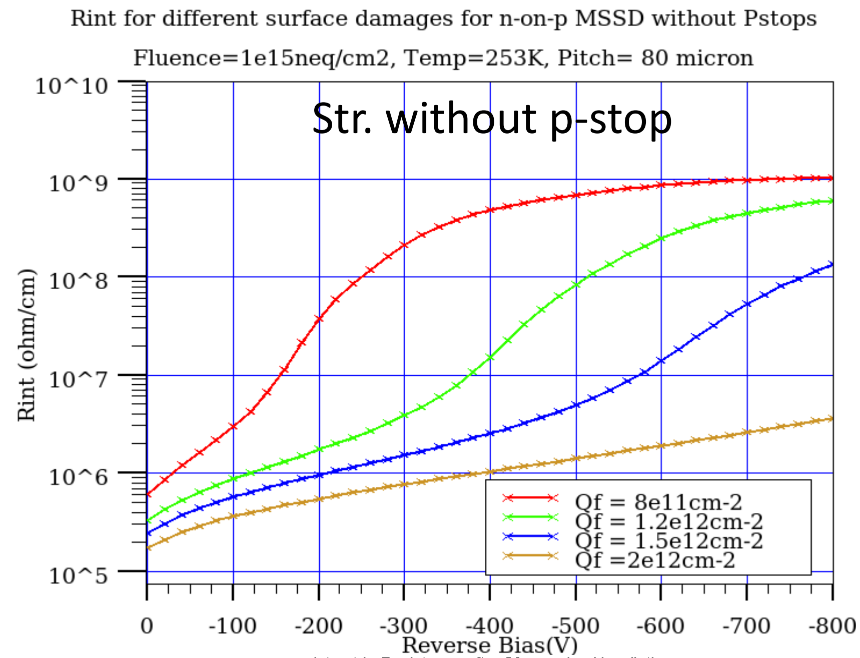


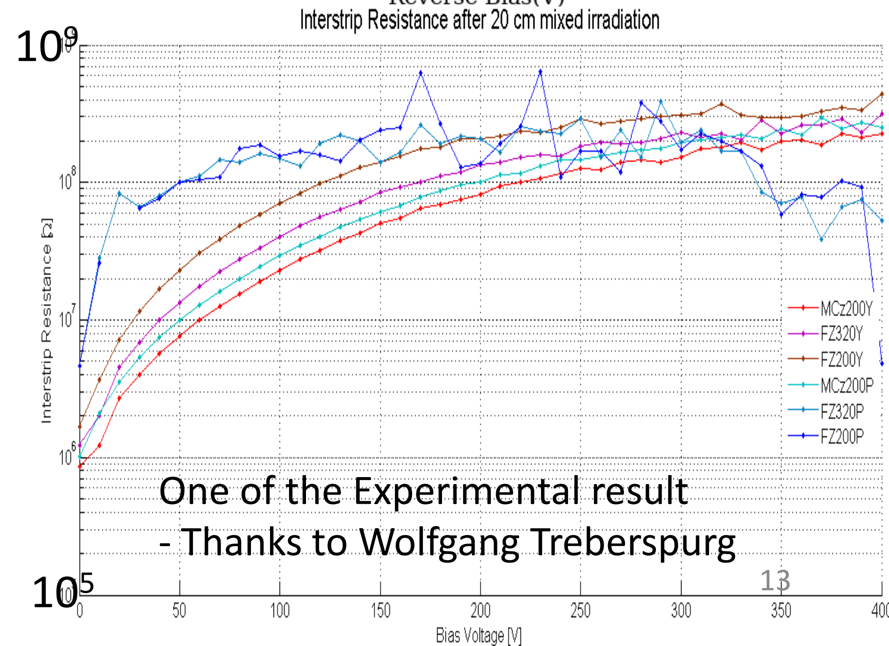
- Both Bulk + Surface damage (N_{it} + Q_F) are used
- Rint values of more then 300MOhm is possible for Q_F = $1.2cm^{-2}$
- Significant improvement in Rint values, after addition of bulk damage and N_{it} for higher values of Q_F (compared to the Q_F only case, say for QF=$5e11cm^{-2}$, n^+ strips were shorted but after radiation damage, we are having very good Rint)

Simulations of Rint for Fluence = 1×10^{15}neq/cm^2



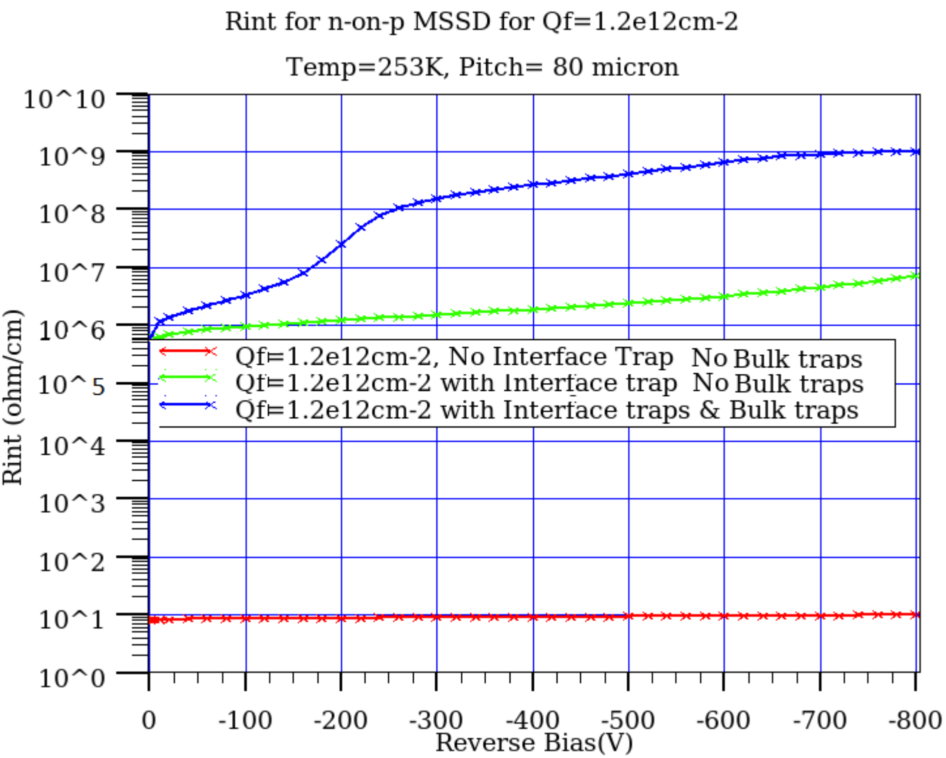
Str. With double p-stop

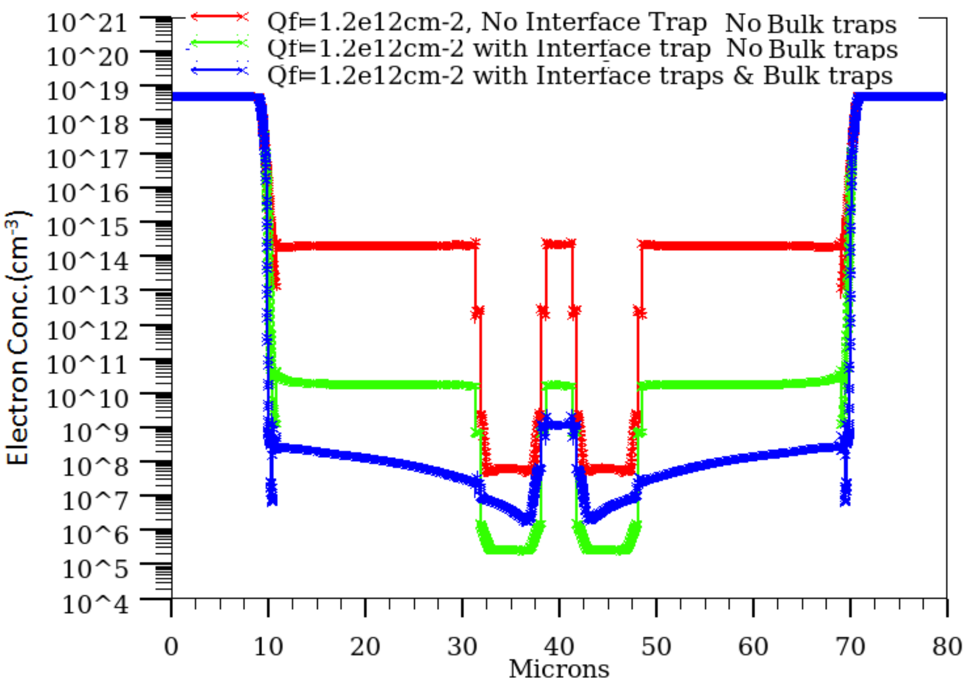




- ➢ Rint values of more then 100MOhm is possible for Q_F = 1.5e12cm^{-2}
- ➢Significant improvement in Rint values for higher values of Q_F (Compared to Q_F only case)
- ➢ Good strip insulation is possible even without any isolation structure! This explain the observed good Rint by Y. Unno et al, (NIM A 579)

