Simulations for Hadron Irradiated n^+p^- Si Strip Sensors Incorporating Bulk and Surface Damage

Ranjeet* , A. Bhardwaj, K. Ranjan, M. Moll & A. Peisert , Kavita, Geetika
for
Uni. of Delhi & CERN
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under ISJRP and RD-50

Contents of presentation

- **Simulation approaches for irradiated sensors : up to now!**
- **Some puzzling observations!**
- **Simulation framework**
- **Simulation of Cint & Rint and E field for n+p- strip sensor**
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- **Summary**

Simulation approaches for irradiated sensors : Up to now !

-Either considered surface damage only or considered bulk damage only

No simulation study which incorporate both of these effects 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 Made on p-Type Substrates	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 !

- Previous simulation studies indicates that to ensure strip isolation (in case of high surface oxide charge density ~ 1-2x10^{12}cm^{-2}) between n+ strips, Pstop/Pspray peak doping densities should be ~ 1x10^{17}cm^{-3} (P. Claudio, IEEE 2006).

It is common practice in sensor studies (till now) to use

Pspray ~ few times 1x10^{16} cm^{-3} (above it breakdown voltage will be very low)

Pstop ~ 1x10^{17}cm^{-3}

So in case of Si sensors irradiated with very high fluence of ionizing radiation (proton or pion) there must not be strip insulation for very low p-stop/p-spray doping densities.

But contrary to this experience :

- Strip Insulation is not a problem for Si sensor with very low p-stop (~ 5x10^{15}cm^{-3}) and p-spray doping densities (~1x10^{15}cm^{-2}) and irradiated with high fluence of protons (~1x10^{15}cm^{-2}neq) (CMS-HPK tracker phase-II upgrade study)
- Observations of other parameters like Cint, also do not follow the expected trends for oxide charge density build up with irradiation.

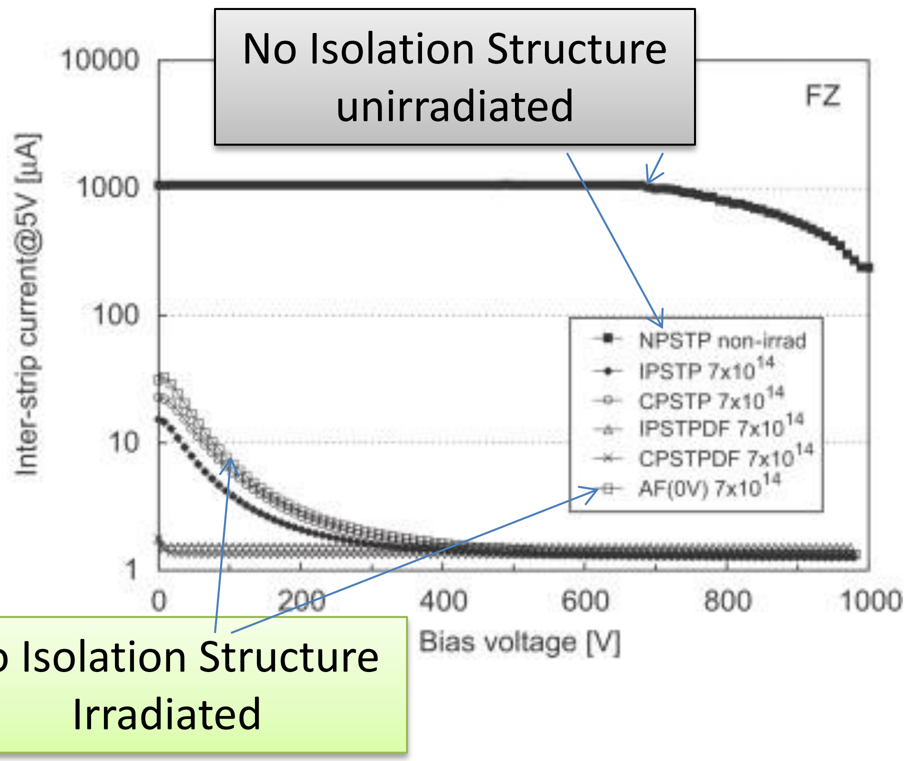
Oxide charge density (Q_F) appears to be suppressed in the HPK sensors!

