TCAD simulations of irradiated silicon sensors

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- Simulation work under RD-50 and CMS simulation group

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- Simulation approach using TCAD tools
- Surface Damage
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  - Interface Trap Density (N_{it})
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- E field simulations for irradiated Si strip sensors
- Summary

Simulation approach using TCAD tools

Simultaneous use of Bulk & surface damage for hadron irradiated sensors

- Bulk damage is included into TCAD simulations using an "Effective Trap Model"
  - Must reproduce the expected leakage current
  - Should produce the appropriate full depletion voltages for irradiated sensors
  - Should reproduce the TCT and CCE measurements
- Surface damage is included into TCAD framework using different values of "Oxide Charge Density (Q_F)" only (till now !)
  - Good Q_F measurements are available for different X-ray ionization doses (See DESY thesis by Thomas Pohlsen and J. Zhang)
  - Educated TID guess (hence Q_F range too) can be made for the hadron irradiated sensors
  - Even the neutron irradiation is accompanied by good gamma TID in reactors (see talk by Vladimir Cindro, Vertex-2014)
  - Should give good R_{int}, C_{int} prediction, at least for X-ray irradiated strip sensor

Calculation for equivalent TID (Total ionization dose) for proton fluences for SiO_2

$(dE/dX)^*_{min} = 1.7\ \mathrm{MeVcm^2g^{-1}} = 2.72 \times 10^{-10}\ \mathrm{Jcm^2\ Kg^{-1}}$ (mostly by ionization)

No. of particles for 23 GeV proton fluence of $1\mathrm{x}10^{15} n_{eq}\mathrm{cm}^{-2} = 1\mathrm{x}10^{15}\ n_{eq}\mathrm{cm}^{-2}/ 0.62$

$= 1.61 \times 10^{15}\ \mathrm{cm}^{-2}$

Hence, TID equivalent of $1\mathrm{e}15 n_{eq}\mathrm{cm}^{-2}$ for 23 GeV protons $= 2.72\mathrm{x}10^{-10} \times 1.61\mathrm{x}10^{15}$ J/Kg

$= 0.44$ MGy (Minimum TID value)

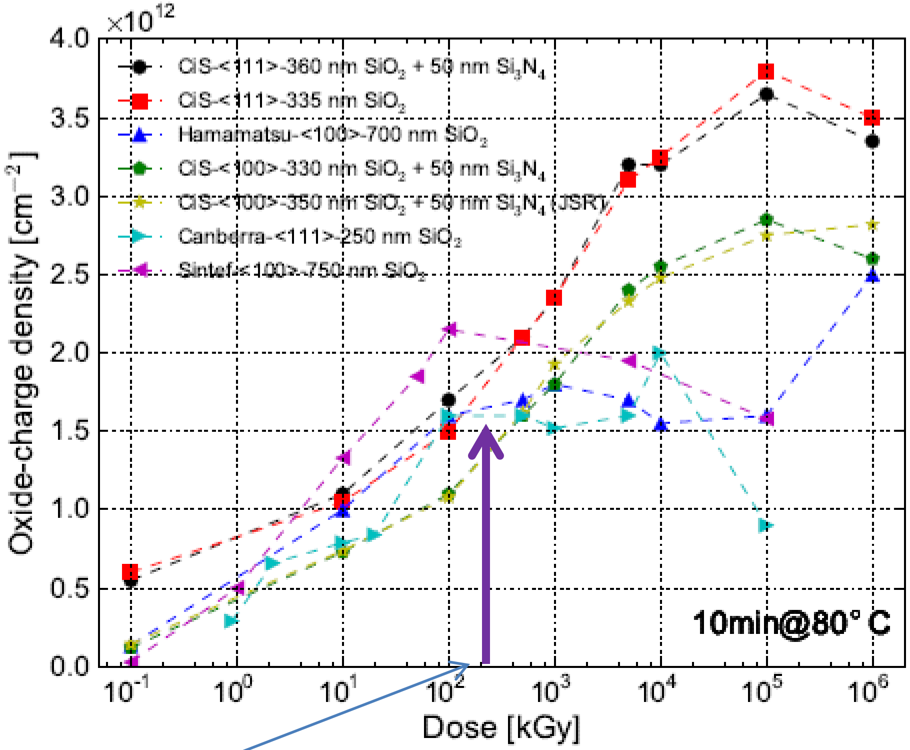
*Murat M. et al; *IEEE Trans. Nucl. Sci., 2004, vol. 51,* pp. 3211–3218.

Surface damage - Oxide charge density (Q_F)

- Surface damage had been incorporated into TCAD simulations using the Oxide charge density (Q_F) only
- Oxide charge density (Q_F) is a complex function of fabrication process, dose rate, 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

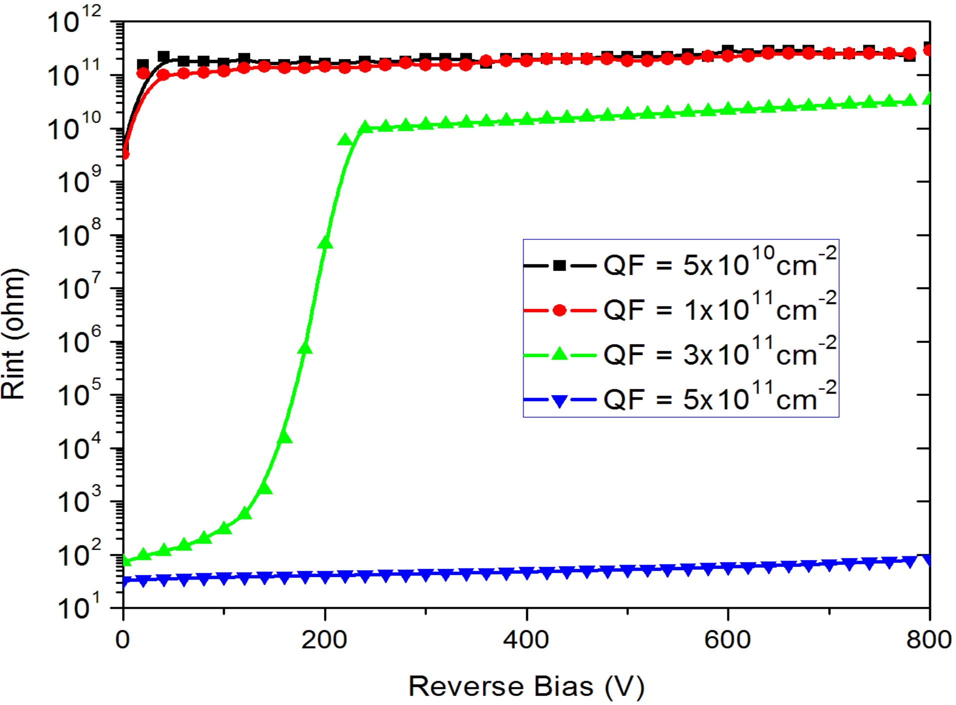
Ranges of Oxide charge density (Q_F) used for different fluences



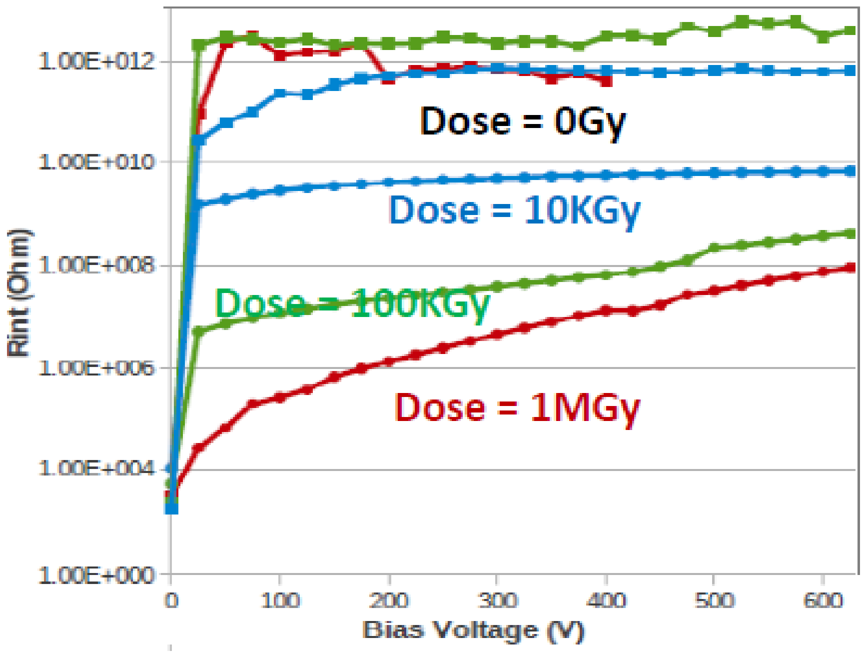
Robert Klanner, RESMDD-2013

Minimum TID for proton fluence 1e15 $n_{eq}cm^{-2}$

R_{int} simulations (using Q_F only) for X-ray irradiated n-on-p strip sensors



Simulated R_{int} for Pitch = 80µm



Measured R_{int} for Pitch = 80µm

Thanks to Anna Peisert and Hadi Behnamian

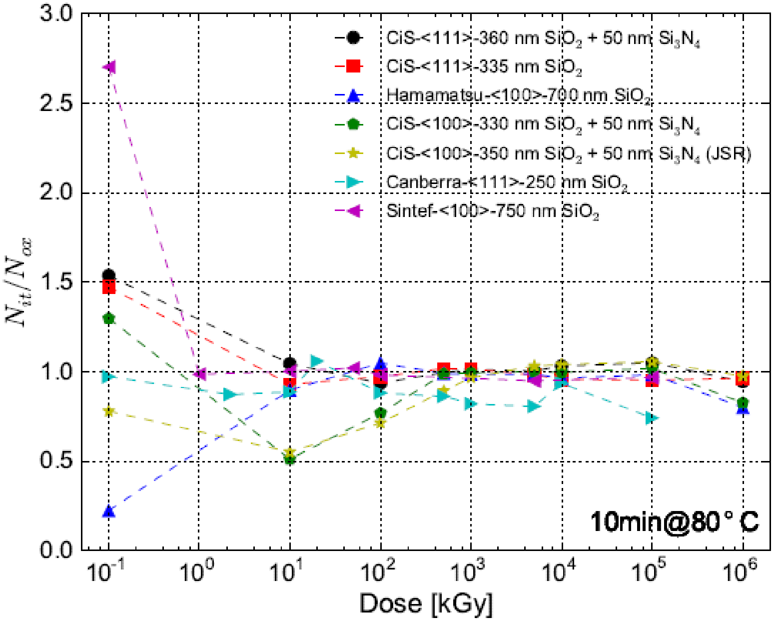
N-on-p Strip sensors (HPK Campaign) were irradiated with different TID of X-ray and interstrip resistance was measured in CERN lab (Anna Peissert, Hadi Behnamian)

- Results were shown in various meetings
- R_{int} simulations and measurements for X-ray irradiated sensors are inconsistent
- Second batch of strip sensors was irradiated to confirm the measured results
- Similar R_{int} results are obtained using the Synopsis TCAD simulations (Timo Peltola)
- The incorporation Q_F only for surface damage simulations is not sufficient !
- Need to incorporate the N_{it} also !