Effect of Bulk and Surface Damages on Rint

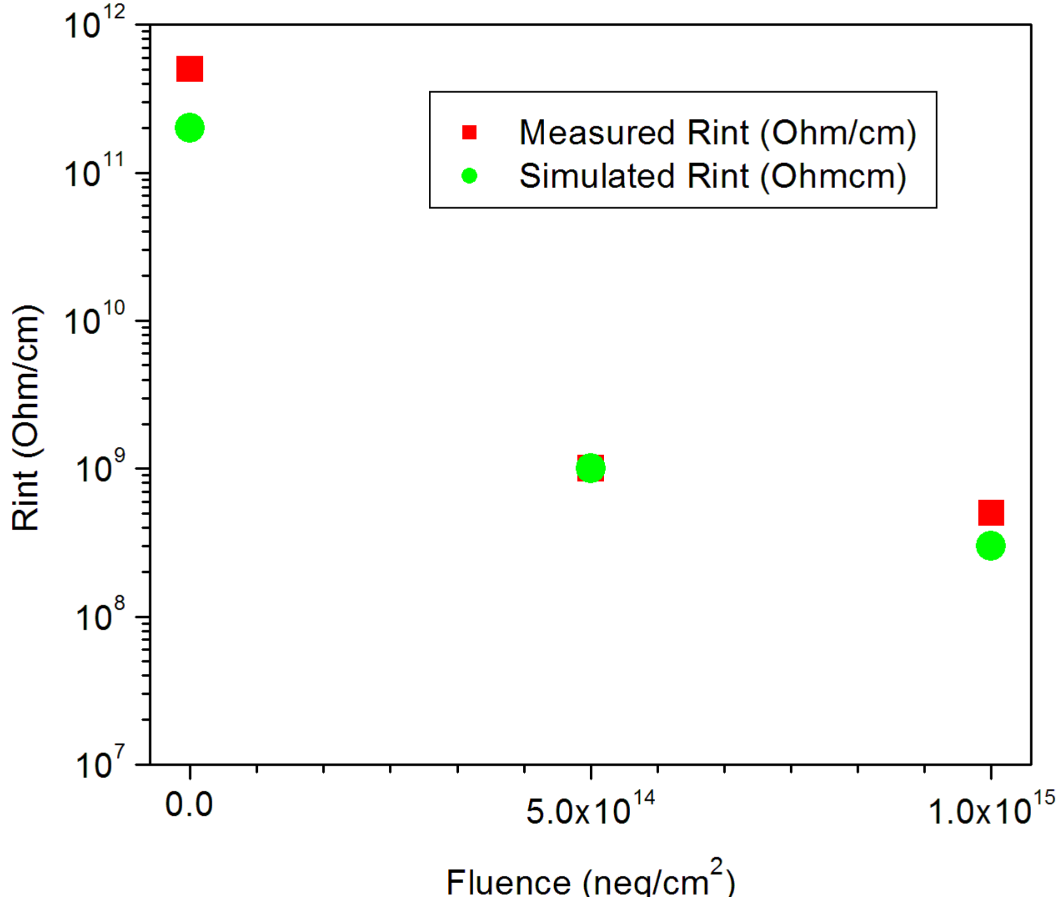




Electron conc. 0.1µm below SiO_2/Si interface

- For a given Oxide charge density value, Rint increases very significantly with inclusion of Interface states
- Rint further increases with inclusion of Bulk traps, which introduces negative space charge near n^+ strip side and further reducing the electron accumulation layer

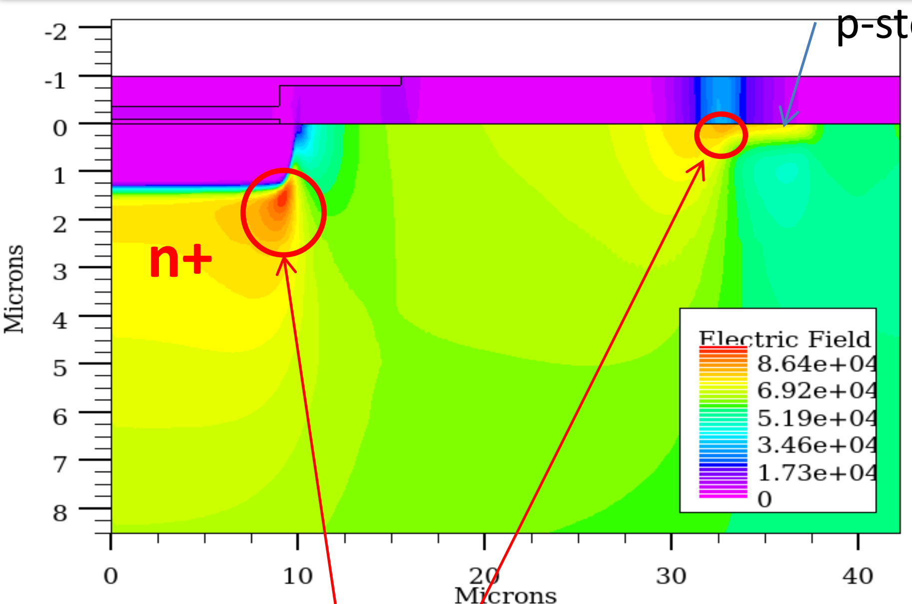
Rint simulation and measurements: Comparison

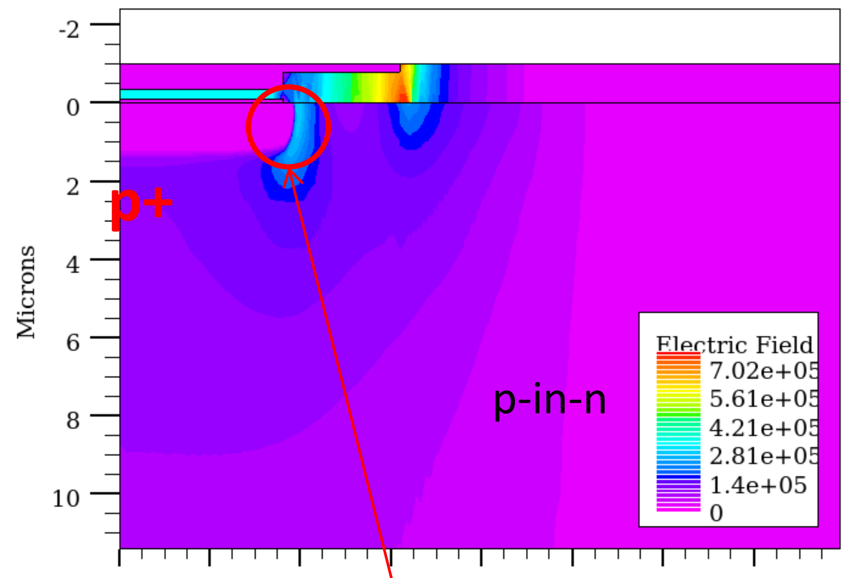


- Good agreement between measured and simulated Rint
- There is variations in measured Rint [4] (for different samples, irradiated with same fluences) and simulated Rint too (assuming different Q_Fs)

[4] Alexander D., POS, VERTEX-2012, 016

Maximum E field regions in p-type and n-type sensors





Maximum E field for n-on-p MSSD is near the curvature region of n^+ strip
Or just near p-stop, just below SiO_2/Si interface
- Shown by cutline 1.3µm below SiO_2/Si interface

Maximum E field for p-on-n MSSD is just below SiO_2/Si interface near p^+ strip
- Shown by cutline 0.1µm below SiO_2

- ➢ For p-stop (at least) up to 2e16cm-3, highest E field is near n^+ strip curvature (see R. Dalal et al, 23rd RD-50)
- ➢ For low and intermediate p-stops dopings densities, it is quite possible, that microdischarges are taking place at n^+ curvature.
- ➢ Explanation need Bulk + Surface damage. Use of Q_F only for simulations leads to wrong conclusion!

Y. Unno et al.
NIMA 636 (2011)

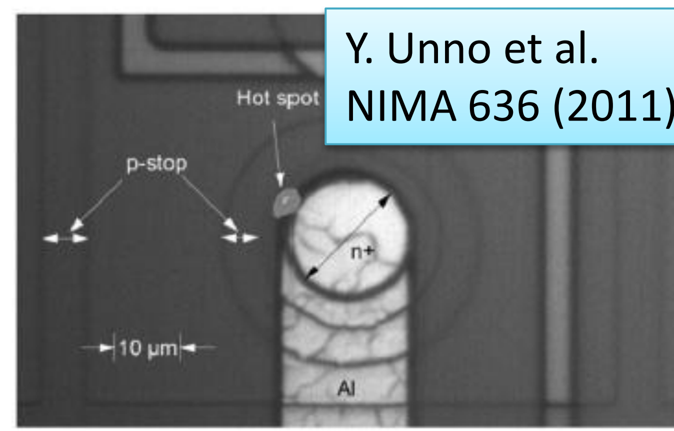


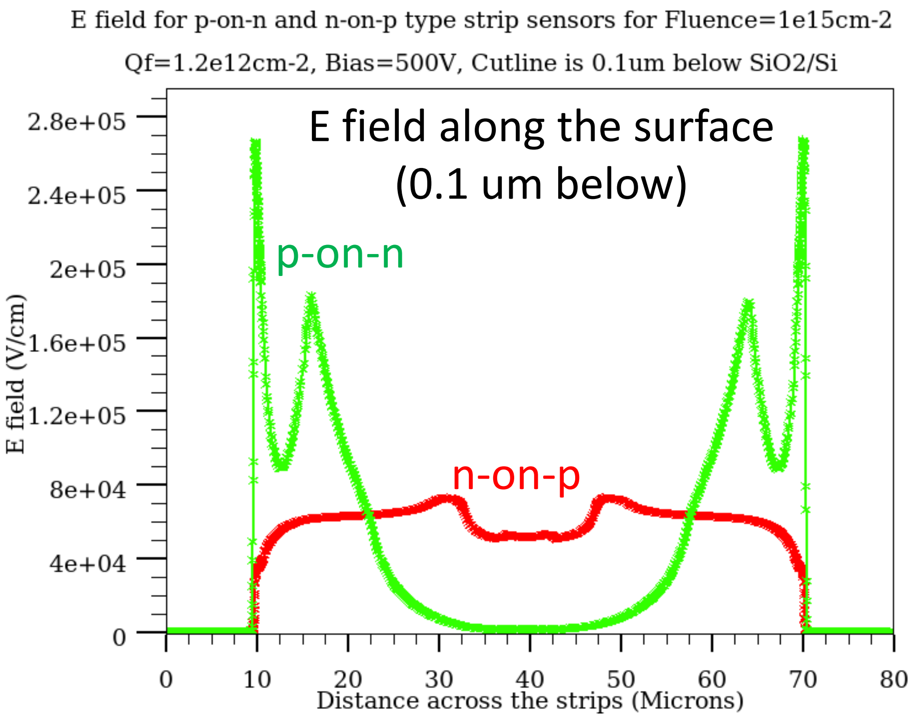
Fig. 1. Hot spot of microdischarge observed in an n-in-p sensor by an infrared camera. The spot is at the edge of the n^+ electrode.