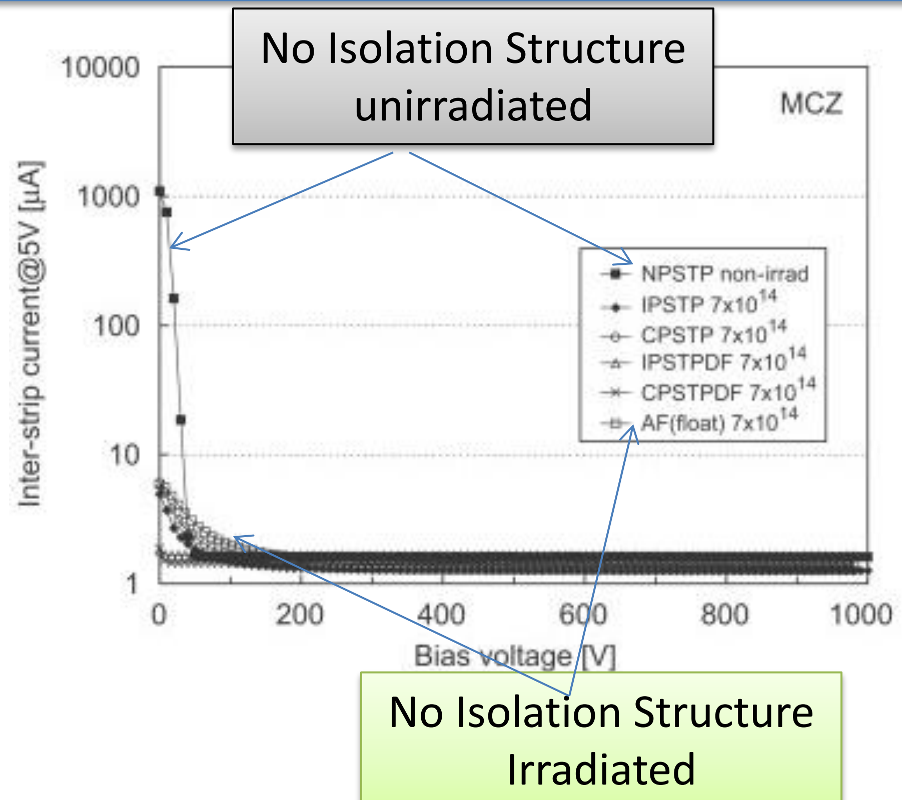
Further, for irradiated n-in-p type sensors, it was expected that maximum E field would be near p-stop curvature. But microdischarge have been observed near n+ strips (Atlas tracker upgrade work)

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 !