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

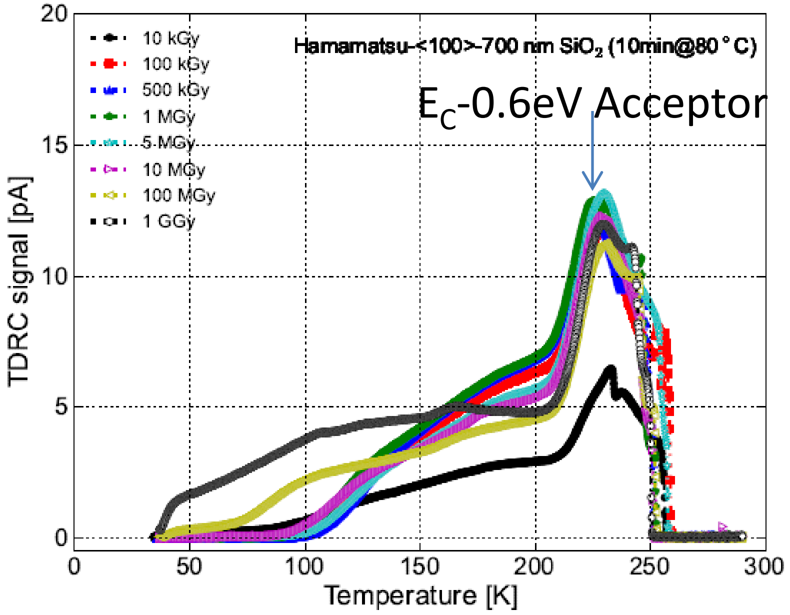
The interface trap states can play very important role in irradiated Si sensor, because,

- Its density (N_{it}) is comparable to the Oxide charge density (Q_F) as shown in the right side plot*
- 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*)
- R_{int} simulations indicates that these interface traps are acceptor type states (next slide)



Assumptions for N_{it} implementation in simulation;

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}*



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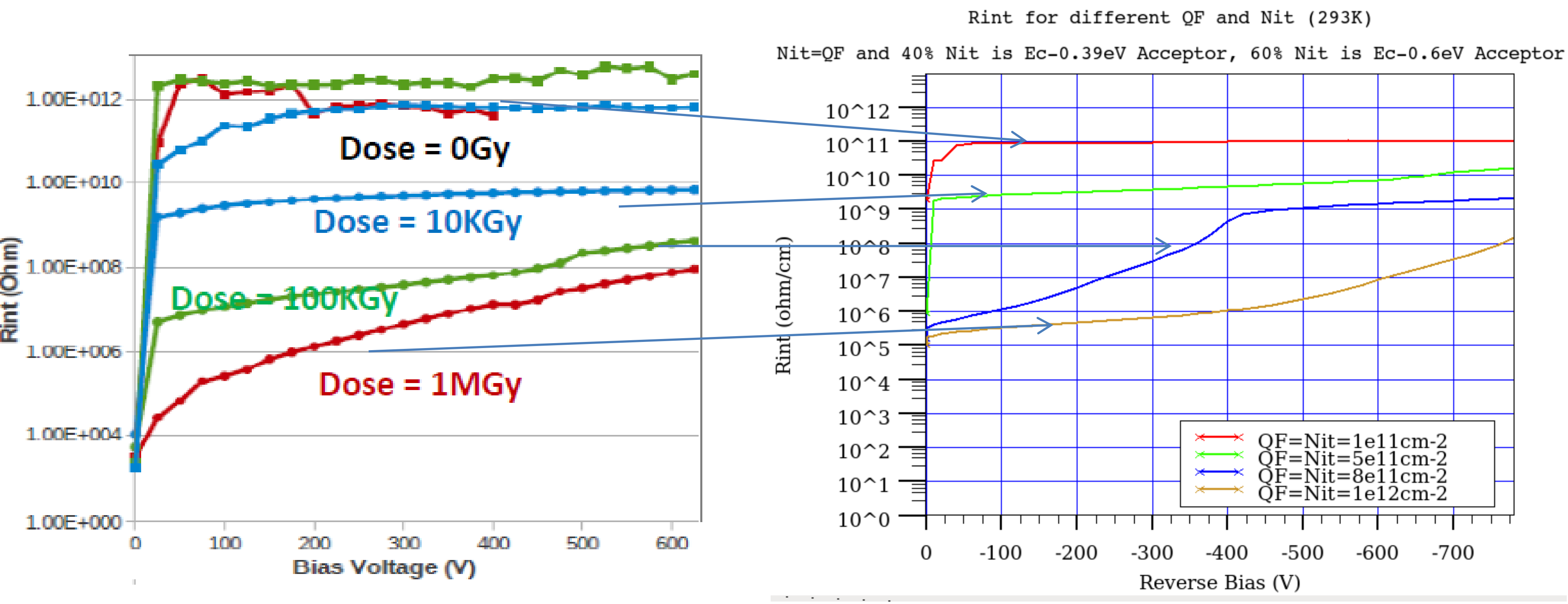
*J. Zhang, DESY Thesis-2013, "X-ray radiation damage studies and design of a Si Pixel sensor for different fluences for science at the XFEL"

R_{int} simulations (using Q_F + N_{it}) for X-ray irradiated n-on-p strip sensors

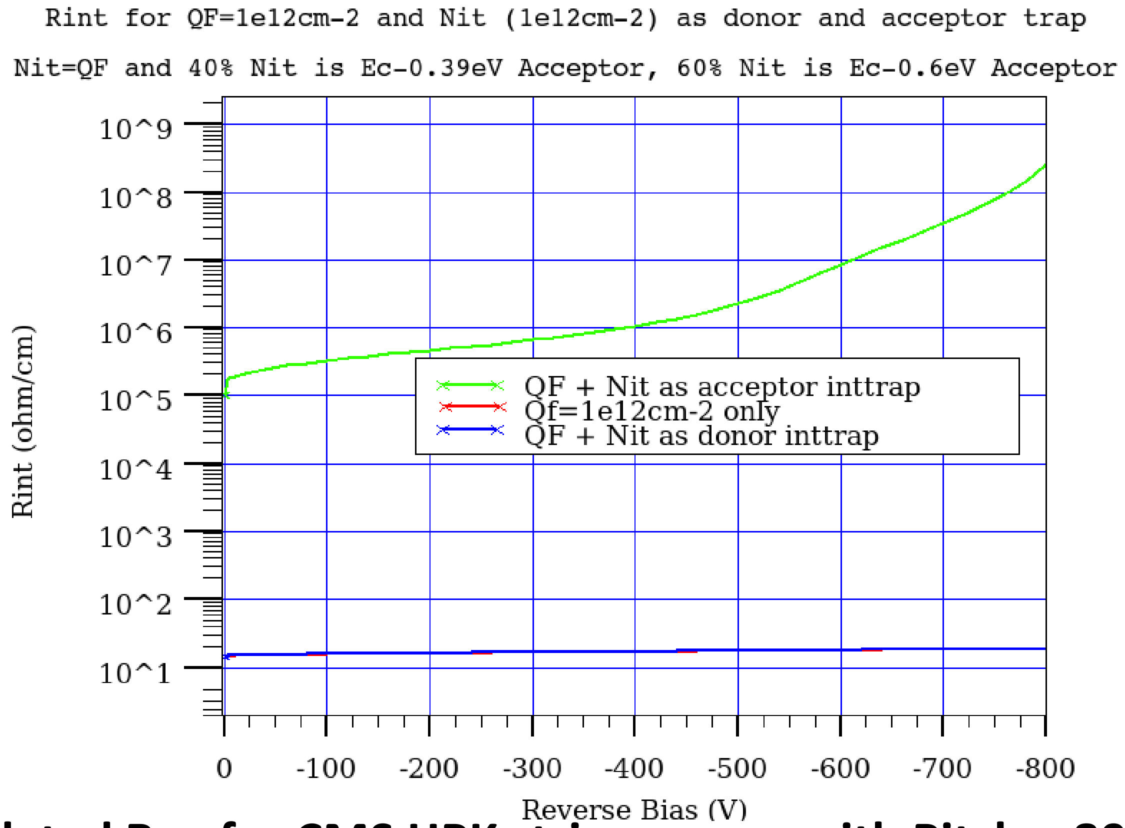


Measured R_{int} for Pitch = 80µm

Simulated R_{int} for Pitch = 80µm

- Much better agreement between the measured R_{int} and simulated one assuming that higher Q_F and N_{it} are produced for the higher X-ray dose.
- Simulated R_{int} is of the similar order and shows trends similar to measurements
- For R_{int} simulations, assumptions discussed in last slide are used.

R_{int} simulations - Nature of Interface traps



Simulated R_{int} for CMS HPK strip sensors with Pitch = 80µm

- Use of only Q_F produces very low R_{int} which does not match with the R_{int} of X-ray irradiated strip sensors

- Use of Q_F + N_{it} (as Donor) also produces very low R_{int}

- Q_F + N_{it} as Acceptor traps produces R_{int} similar to the measured R_{int} (see slide 7)
  Hence N_{it} traps should be taken as Acceptor type.

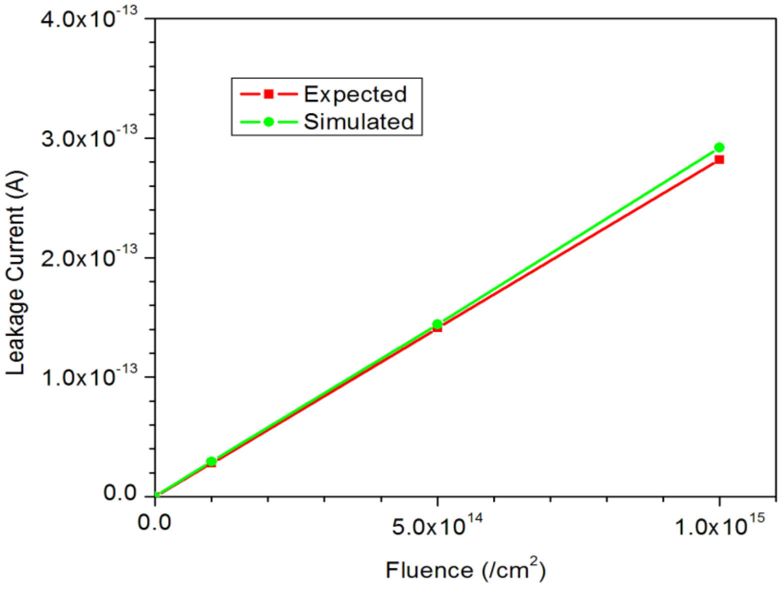
Probably, it is because of the strong positive space charge due to nearby oxide charge density, that only acceptor traps along the interface are activated.