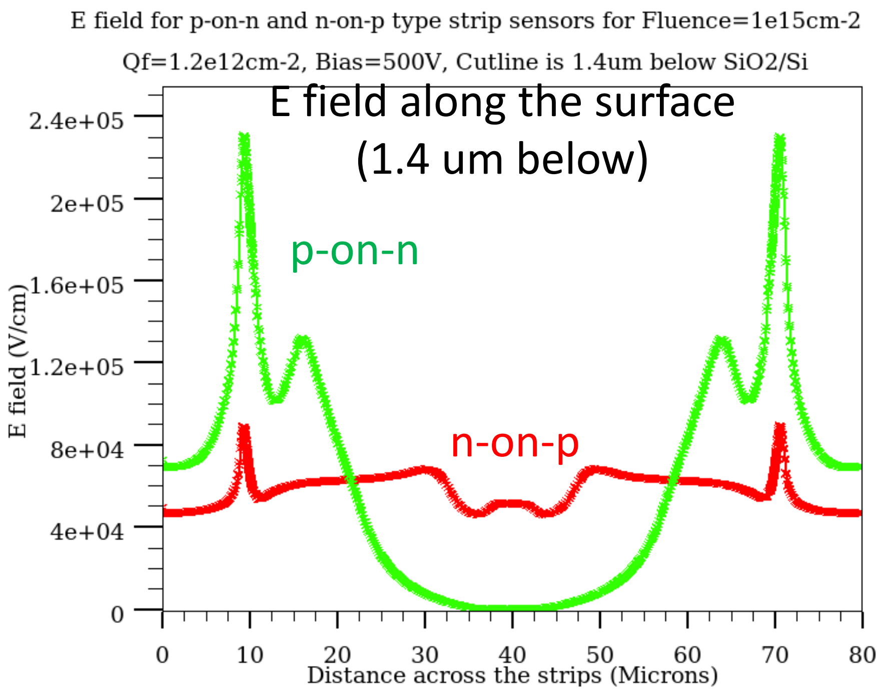
Effect of very high E field in irradiated sensor

- E field inside irradiated sensors is a strong function of space charge .
- Very high E field in a region can initiate avalanche in that region.
- Once avalanche is started, a lot of free e/h pairs are produced which will compensate the nearby space charge, changing the electric field, thus stopping the further breakdown.

This mechanism may stop the avalanche from turning global and continuous. Thus high E field near the strips can be a reason of non – Gaussian noise events which occur randomly (RGH- Random Gaussian Hits)

E. Field (Irradiated) comparison : p-in-n & n-in-p sensor

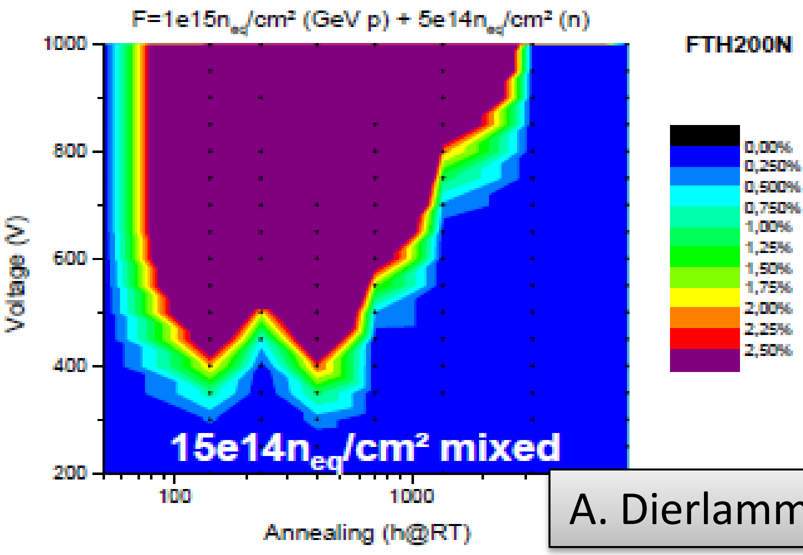




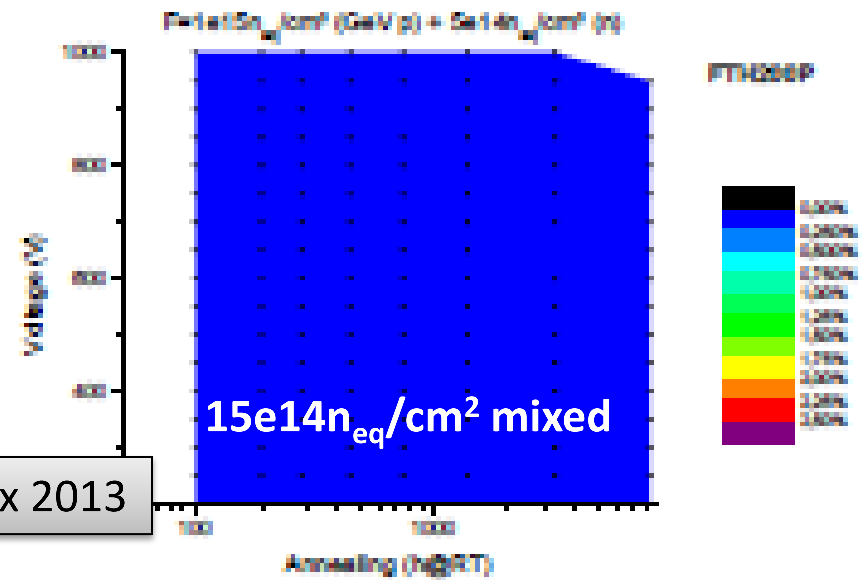
Flux = 1×10^{15}cm^{-2} ; Q_F = 1.2×10^{12}cm^{-2}; Bias = 500 V

- Peak electric field is more for p-in-n (n-type) sensor as compared to n-in-p (p-type) sensor for a given bias.
  - Micro-discharge possibility is much more in p-in-n sensors.

Amount of RGH for irra. n-type and p-type of sensor



A. Dierlamm, Vertex 2013

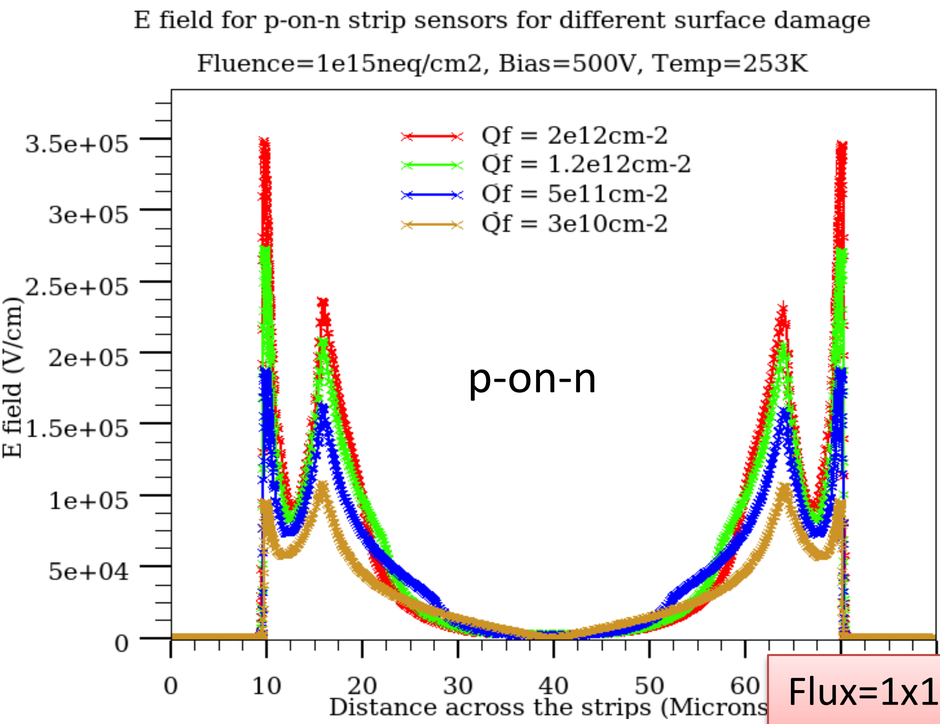


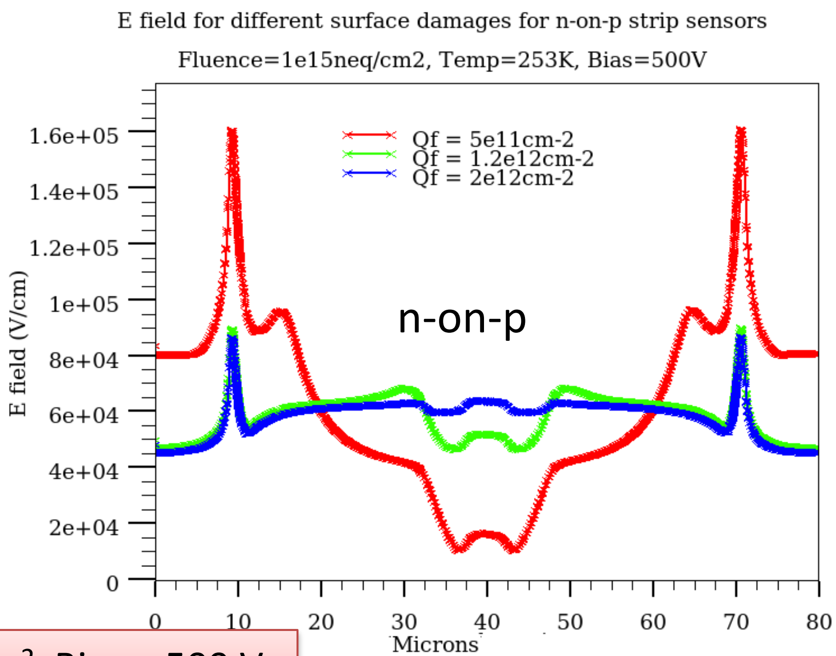
N-type sensor

P-type sensor

- Significant amount of non-Gaussian noise (RGH) observed in p-in-n sensor (n-type)
- Very less amount of RGH rates observed for n-in-p (p-type) sensor