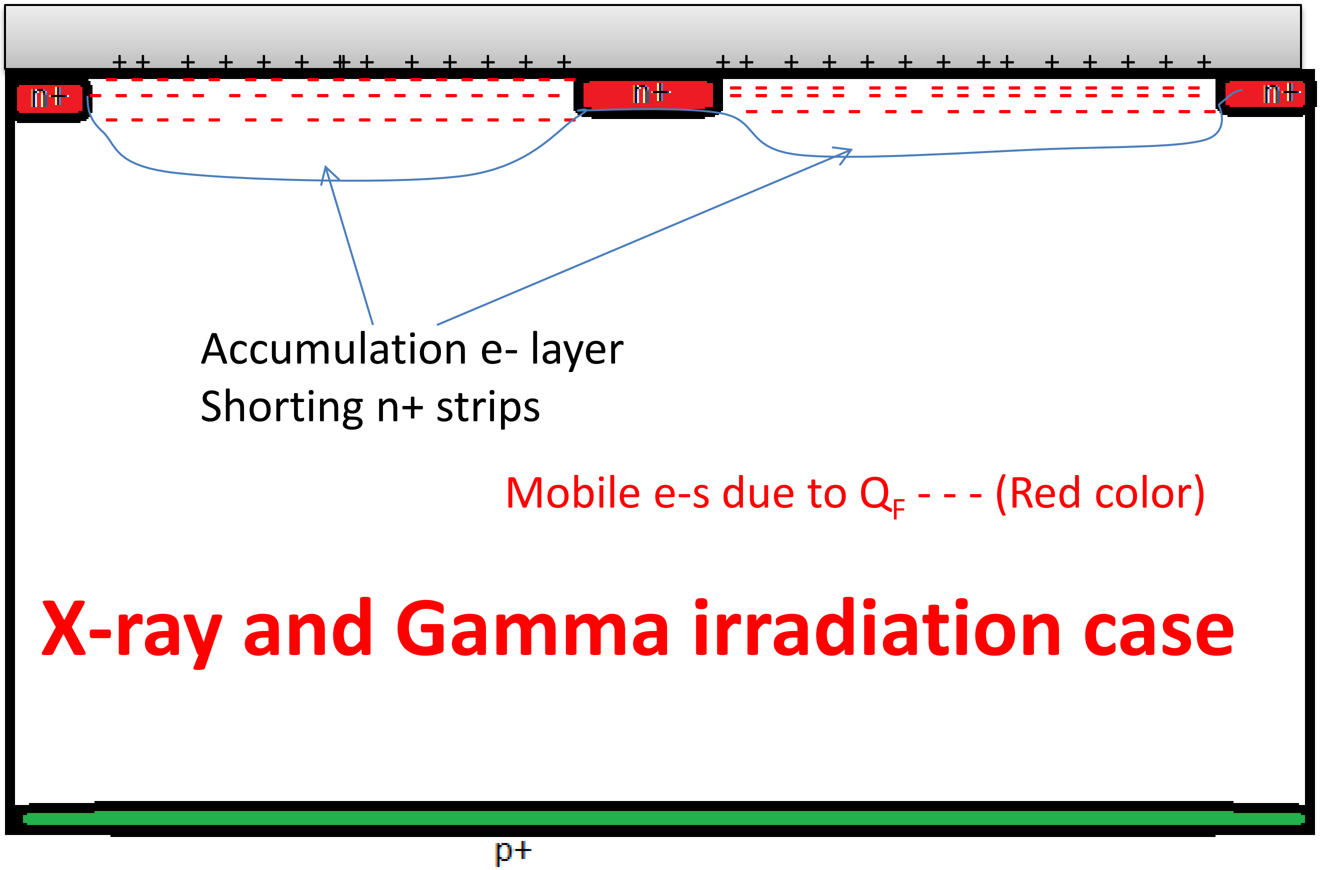




Plot of Interstrip current vs. applied reverse bias.

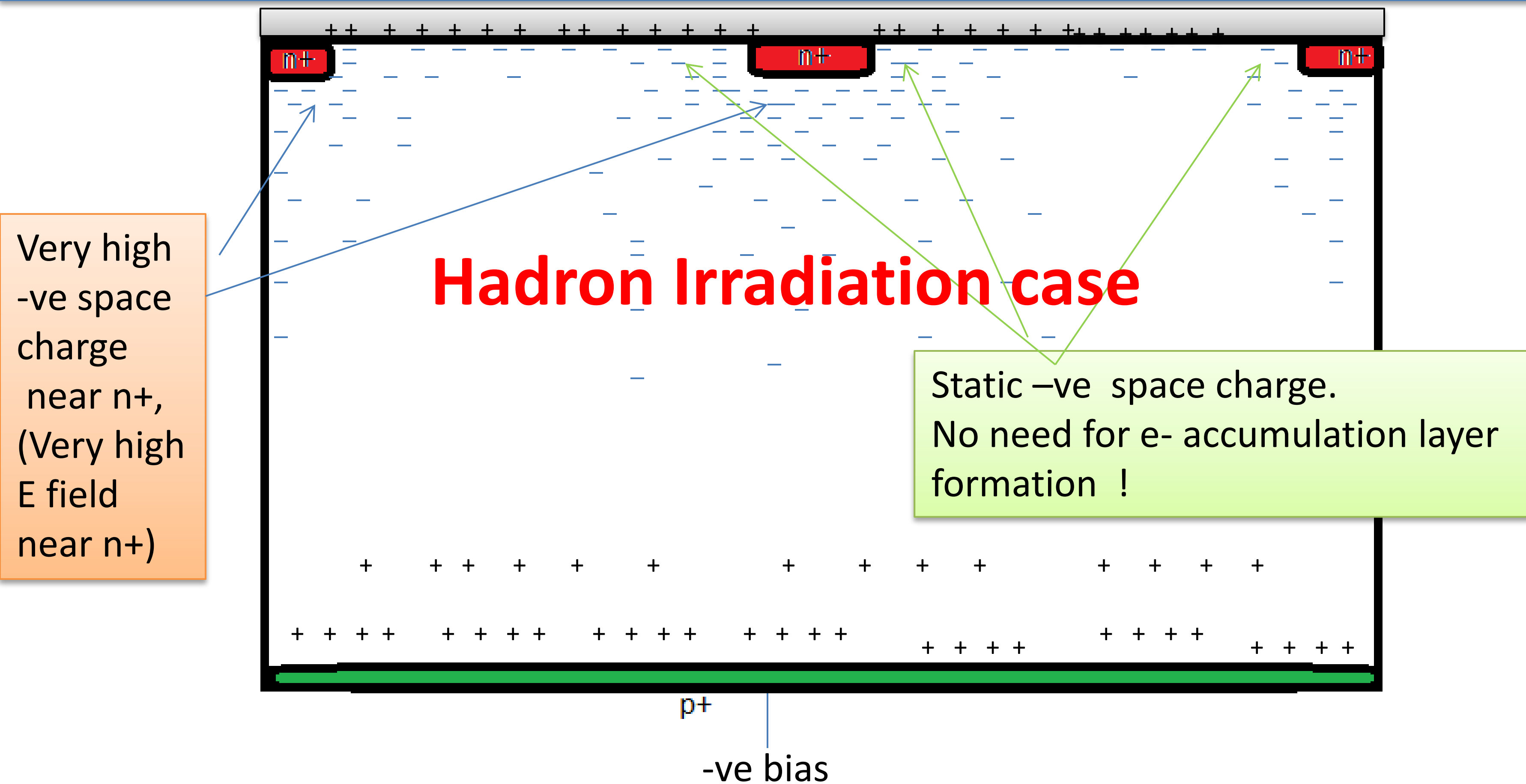
- NPSTP – No Isolation structure (non-irradiated).
- AF – No isolation structure (irradiated by flux = $7 \times 10^{14} cm^{-2}$).
- All other structures are with different layouts of Pstops (Irradiated)
- Voltage difference between two neighboring strips = 5V