Bulk (two trap) damage model

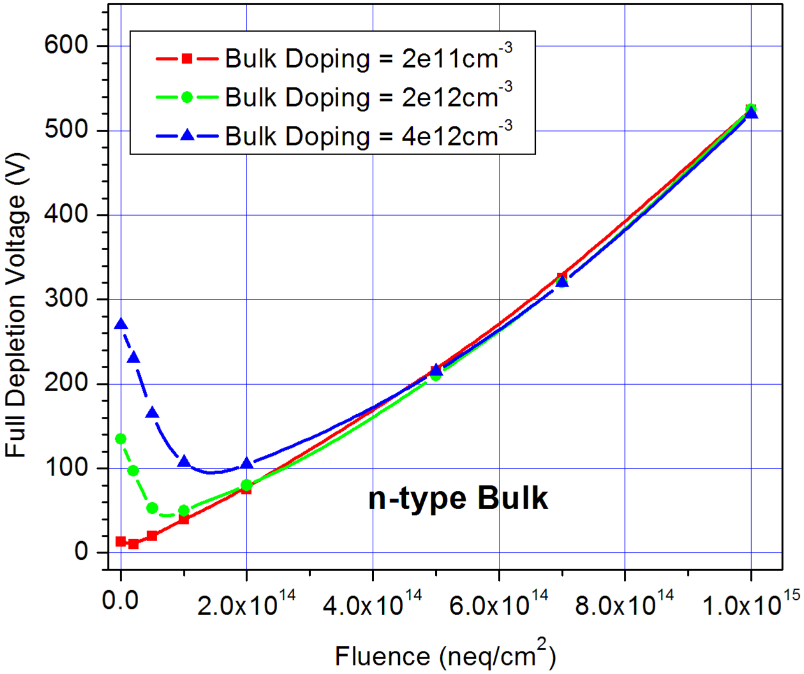
Bulk damage model (for proton irradiation)

- Produce experimentally measured currents for irradiated diodes
- Correct full depletion voltages (say, ~500V for 1e15neq/cm^2 fluence of proton irradiation)
- Produces electric fields from both sides

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}

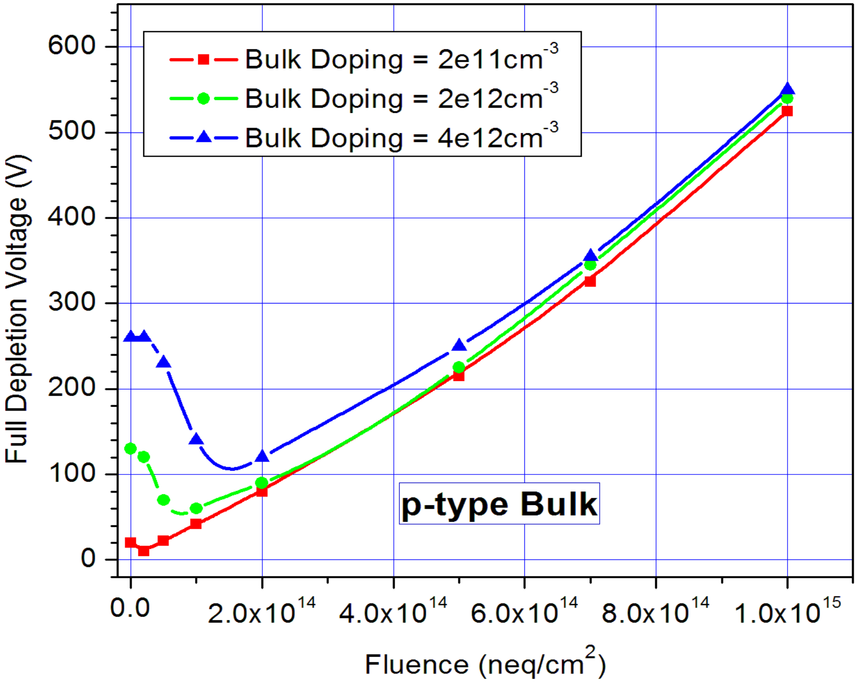


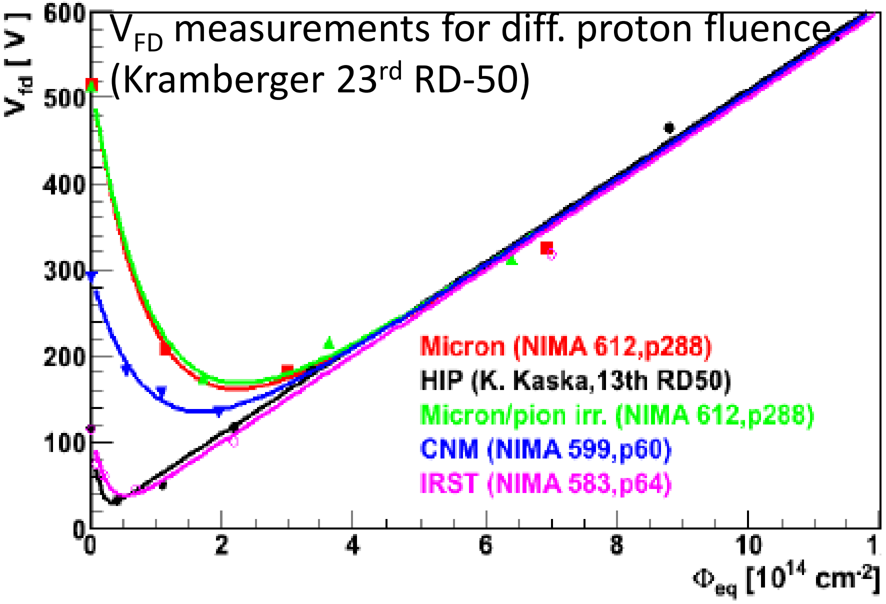
Leakage current comparison (@253K) for 1x1x300µm diode



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

Double junction effect on V_{FD}




V_{FD} measurements for diff. proton fluence (Kramberger 23rd RD-50)

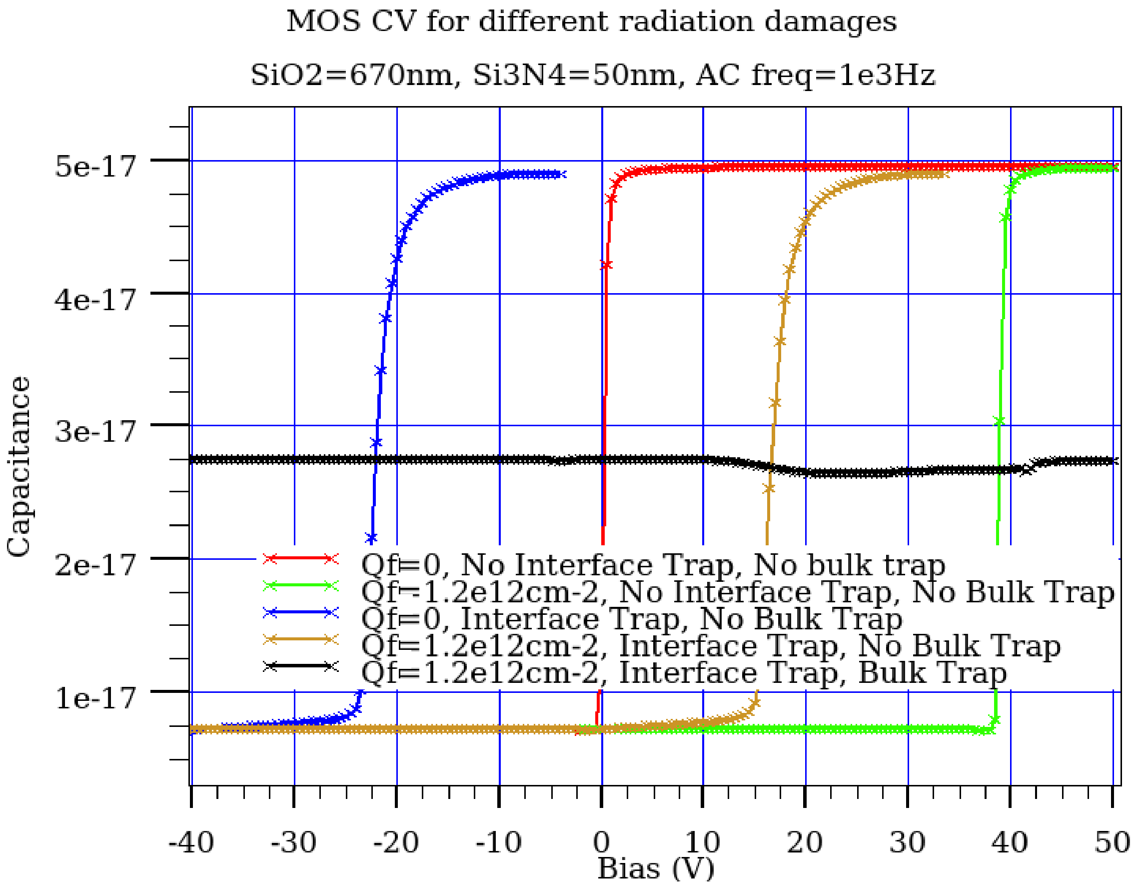
- Initial V_{FD} drop for all of the three bulk doping
- V_{FD} minimum for bulk doping 2e11cm^{-3} happen at very low fluence but for higher bulk doping, V_{FD} minimum is at higher fluence

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 leading to lower V_{FD} bias , for initial fluence.
- There may not be any need for the “Donor/Acceptor Removal” terms.

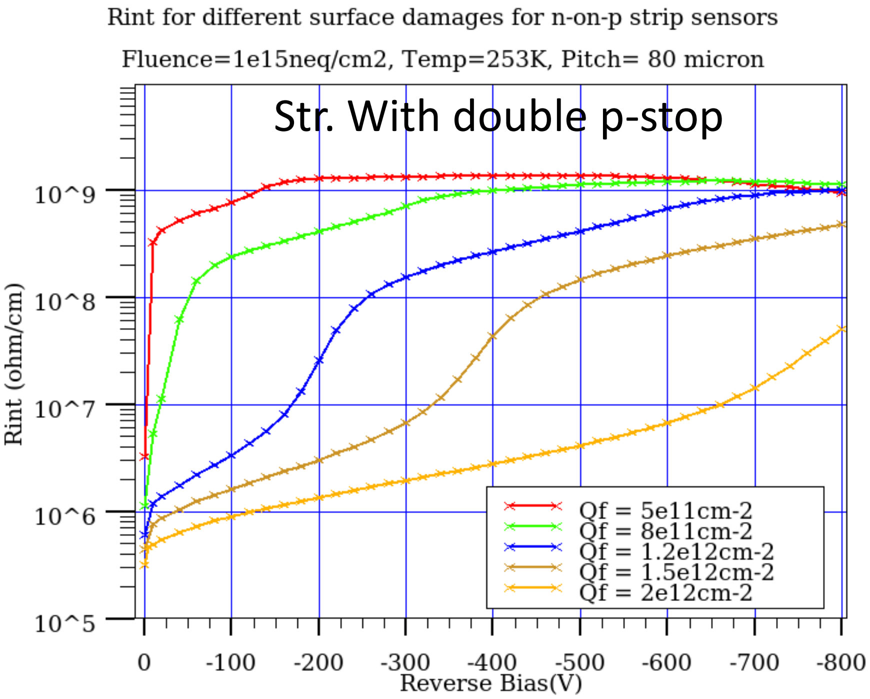
- see 24th RD-50 talk further discussions!