E. Field (Irradiated) : Effect of Q_F





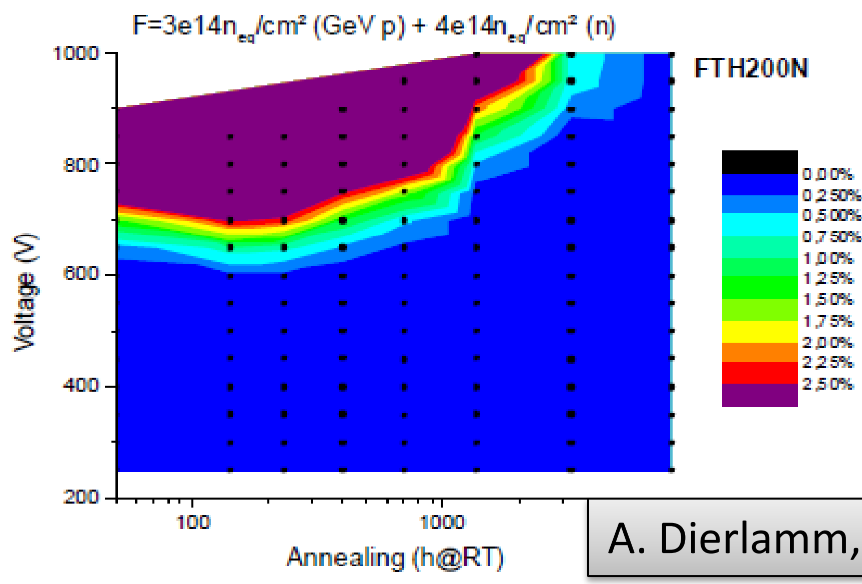
Flux=$1\times10^{15}cm^{-2}$ Bias = 500 V

- **p-on-n strip sensors**
  - **As Q_F increases = > Peak Efield increases.**
  - **Micro-discharge possibility is more for p-on-n strip sensors after proton irradiation or less possibility after neutron irradiation**

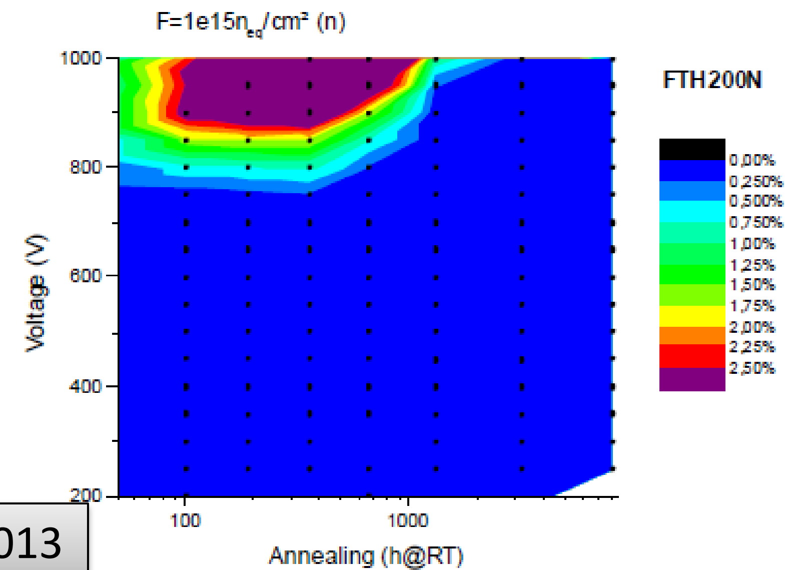
- **n-on-p strip sensors**
  - **Peak field is much less compare to p-in-n sensors**
  - **As Q_F increases = > Peak E field decreases.**
  - **Charge multiplication should be more for neutron irradiated n-on-p strip sensors compare to proton irradiated n-on-p (for same fluence)**

RGH for different type of irradiation (for p-in-n)

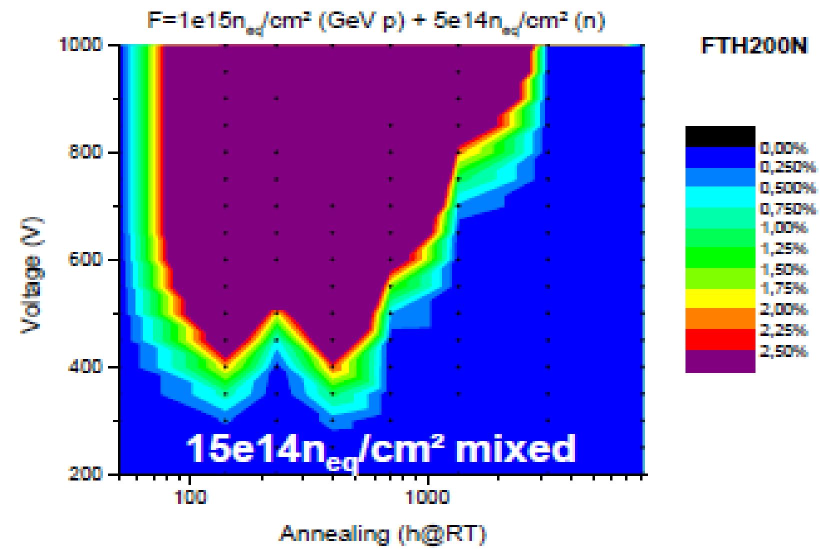
7e14n_{eq}/cm² mixed



10e14n_{eq}/cm² neutrons



A. Dierlamm, Vertex 2013



- Much less RGH for neutron irradiation clearly indicate the role of surface damage
- The dependence on ionizing radiation hints toward a combined effect of bulk damage and surface damage
- The Q_F effect simulation were carried out before these measurements

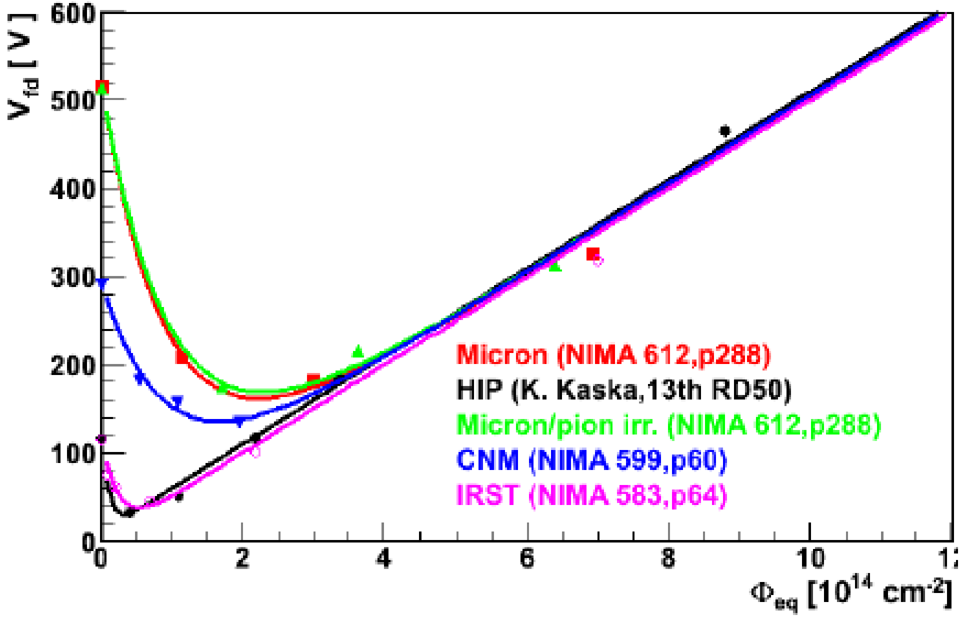
Summary

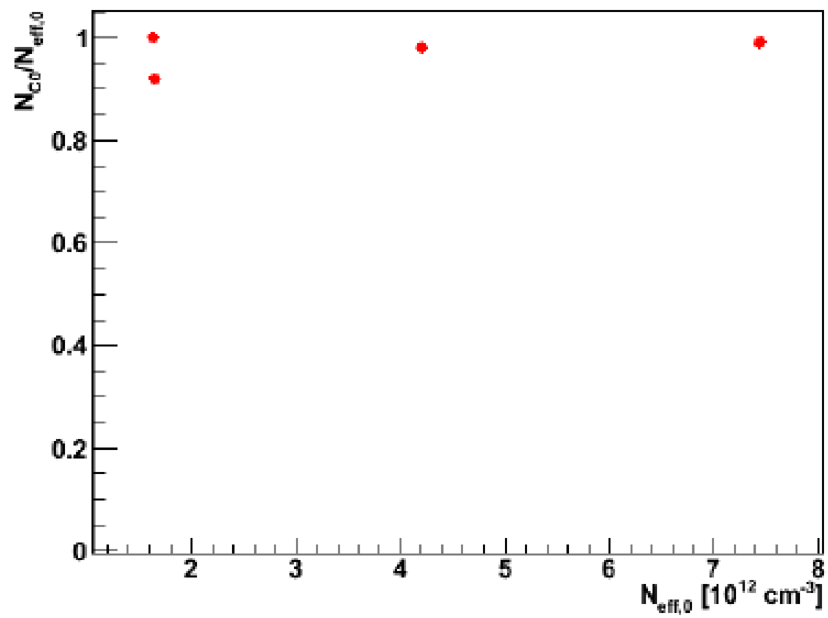
- Both bulk and surface damages take place during the hadron irradiation of Si sensors
- Simultaneous incorporations of bulk damage and surface damage is essential for correct interpretation of observed radiation damage effects
  - Use of only bulk damage or only surface damage may lead to wrong conclusions!
- Use of interface states, along with Oxide charge density is essential for proper surface damage inclusion in simulations
  - Conc. of N_{it} and Q_F (or N_{OX}) are comparable
  - Significant fraction of deep traps in N_{it}
- There may be initial lowering of V_{FD} with irradiation
  - Double junction effect
  - Acceptor/Donor removal may be avoided
- Interface trap states and negative space charge, near n^+, due to bulk damage results in good Rint values for low pstop doping and even without any pstop
- Highest electric field in irradiated n-on-p is much lower compared to irradiated p-on-n

-Most of the present work is carried out under RD-50 and CMS Phase-II upgrade
- I am thankful to Michael Moll for lots of suggestions and interesting discussion
- Really thankful to many people for their excellent measurements, which are used to understand the various aspect of radiation damage (like J. Zhang, T. Pohlson, Kramberger, Hadi, Y. Unno, Wolfgang… and many more)
- Finally, many thanks to 23rd Vertex Organizers for financial assistance and perfect conference !