How these observations can be explained !



- For X-ray and γ ray irradiation, low leakage current and no/or very low bulk damage results in absence of space charge
- Accumulation e- layer will result in shorting of n+ strips unless sufficient pspray/pstop doping is used.

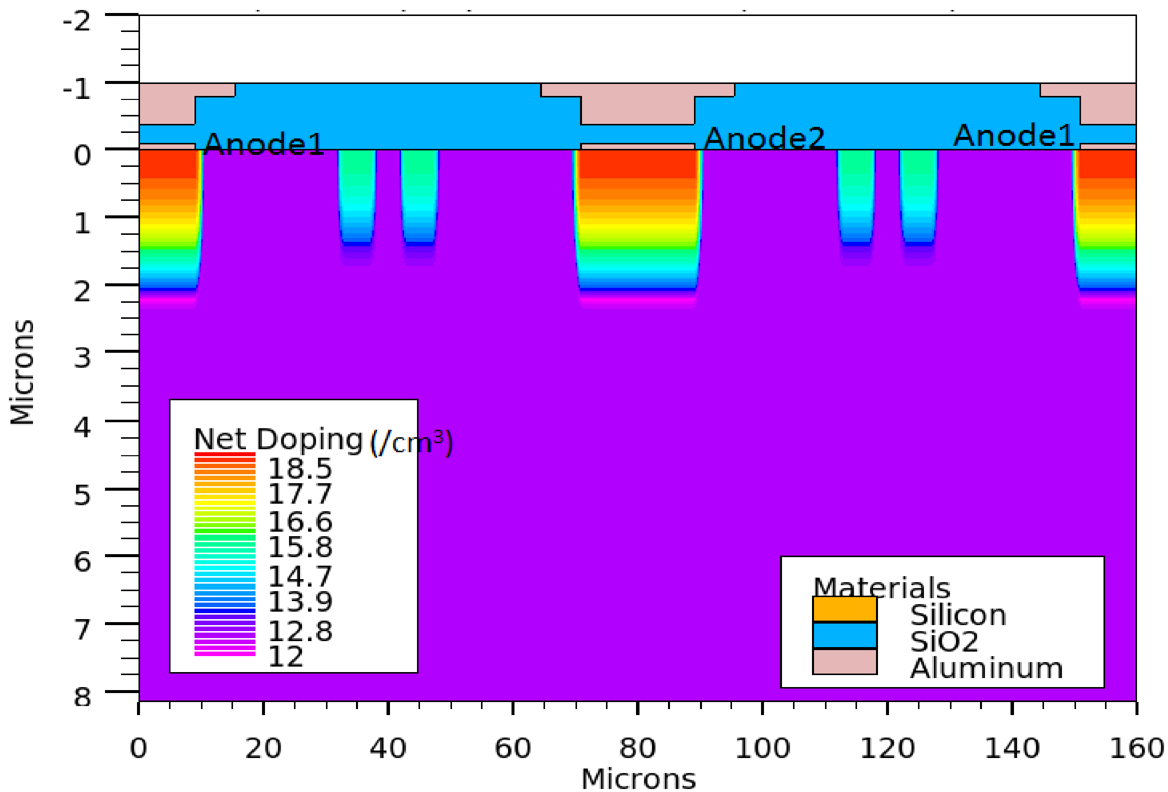
- Very high –ve space charge density near n+ strips. Moreover, this space charge will be even more higher near the both ends of n+ strip (curved) because this area is collecting current from a large volume between the strips (leading to higher e- current density).
-This -ve space charge will act like a Pspray whose density increases with irradiation flux !
No need for formation of accumulation layer due to +ve Oxide charge density !