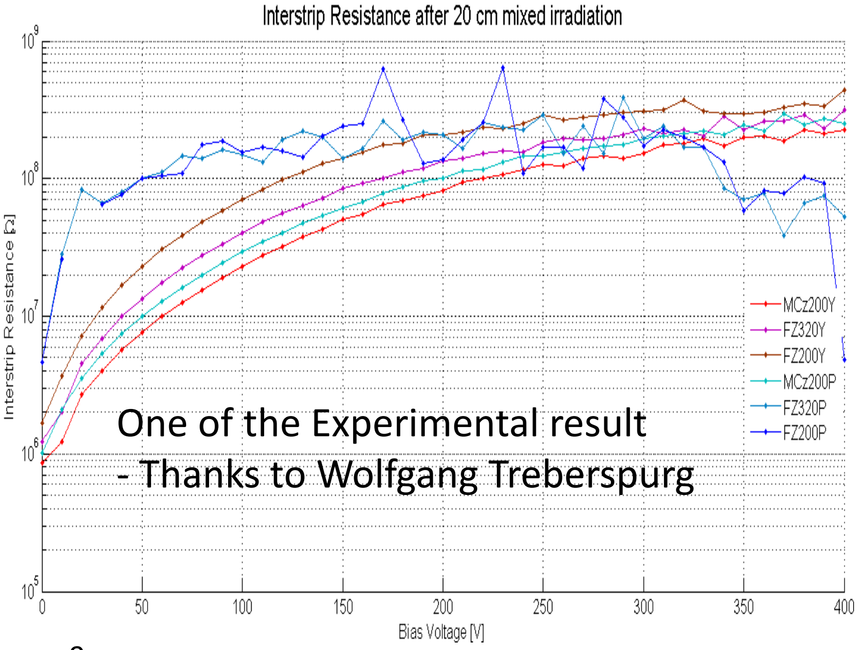
Effect of radiation damage - CV for MOS



- Interface states can significantly lower the flat band voltage value for MOS
- Effect of Q_F and N_{it} are opposite !
- It is not possible to extract any meaningful flat band voltage for hadron irradiated MOS (CV curve is almost flat for them, as shown by black curve, for fluence=1e15 n_{eq}/cm^2). A similar effect is reported in Maria Bernard-Schwarz's diploma thesis.

Simulations of R_{int} for Fluence = $1x10^{15}n_{eq}/cm^2$

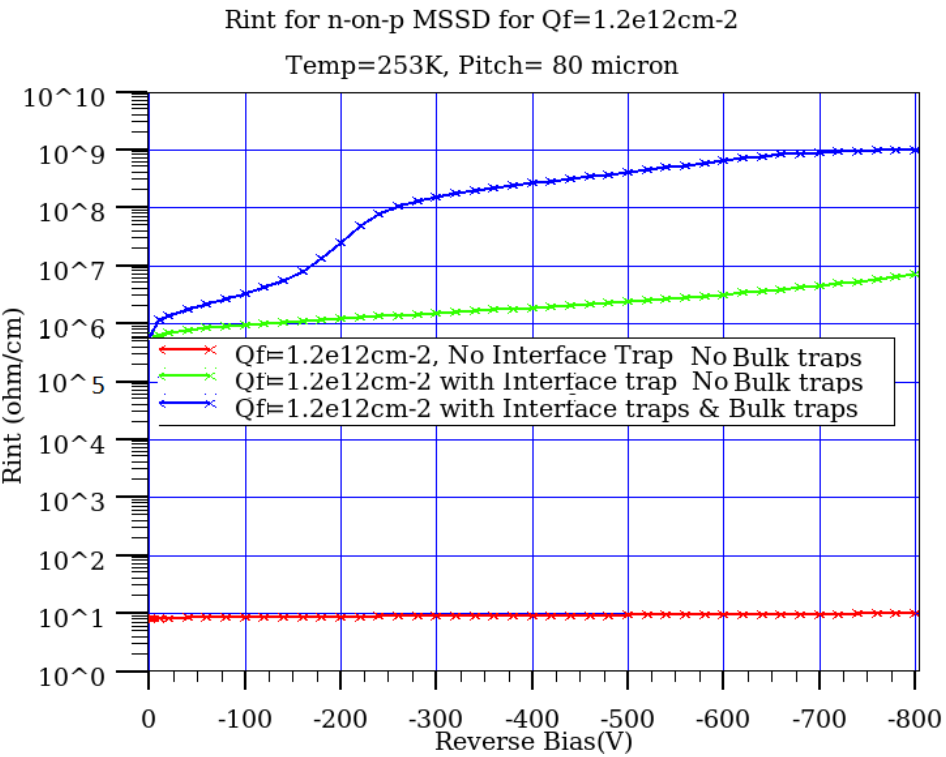


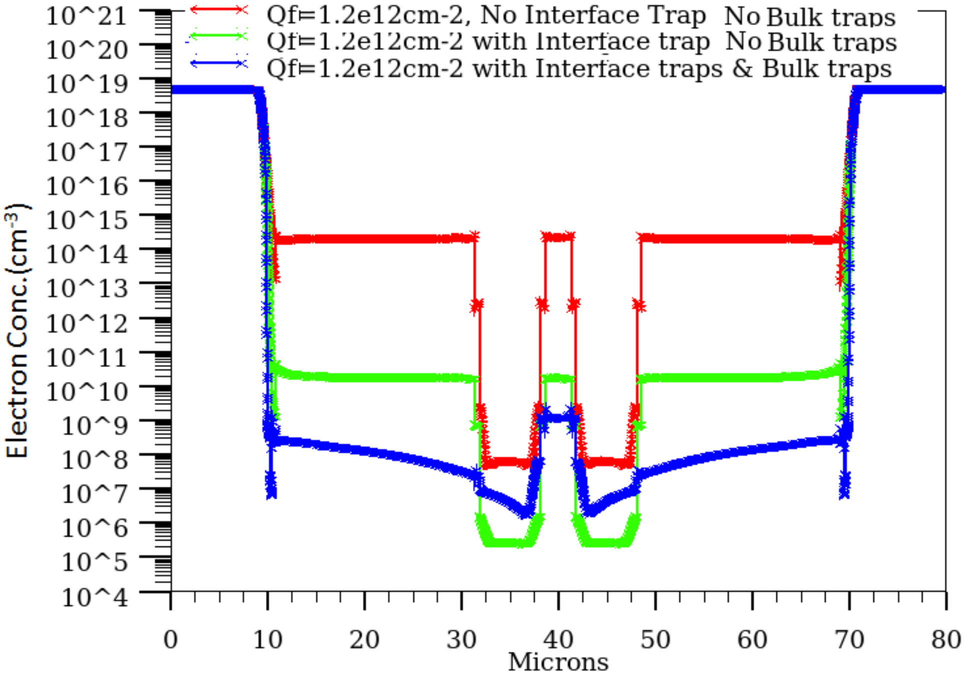


10^9

- R_{int} values of more then 100MOhm at 600V is possible for $Q_F = 1.5e12cm^{-2}$
- Q_F & N_{it} are used (in equal amounts) for the surface damage
- When proper N_{it} is used with Q_F, there is no need to use very high acceptor conc. in the bulk damage model for R_{int} simulation (which we had to do in five trap model when we were using only Q_F as surface damage, see our talks in 23rd 50)

Effect of Bulk and Surface Damages on R_{int}

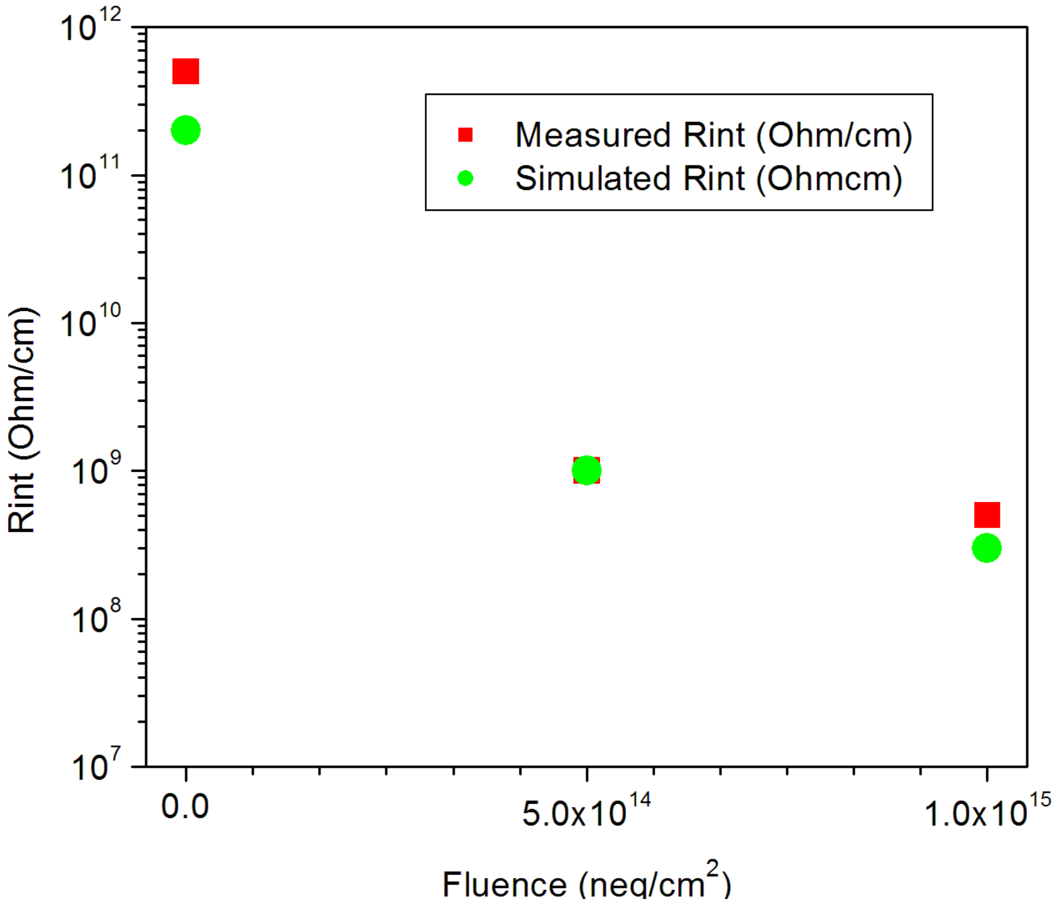




Electron conc. 0.1µm below SiO_2/Si interface

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

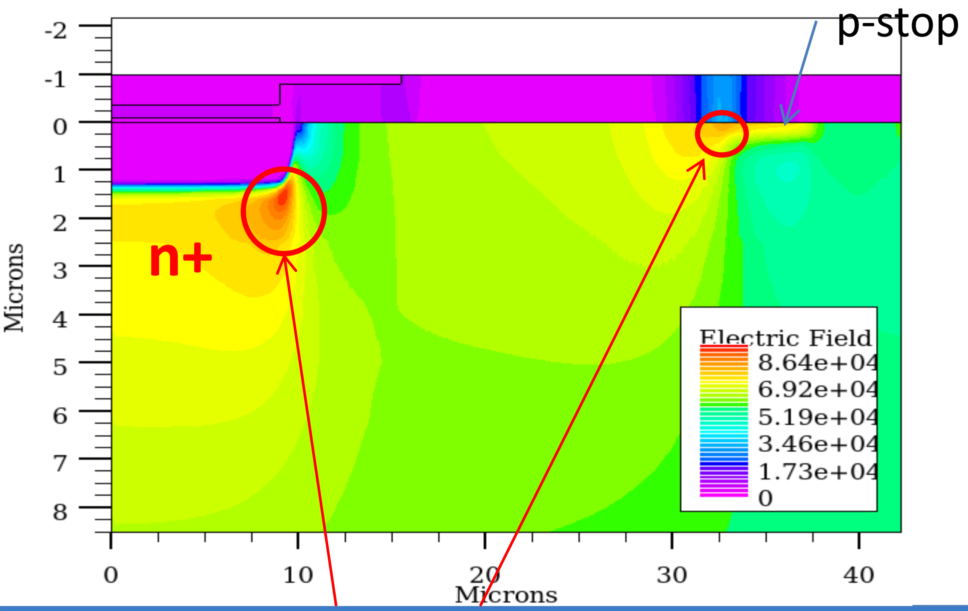
R_{int} simulation and measurements: Comparison