Thanks for your attention!

MCz-p irradiated with charged hadrons





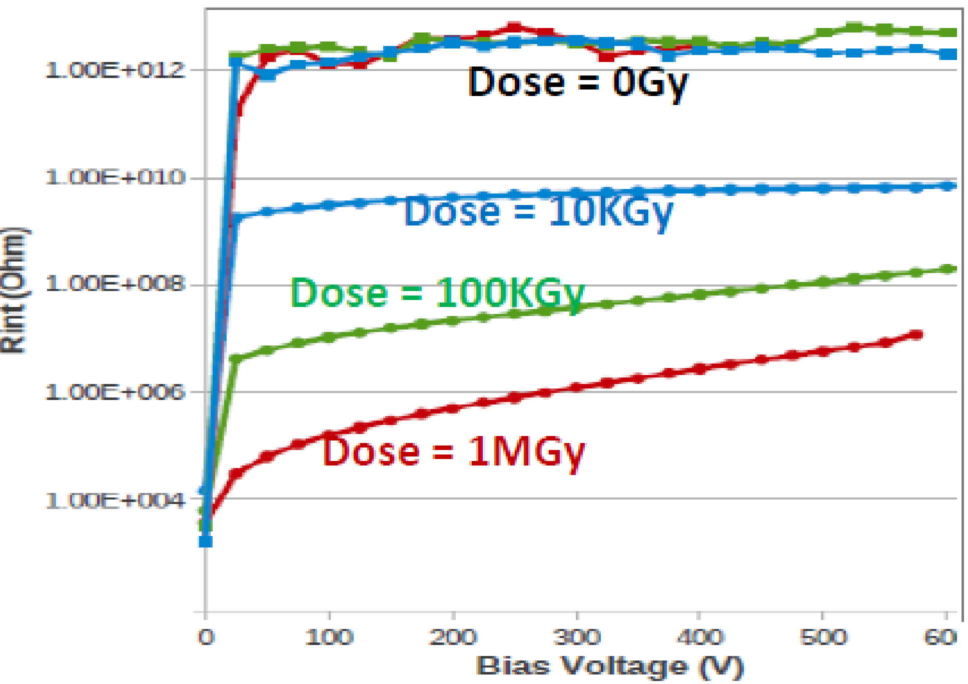
- g_{eff}=0.0071 cm^{-1} (taken from O rich measurements from RD48/50) and seems to be adequate, c and N_{C0} were determined from the fit.
- Different producers – no impact of processing on behavior
- *Acceptor removal seems to be complete*
- c~$1\cdot10^{-14}$ cm^2 (seems larger for lower resistivity, but uncertainty is too large for any firm conclusion)

Rint measurements for irradiated DC-CAP Sensors

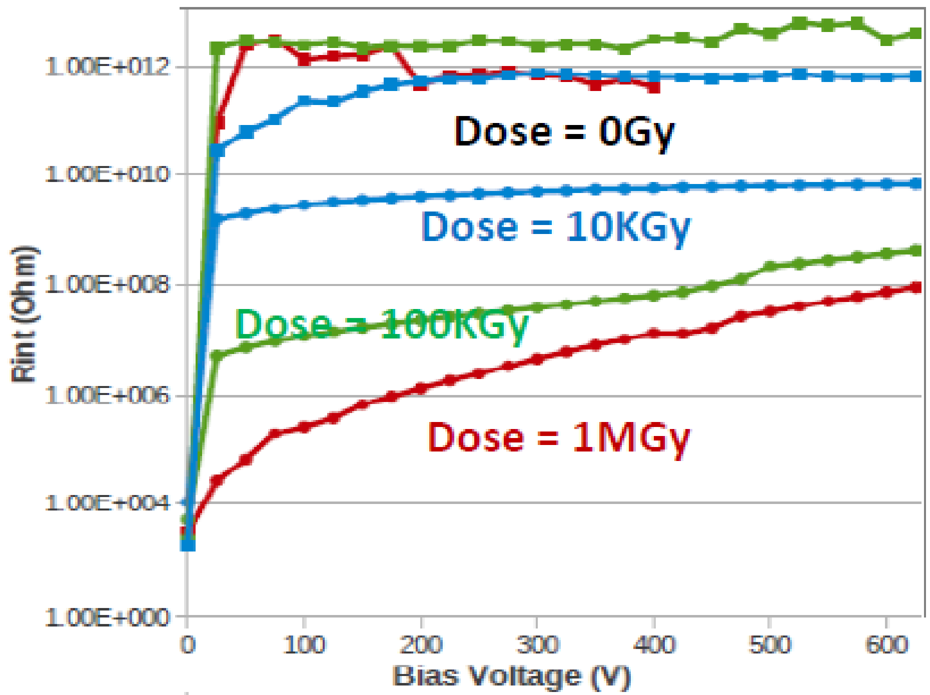
-Very high Rint (~ $1x10^{12}$Ohm for unirradiated DC-CAD test structures)

- Rint decreases with irradiation dose

- For highest dose of 1MGy, Rint is around $1x10^6$ Ohm, Strip Isolation is effectively lost.



Pitch = 120 µm



Pitch = 80 µm

Rint measurements by Anna Peisert and Hadi, CERN for different X-ray dose

What is going inside hadron irradiated sensors !

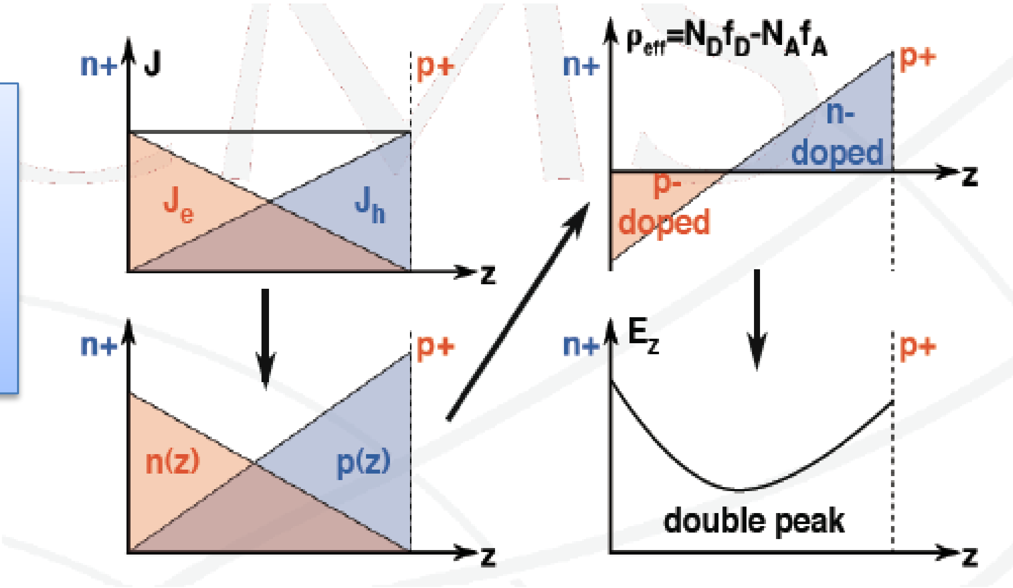
Irradiation of n+p-p+ Si sensor by hadrons :

- Acceptor and Donor traps are created
- Deep traps leads to quite higher leakage current
- Electrons move toward n+ strips while holes move toward p+ backside
- Electron density near n+ is very high leading to filling of Acceptor traps and thus creating negative space charge near n+ strip.
- Similarly, positive space charge is created near p+ by filling of Donor traps by holes

High negative space charge near n+ strips result in high E-fields near strips (similar for pixel)

Can we see this....?

Yes by eTCT



Two type of irradiation

❖ **Irradiation with Photons (x-ray and γ-ray irradiation)**

- Only surface damage is significant, resulting in very high Q_F (see backup slides)
- Leakage current is very low, α is at least three orders lower than hadron irradiation and no effect of annealing (very low bulk damage, M.Moll thesis)

For this type irradiation : No High electric field near strips

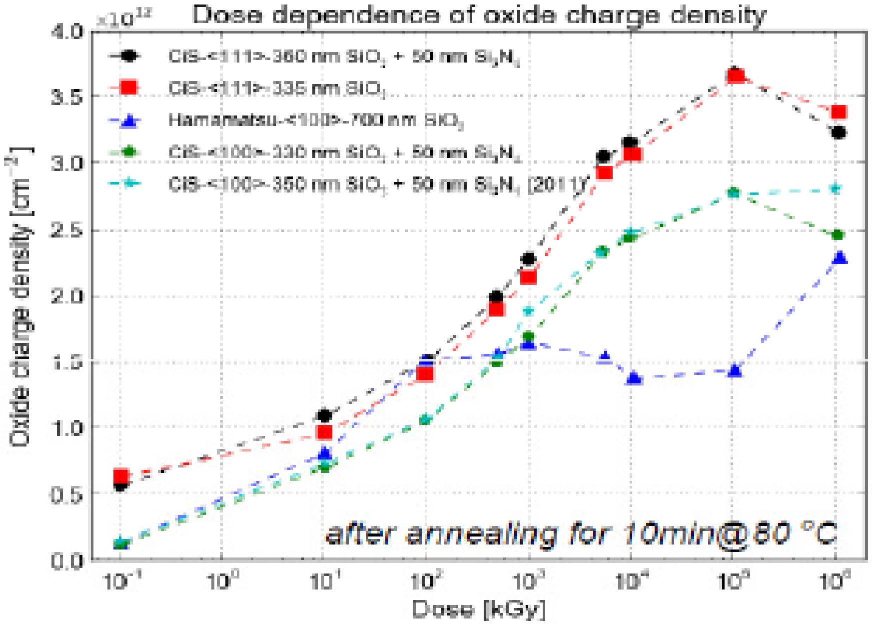
- Oxide charge density ~ 2-3x10^{12} cm^{-2} after irradiation ~ 1MGy (in MOS as well as in strips and pixel sensors), leading to very serious problems for isolation, Cint & breakdown.