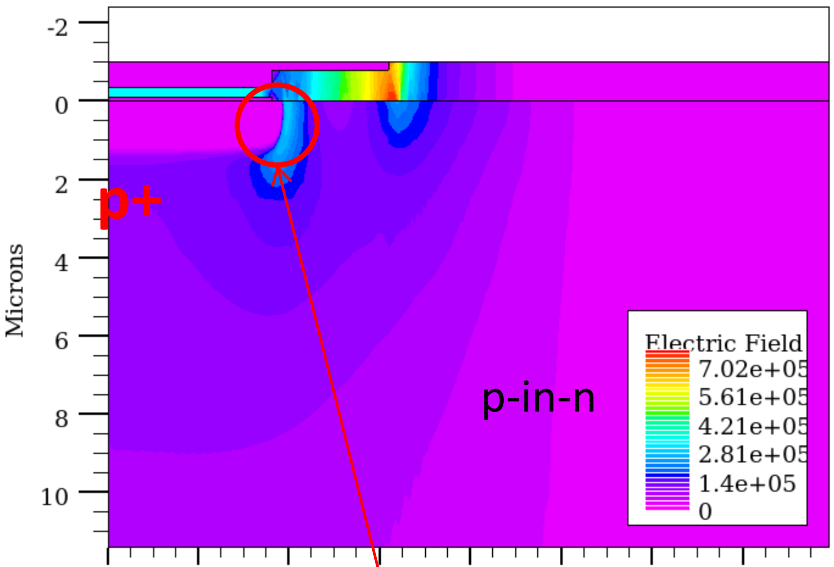


- Good agreement between measured and simulated R_{int}
- Q_F & N_{it} are used (in equal amounts) for the surface damage
- There is variations in measured* R_{int} (for different samples, irradiated with same fluences) and simulated R_{int} too (assuming different Q_F)

*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

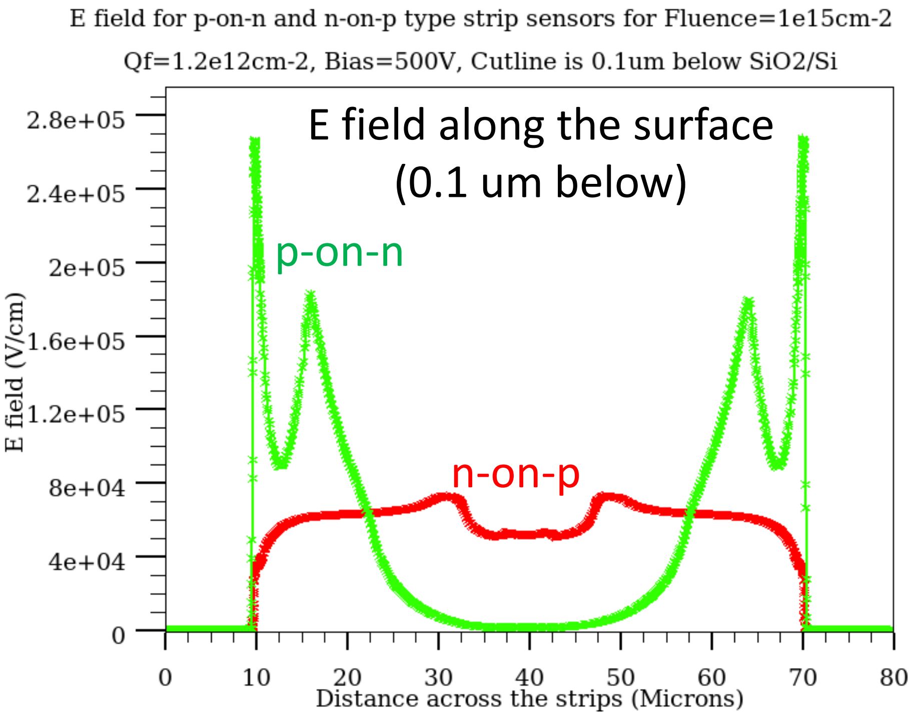
Maximum E field for p-on-n MSSD is just below SiO$_2$/Si interface near p$^+$ strip

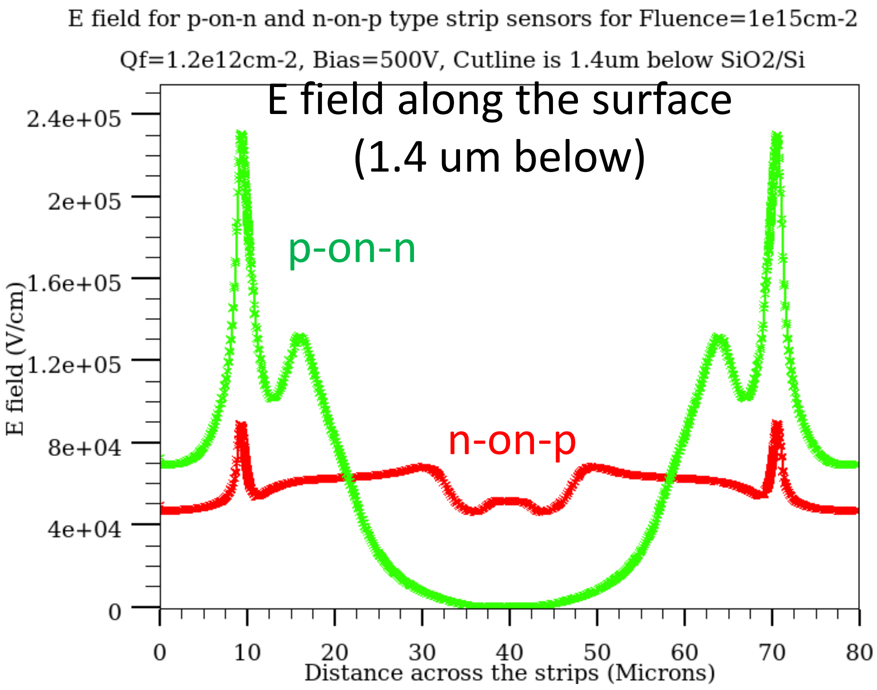
- Shown by cutline 0.1µm below SiO$_2$

➢ 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-stop doping densities, it is quite possible, that microdischarges are taking place at n$^+$ curvature.

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





Flux = 1×10^{15}cm^{-2} ; $Q_F = 1.2\times10^{12}$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.
  - Q_F & N_{it} are used (in equal amounts) for the surface damage

For more results, see VERTEX-2014 presentation

Summary

- R_{int} trends for X-ray irradiated n-on-p strip sensors can not be reproduced using Q_F onl
  - Need to implement N_{it} 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
- If one uses N_{it} properly, there is no need for higher acceptor trap conc. in bulk damage model for good R_{int} for n-on-p strip sensors having low p-stop doping (CMS HPK)
- Interface trap states and negative space charge, near n^+, due to bulk damage results in good R_{int} values for low p-stop doping and even without any p-stop
- Highest electric field in irradiated n-on-p is much lower compared to irradiated p-on-n
- Further simulations for TCT and CCE are going on

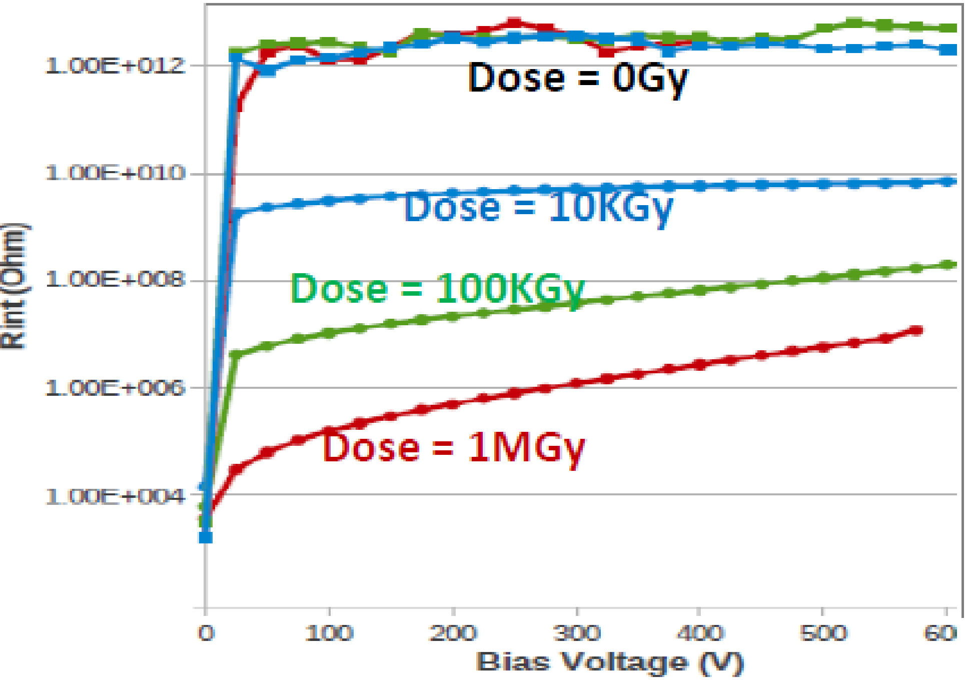
Thanks to Michael Moll for suggesting N_{it} use and for many useful discussions!

Thanks for your attention!

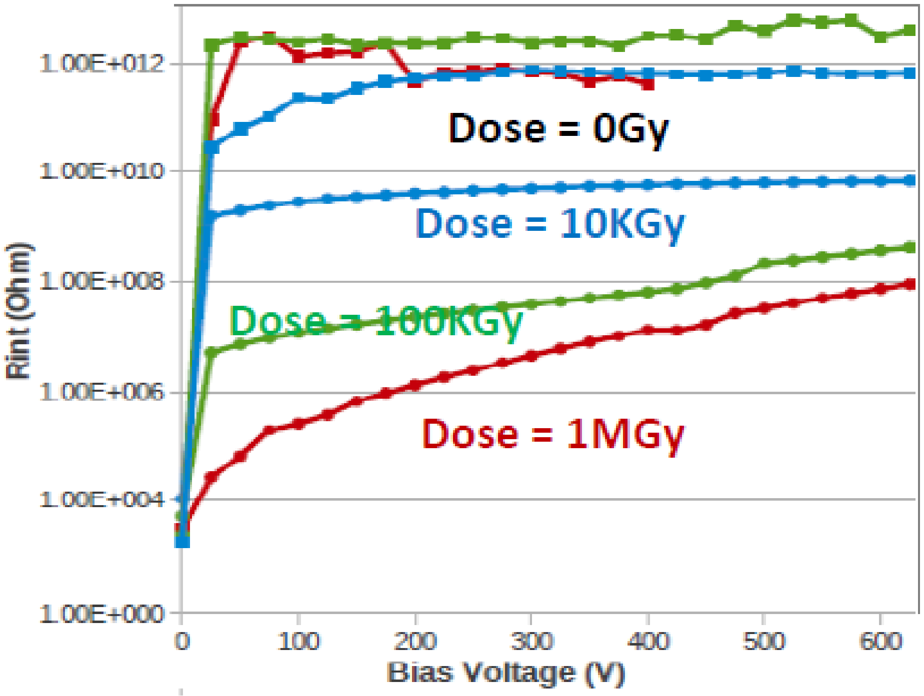
Rint measurements for irradiated DC-CAP Sensors

-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.



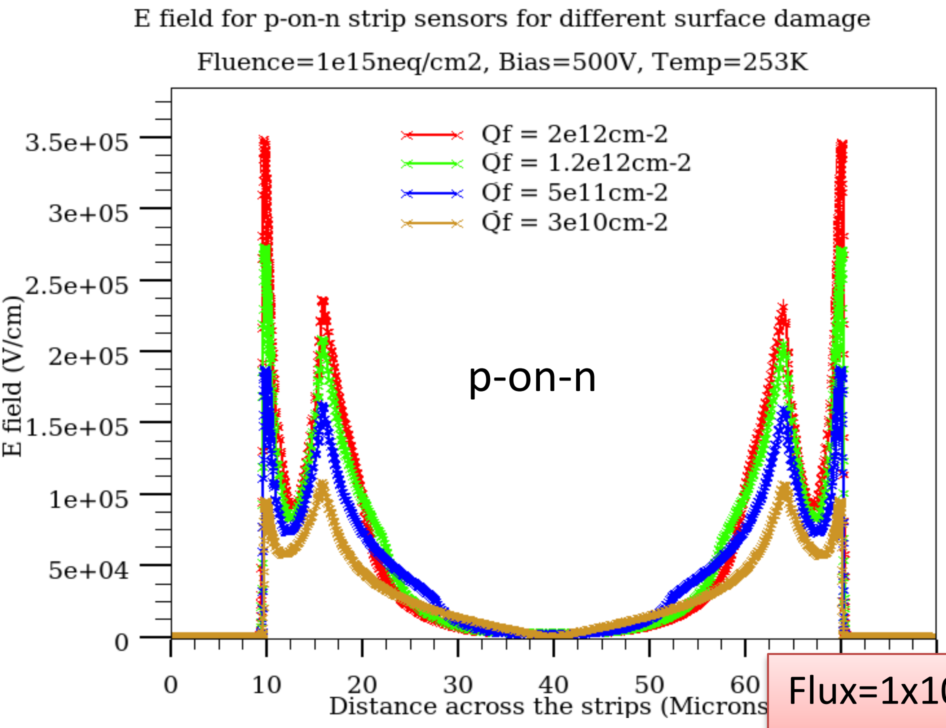
Pitch = 120 µm



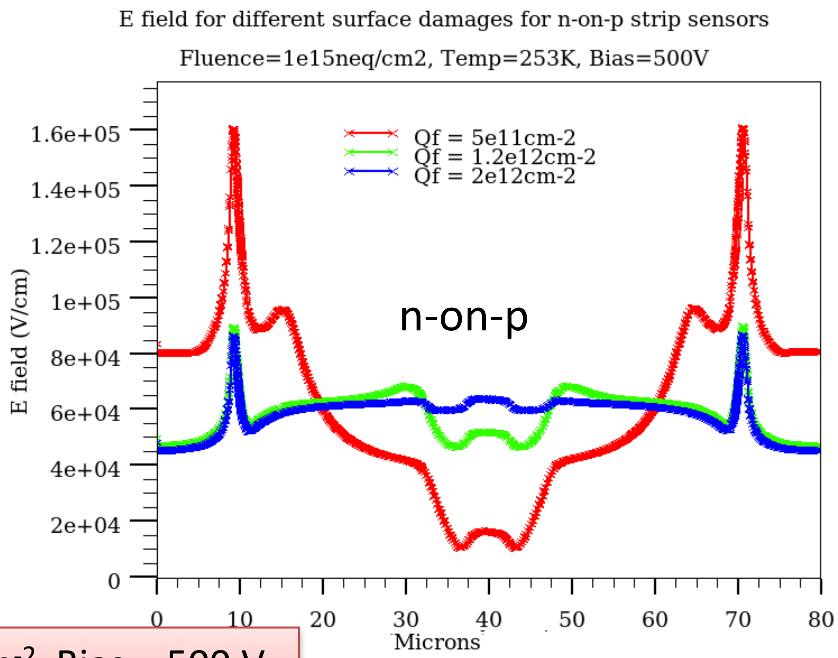
Pitch = 80 µm

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

E. Field (Irradiated) : Effect of Q_F


E field for p-on-n strip sensors for different surface damage

Fluence=1e15neq/cm2, Bias=500V, Temp=253K


E field for different surface damages for n-on-p strip sensors

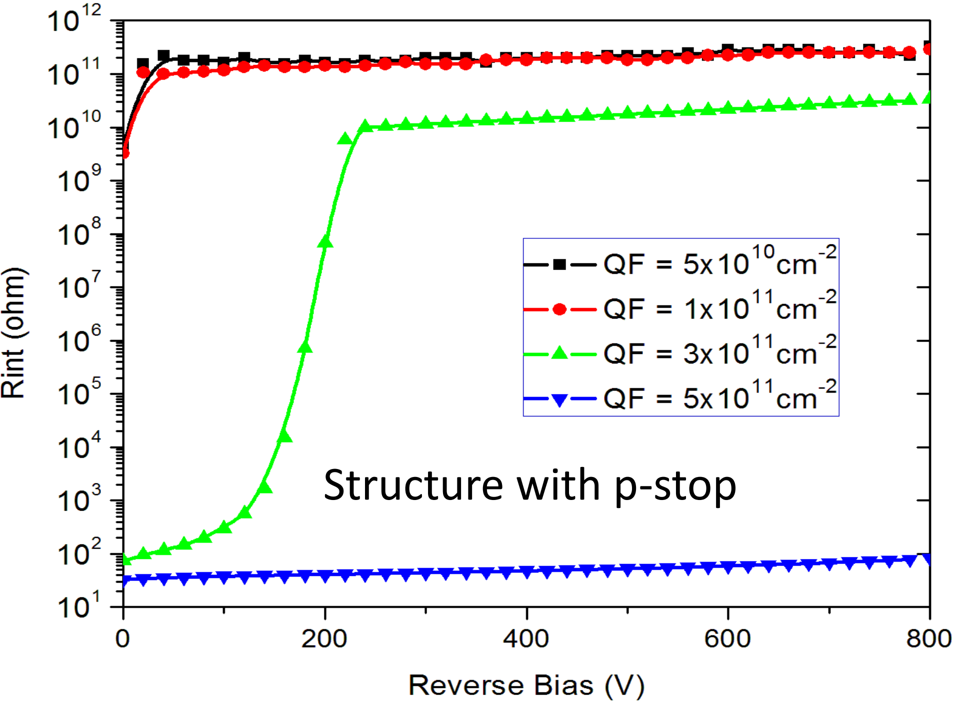
Fluence=1e15neq/cm2, Temp=253K, Bias=500V

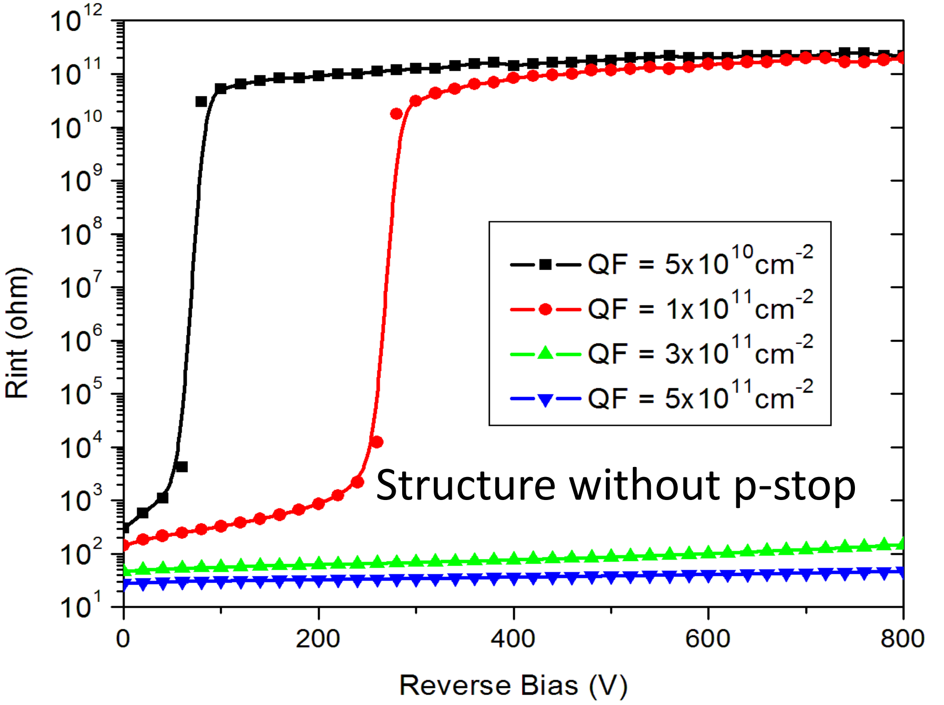
Flux=1×10^{15}cm^{-2} Bias = 500 V

- **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)**

Simulation of Rint without Bulk damage (Only Q_F variation)



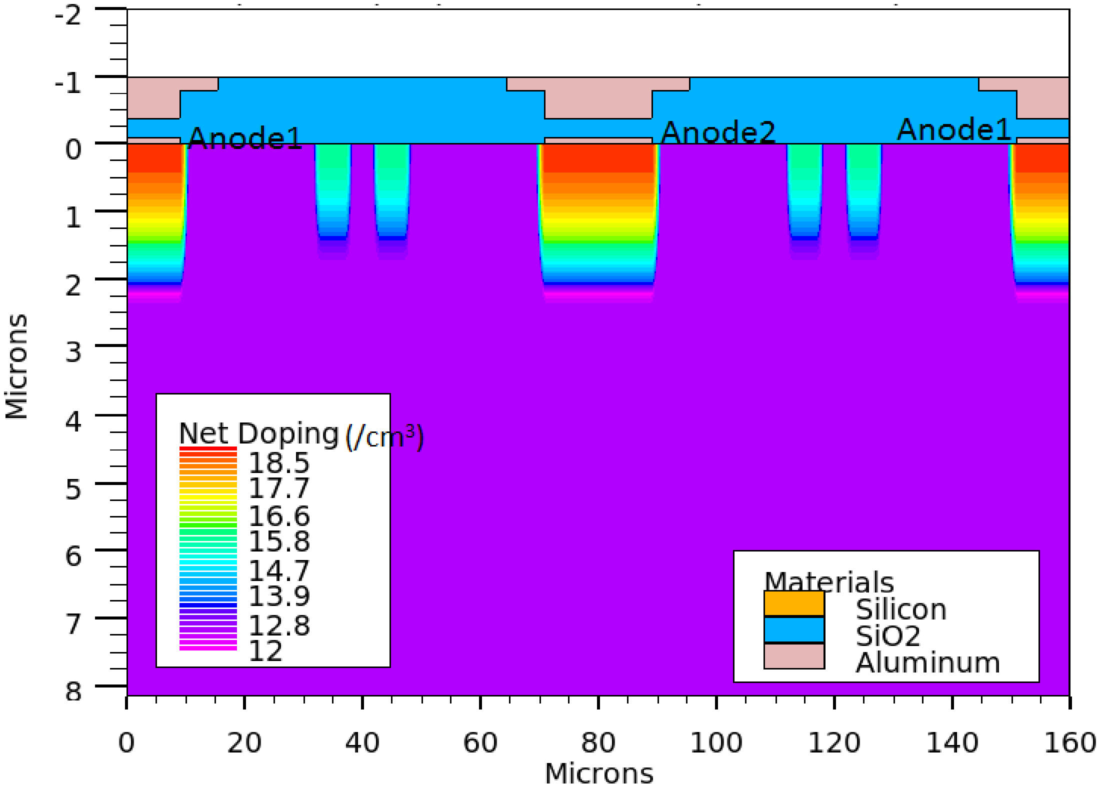


Three different Rint curves

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.