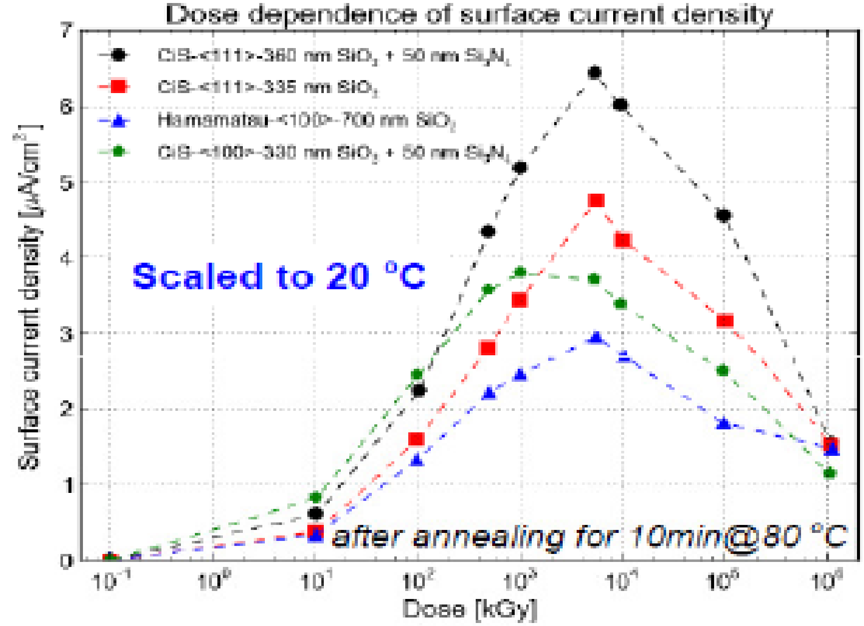
❖ **Irradiations with Hadrons (p,n or pions irradiations)**

- Along with surface damage, significant bulk damage ⟶ very high leakage current
- This leads to high Electric field or high density of negative space charge near the n+ strips.
- No e^- accumulation layer formation ….. No problems for strip isolation, C_{int} etc.
- Measurements using MOS will show expected high Q_F as there is no high leakage current, so, no negative space charge near Si/SiO_2 junction (no suppression of Q_F).

3. Summary: Dose Dependence of N_{ox} and J_{surf}

Vendors: CiS, Hamamatsu, Canberra; **Crystal orientations:** <111>,<100>;
Insulator: SiO_2 (335-700 nm), with and without additional 50 nm Si_3N_4





J.Zhang et al., arXiv:1210.0427(2012)

- Results reproducible (after some annealing)
- Spread of about a factor 2
- N_{ox} saturates for ~1 - 10 MGy
- J_{surf} peaks at 1-10 MGy, then decreases

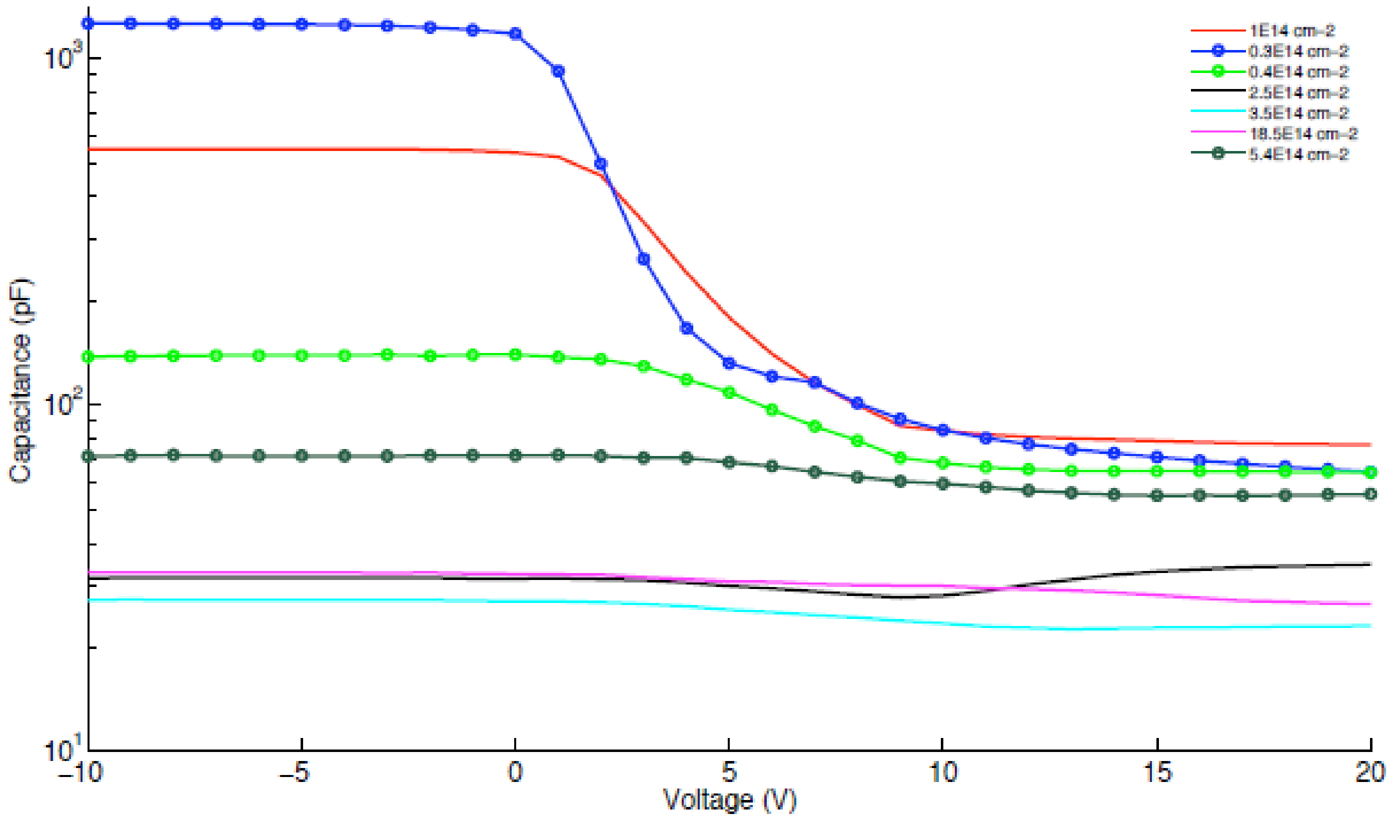
- Equilibrium h-trapping and eh-recombination ?
- E-field effects due to oxide charges ?

→ Understanding needs more studies

X-ray radiation damage saturates !!!

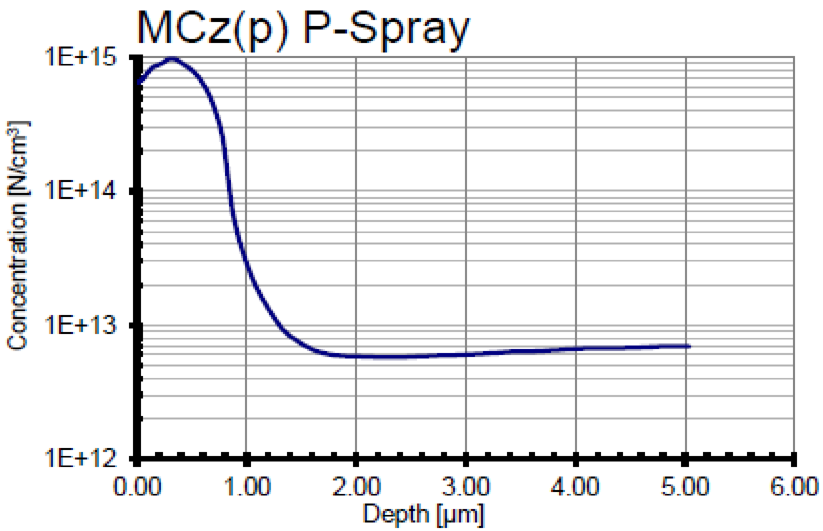
From Maria thesis, MOS measurement

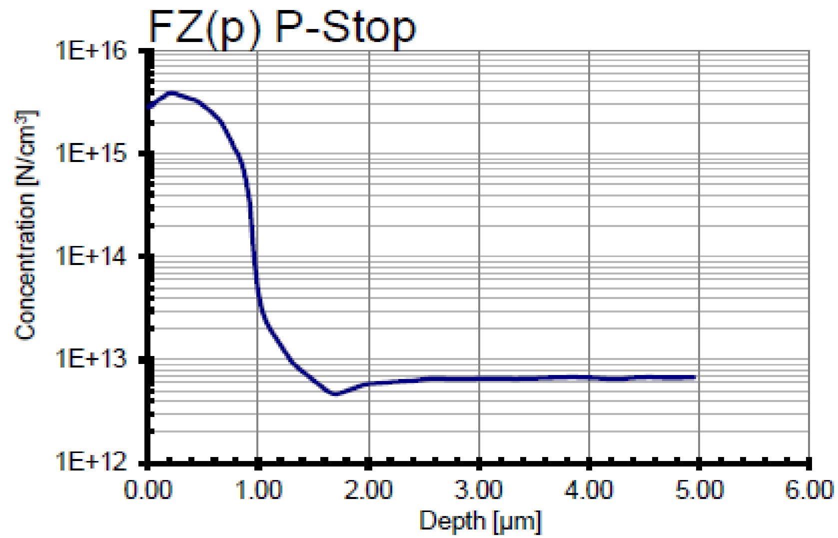
The higher the fluence the more charge traps are introduced. The MOS capacitance decreases with fluence due to trapped charge carriers. The flatband voltage of unirradiated TS is about 1V compared to one of the irradiated result of about 4V. This higher flatband voltage points to additional oxide charges produced by irradiation.