Simulation structure

- Bulk doping = $3\times10^{12}cm^{-3}$
- 2-D simulations
- Double p-stops
- Each 4µm wide separated by 6µm
- P-stop doping = $5\times10^{15}cm^{-2}$
  P-stop doping depth = 1.6um
- CMS HPK tracker upgrade campaign parameters

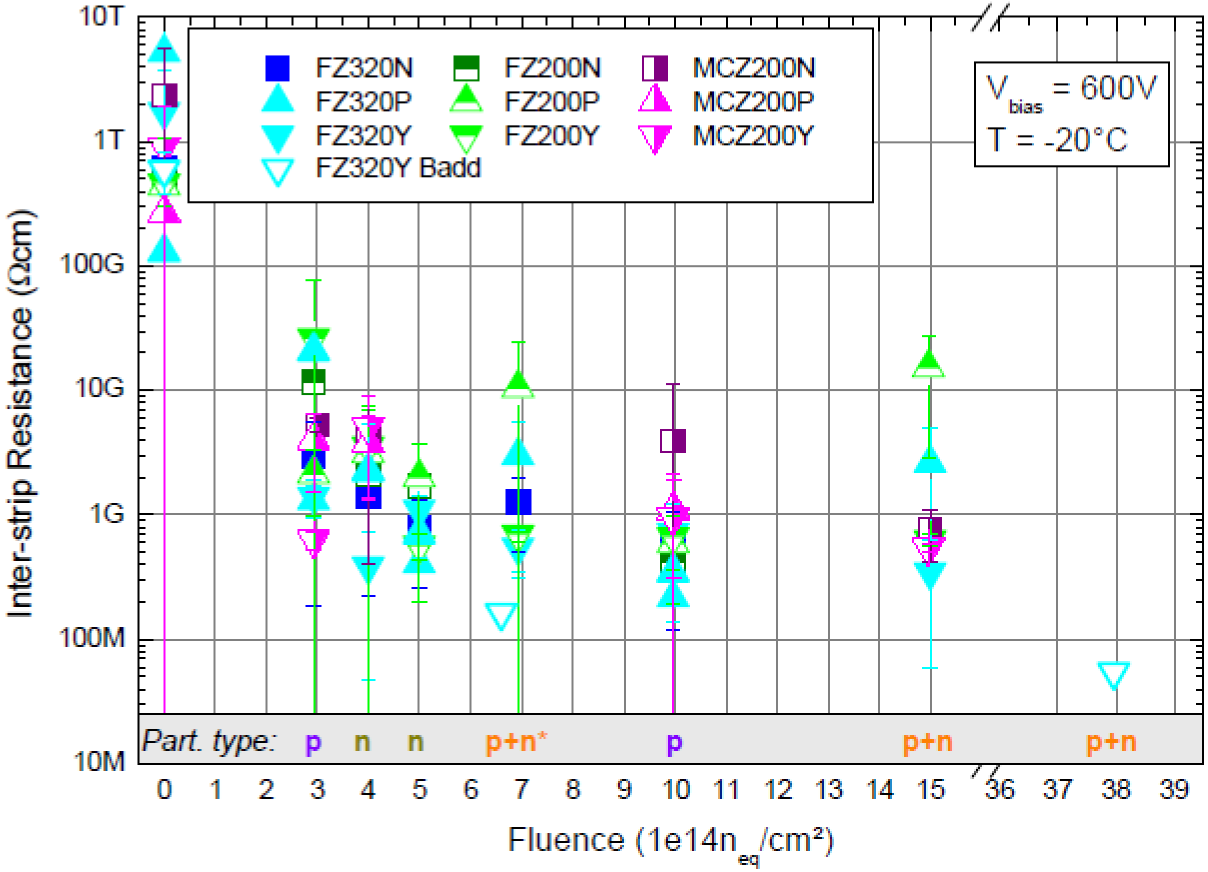


☐ ***Three strips structure*** was used for R_{int} simulations in which bias of 0.2V is given to Central DC Anode while two neighboring Anodes are shorted together. Reverse bias is provided from backside contact (not shown here)

☐ Simulations are carried out using Silvaco TCAD tool.

Rint variations for different fluence

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

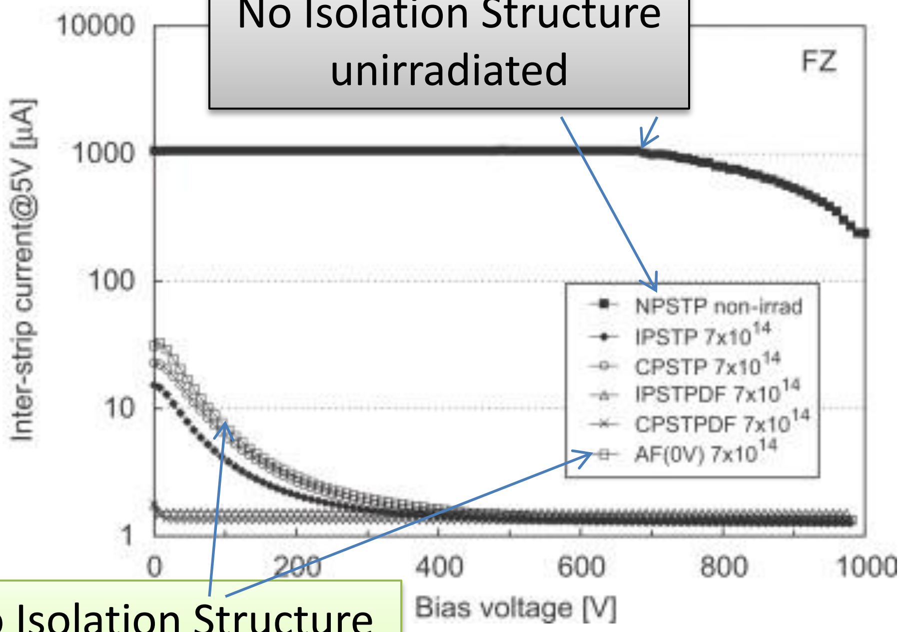


Another experimental evidence …..

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

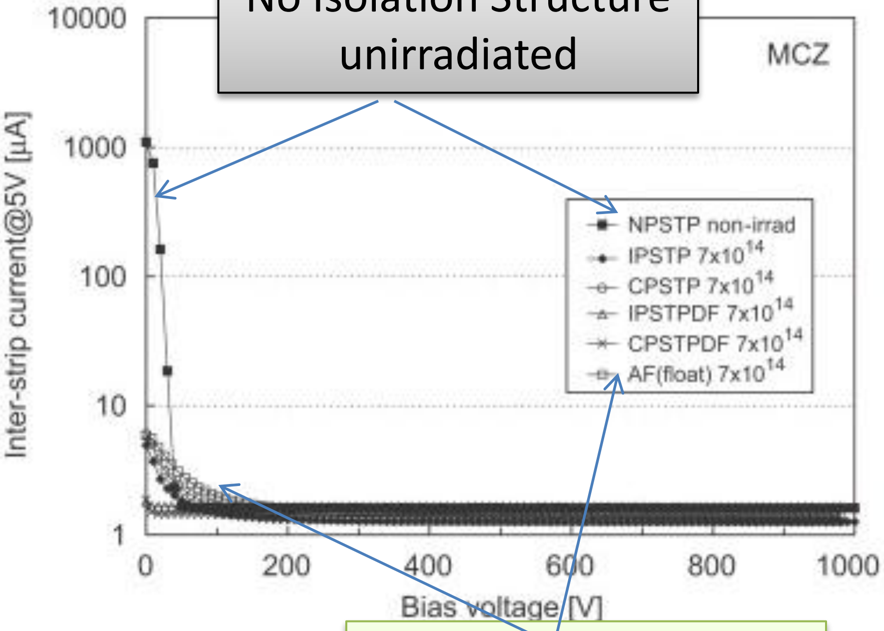
Strip isolation was observed for n+p- sensors without isolation structure after proton irradiation

- Clear signature of proposed mechanism !



No Isolation Structure unirradiated

No Isolation Structure Irradiated



No Isolation Structure unirradiated

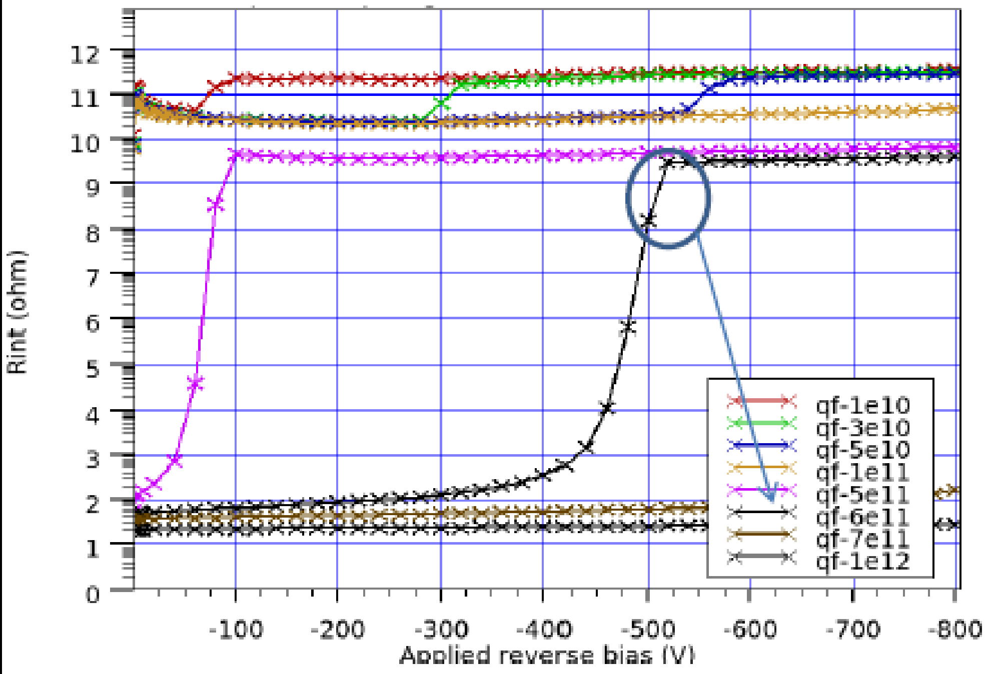
No Isolation Structure Irradiated

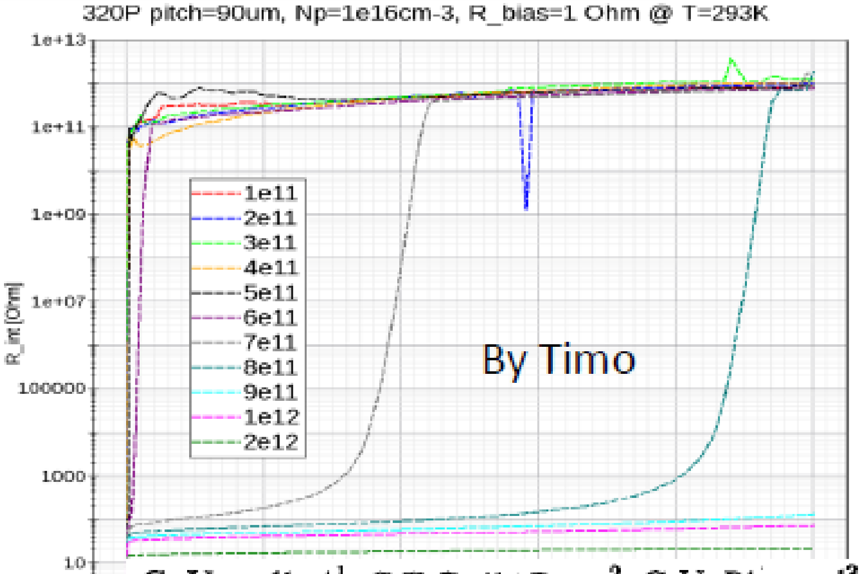
Plot of Interstrip current vs. applied reverse bias.