Pspray/Pstop doping profile measurement

2. Doping Profiles: P Spray/Stop Implant

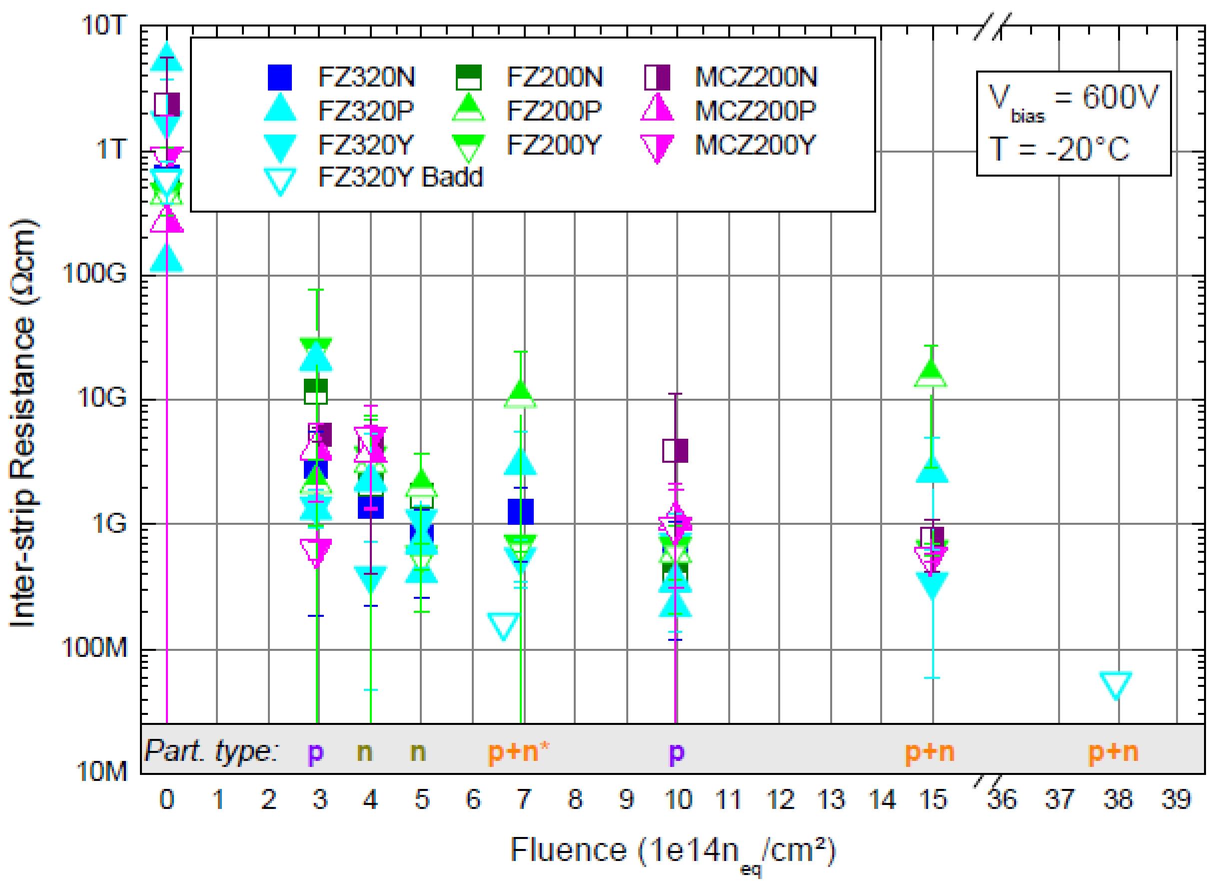




- **P Spray-Implant** in MCz200P: Peak concentration at 1E15, Implant depth app. 1,5 µm, Bulk concentration 8E12
- **P Stop-Implant** in FZ200P: Peak concentration at 4E15, Implant depth app. 1,6 µm, Bulk concentration 8E12
- The P Stop concentration is approximately 4 times higher than the P Spray, the implant depth is almost similar

Rint variations for different fluence

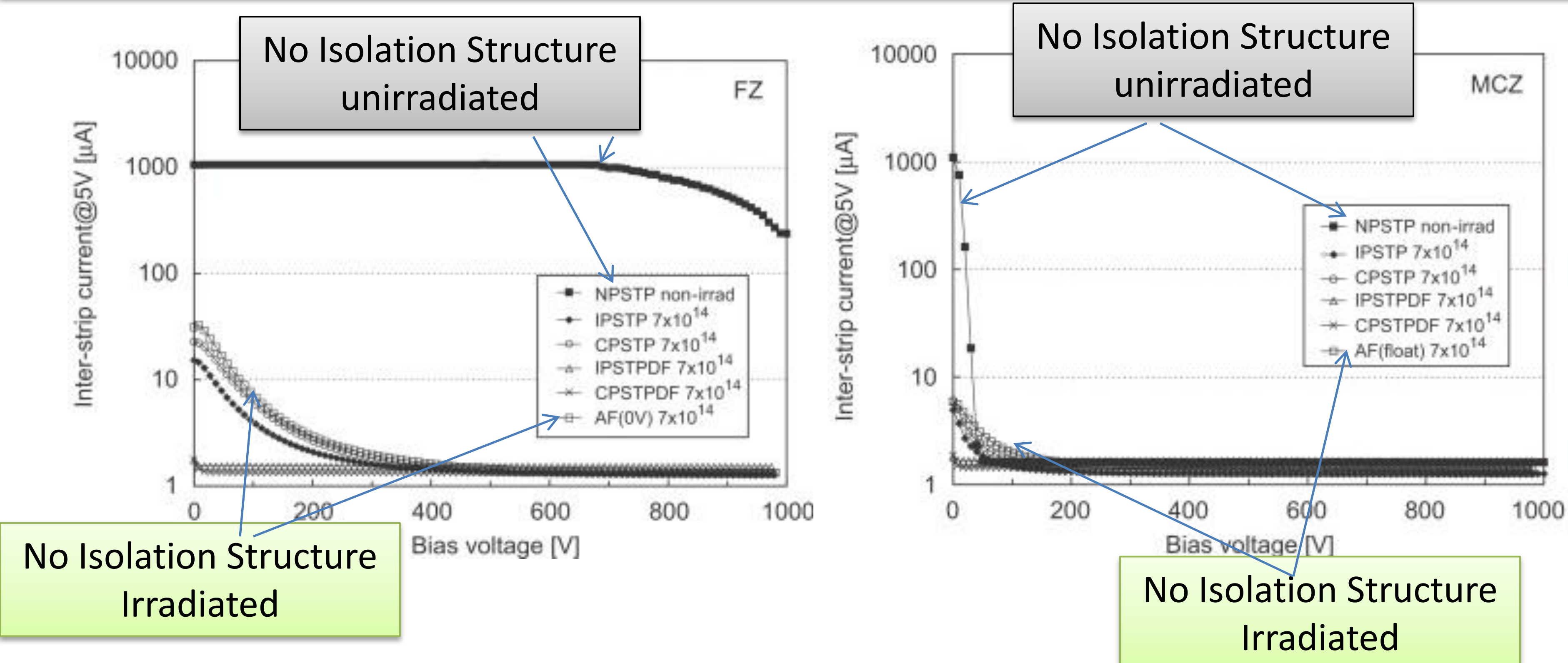
(Alexander D., Vertex-2012, 016 paper)



Another experimental evidence …..

Y. Unno et. Al. (NIM A 579 (2007))

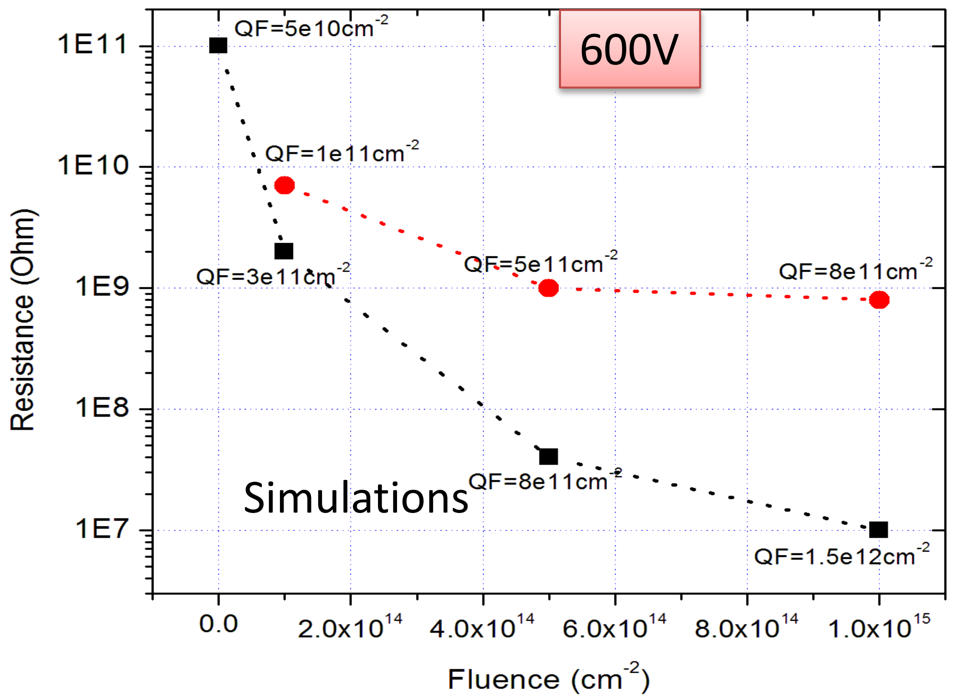
Strip isolation was observed for n+p- sensors without isolation structure after proton irradiation
- Clear signature of proposed mechanism !