- NPSTP – No Isolation structure (non-irradiated).
- AF – No isolation structure (irradiated by flux = $7x10^{14}cm^{-2}$).
- All other structures are with different layouts of Pstops (Irradiated)
- Voltage difference between two neighboring strips = 5V

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

DC external resistance = 1 ohm





By Timo

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

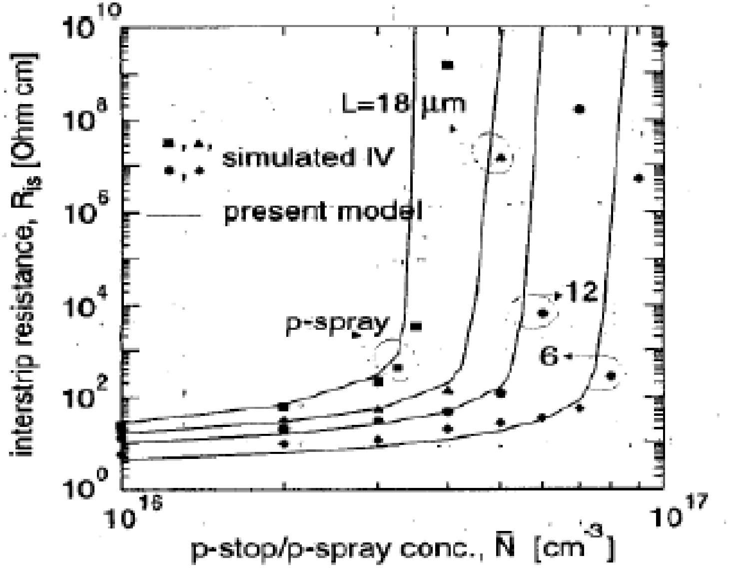
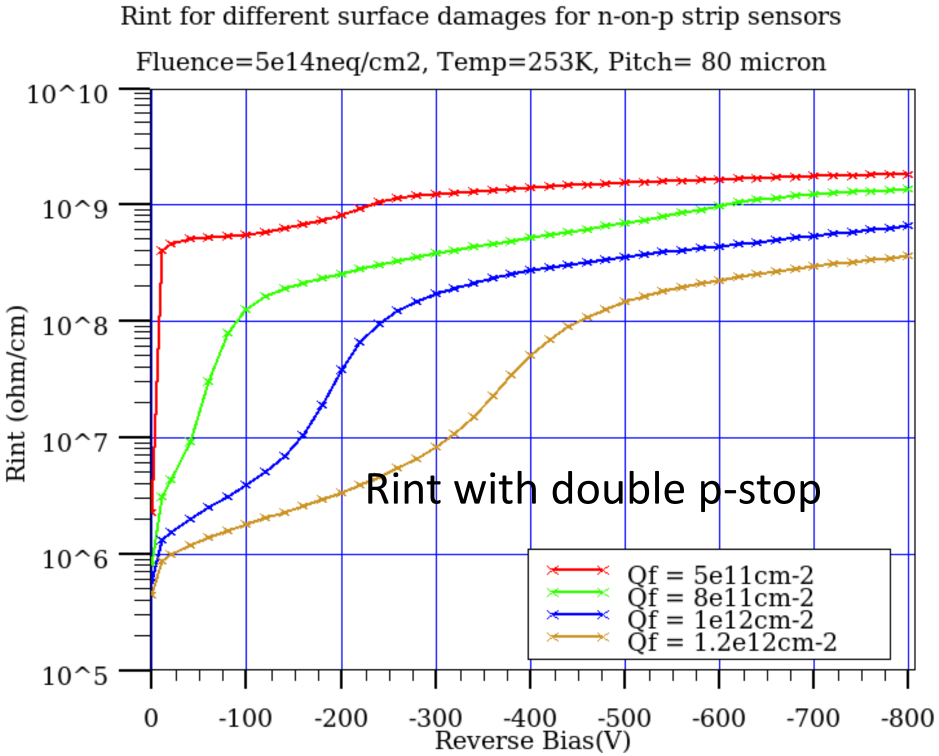


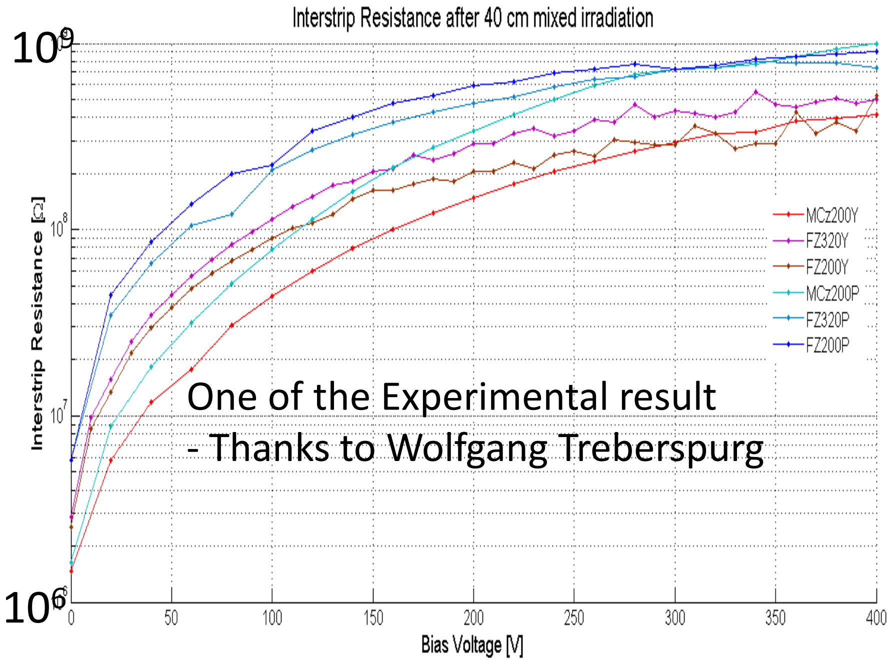
Figure 4: Interstrip resistance values as a function of the p-stop(p-spray) average doping concentration, as obtained from the proposed analytical model and from simulated $I_2(V_1)$ curves. A positive charge density of 2×10^{12} cm^{-2} is assumed in the oxide.

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

Simulations of Rint for Fluence = 5×10^{14}neq/cm^2



Rint with double p-stop

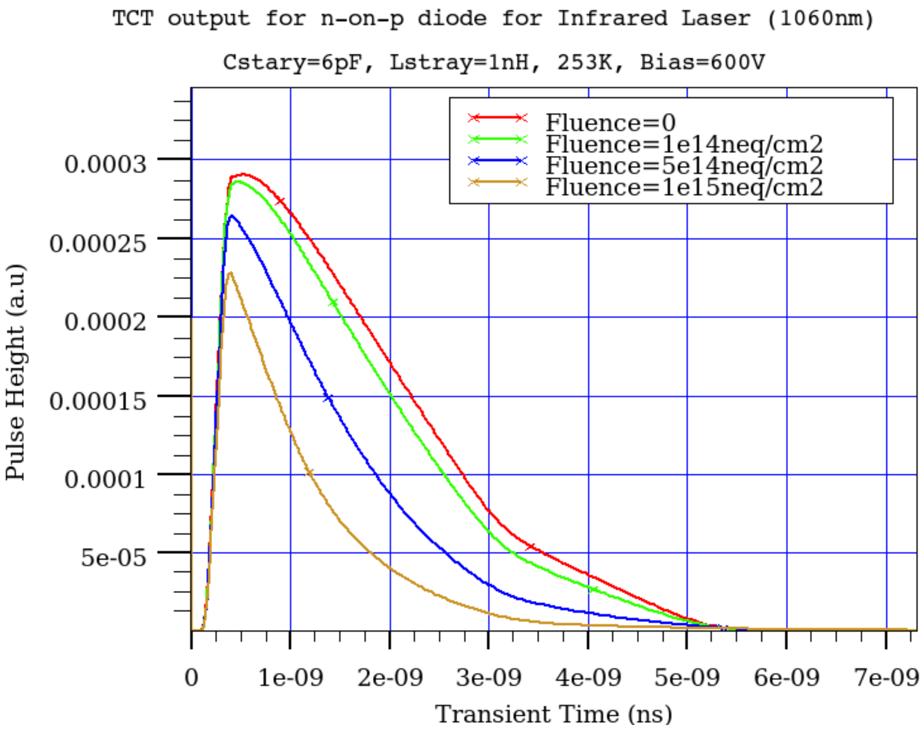


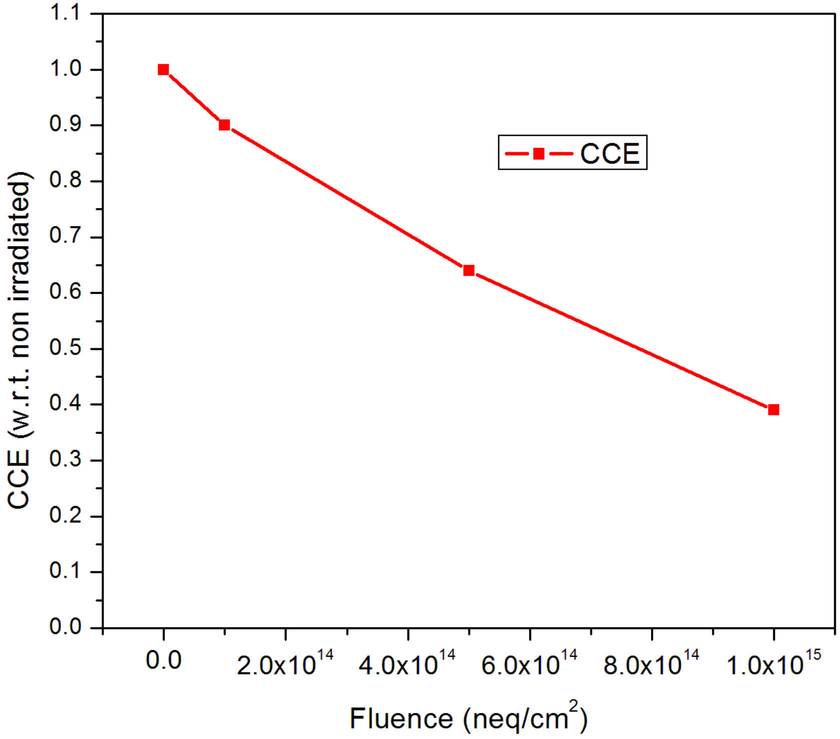
One of the Experimental result

- Thanks to Wolfgang Treberspurg

- ➢ 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 Q_F=5e11cm^{-2}, n$^+$ strips were shorted but after radiation damage, we are having very good Rint)
- ➢ **If one uses N_{it} properly, there is no need for higher acceptor trap concentration for good Rint in n-on-p strip sensors with low pstop/pspray doping (HPK sensors)!!**

CCE simulations using Infrared Laser for n-on-p diode





CCE simulations for diodes

- CCE decreases with fluence (~ 40% for fluence 1e15 neq/cm^2)
- Further simulations for TCT and CCE are going on