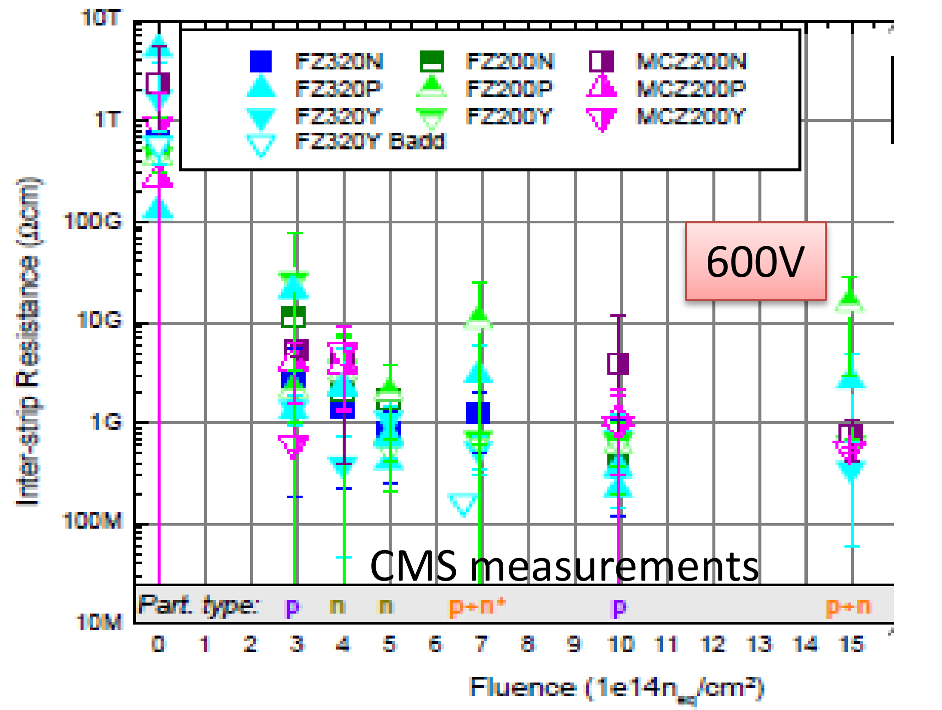


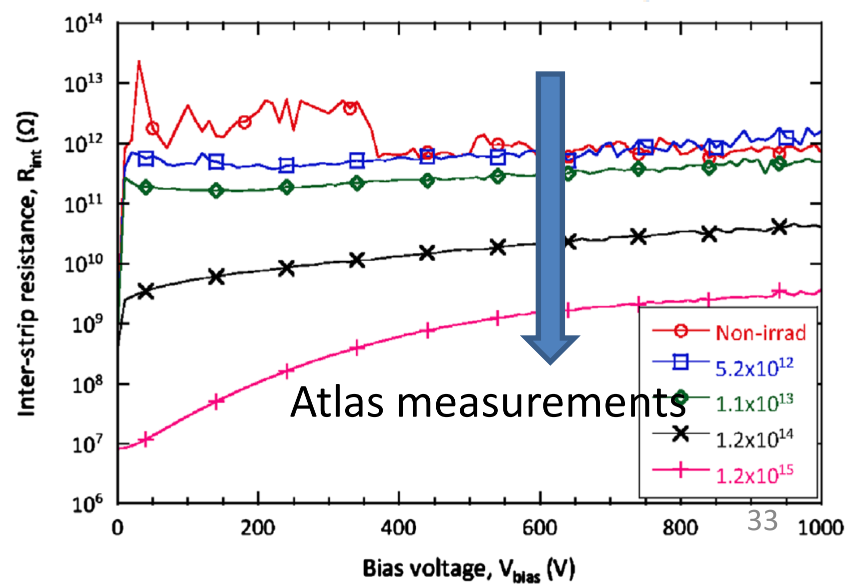
Plot of Interstrip current vs. applied reverse bias.

- NPSTP – No Isolation structure (non-irradiated).
- AF – No isolation structure (irradiated by flux = $7\times10^{14}cm^{-2}$).
- All other structures are with different layouts of Pstops (Irradiated)
- Voltage difference between two neighboring strips = 5V

R_{int} variation with Irradiation flux







-Rint decreases with increase in fluence

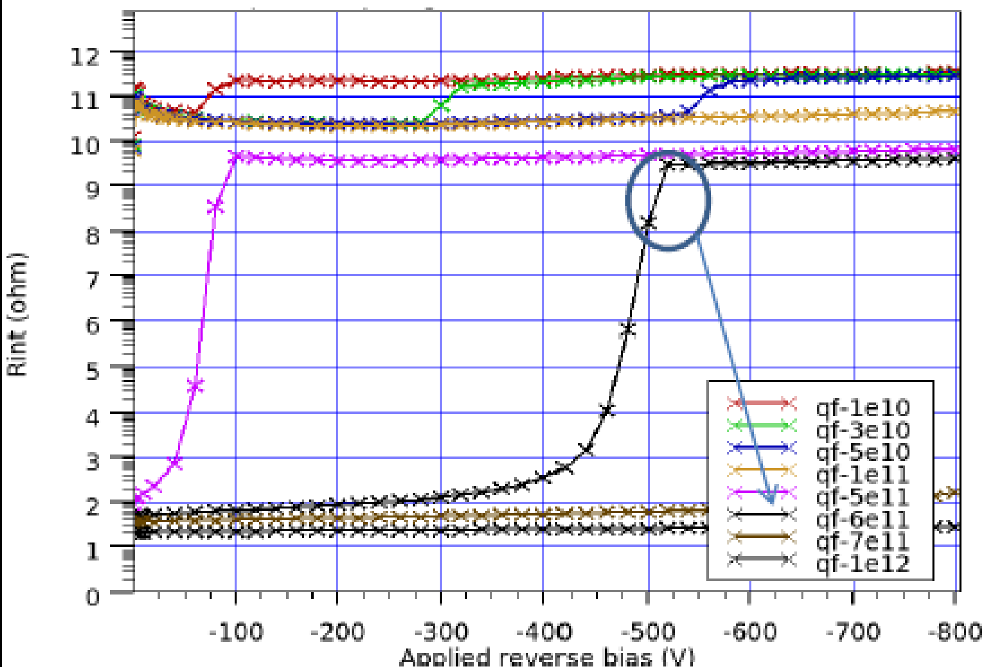
-Similar trends in CMS tracker upgrade measurements (A. Dierlamm, PoS paper, Vertex 2012, 016)

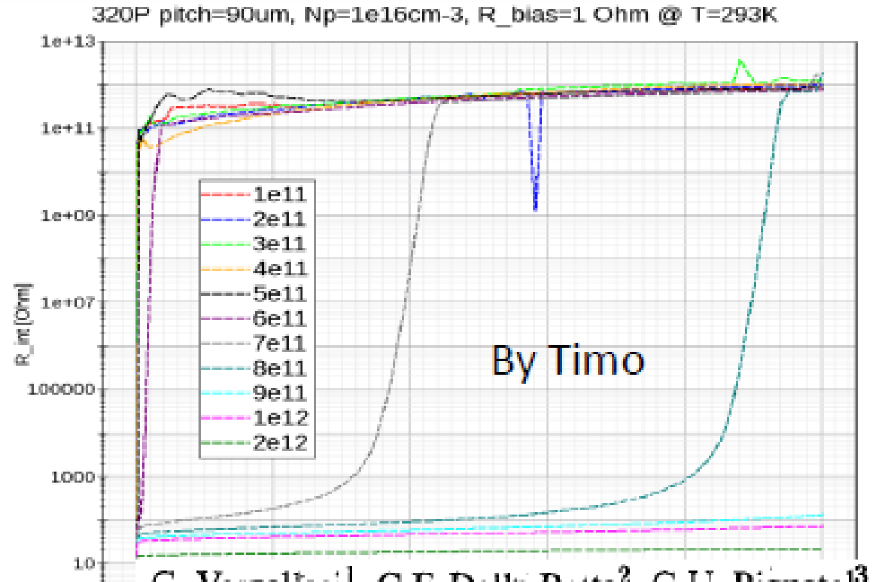
- Similar trends observed in Atlas measurements (Y. Unno et al., NIMA, 2013), [http://dx.doi.org/10.1016/j. nima.2013.04.075](http://dx.doi.org/10.1016/j.nima.2013.04.075)) with different p-stop parameters

- Can not be explained by increase in leakage current

R_{int} comparison (Silvaco Vs Synopsys) (p-type)

DC external resistance = 1 ohm





G. Verzellesi[1], G.F. Dalla Betta[2], G.U. Pignatel[3]

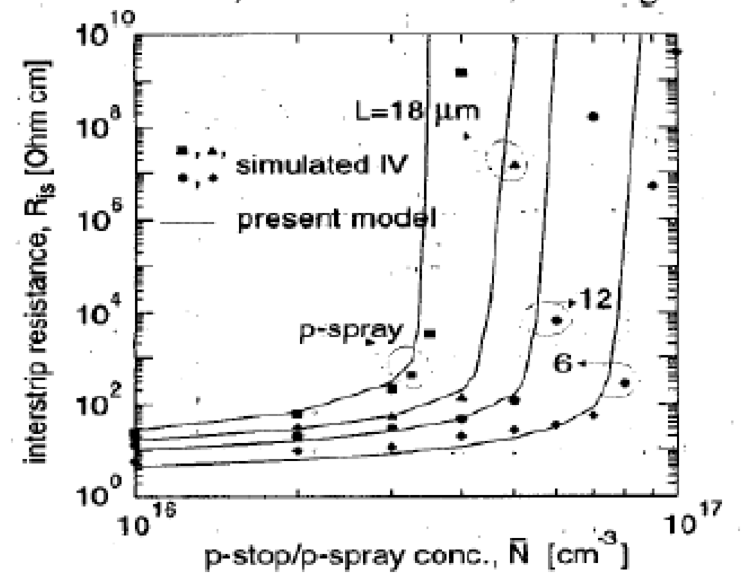


Figure 4: Interstrip resistance values as a function of the p-stop(p-spray) average doping concentration, as obtained from the proposed, analytical model and from simulated $I_2(V_1)$ curves. A positive charge density of 2×10^{12} cm^{-2} is assumed in the oxide.

- ❑ Similar, qualitative features for simulation plots
- ❑ Slight difference for intermediate values of Q_F