Fixed -ve space charge - - - (Blue color) – due to filling of Acceptor traps

Simulation structure

- Bulk doping = 3e12cm-3
- 2-D simulations
- Double p-stops
- Each 4µm wide separated by 6µm
- P-stop doping = 5e15cm-2
  P-stop doping depth = 1.6um
- CMS HPK tracker upgrade campaign parameters [1]



❑ ***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 cathode (not shown), below while a very low DC external resistance of 1Ω is used to avoid scaling confusion.**

❑ **Simulations are carried out using Silvaco TCAD tool.**

A . Deirlamm, 2012 JINST 7 C01110 ,
THE 9th INTERNATIONAL CONFERENCE ON POSITION SENSITIVE DETECTORS, 12–16 SEPTEMBER 2011,

Bulk damage model

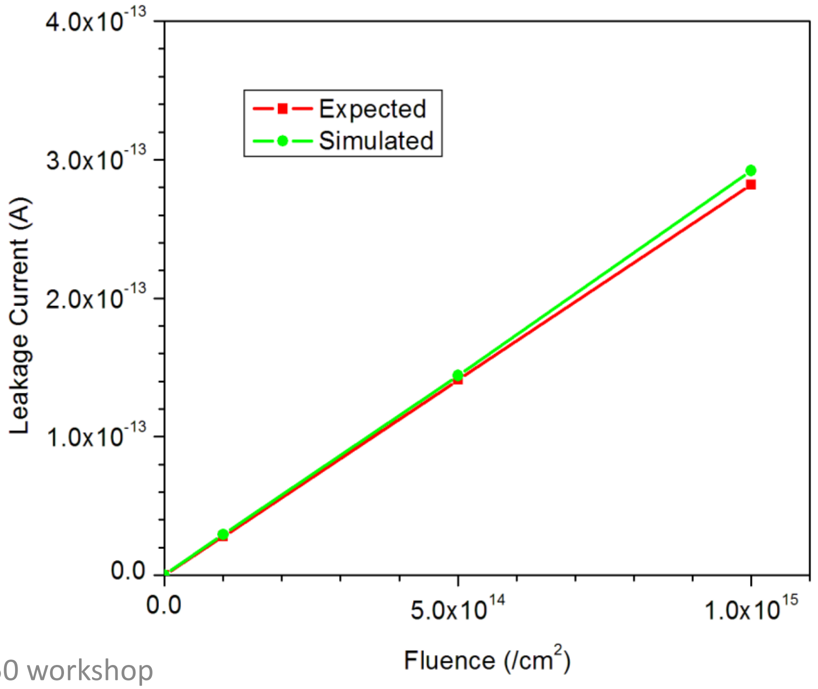
- Two more acceptors & one donor in addition to two deep levels
- Able to remove accumulation e-
- Produce very high E field near n+
- Reproduce experimental observed good Rint and Cint

Trap	Energy Level	Intro.	σ_e (cm^{-2})	σ_h (cm^{-2})
Acceptor	0.525eV	3.0	$1x10^{-14}$	$1.4x10^{-14}$
Acceptor	0.45eV	40	$8x10^{-15}$	$2x10^{-14}$
Acceptor	0.40eV	40	$8x10^{-15}$	$2x10^{-14}$
Donor	0.50eV	0.6	$4x10^{-14}$	$4x10^{-14}$
Donor	0.45eV	20	$4x10^{-14}$	$4x10^{-14}$

(Rough calculation (Thomas Poehlsen):

For Oxide charge density ~ $1x10^{12}cm^{-2}$; assume accumulation e- layer width of ~ 1µm is created. So, accumulation e^- density of ~ $1x10^{16}cm^{-3}$.

To neutralize this: trap density (or p-stop/p-spray) should be much larger then that.



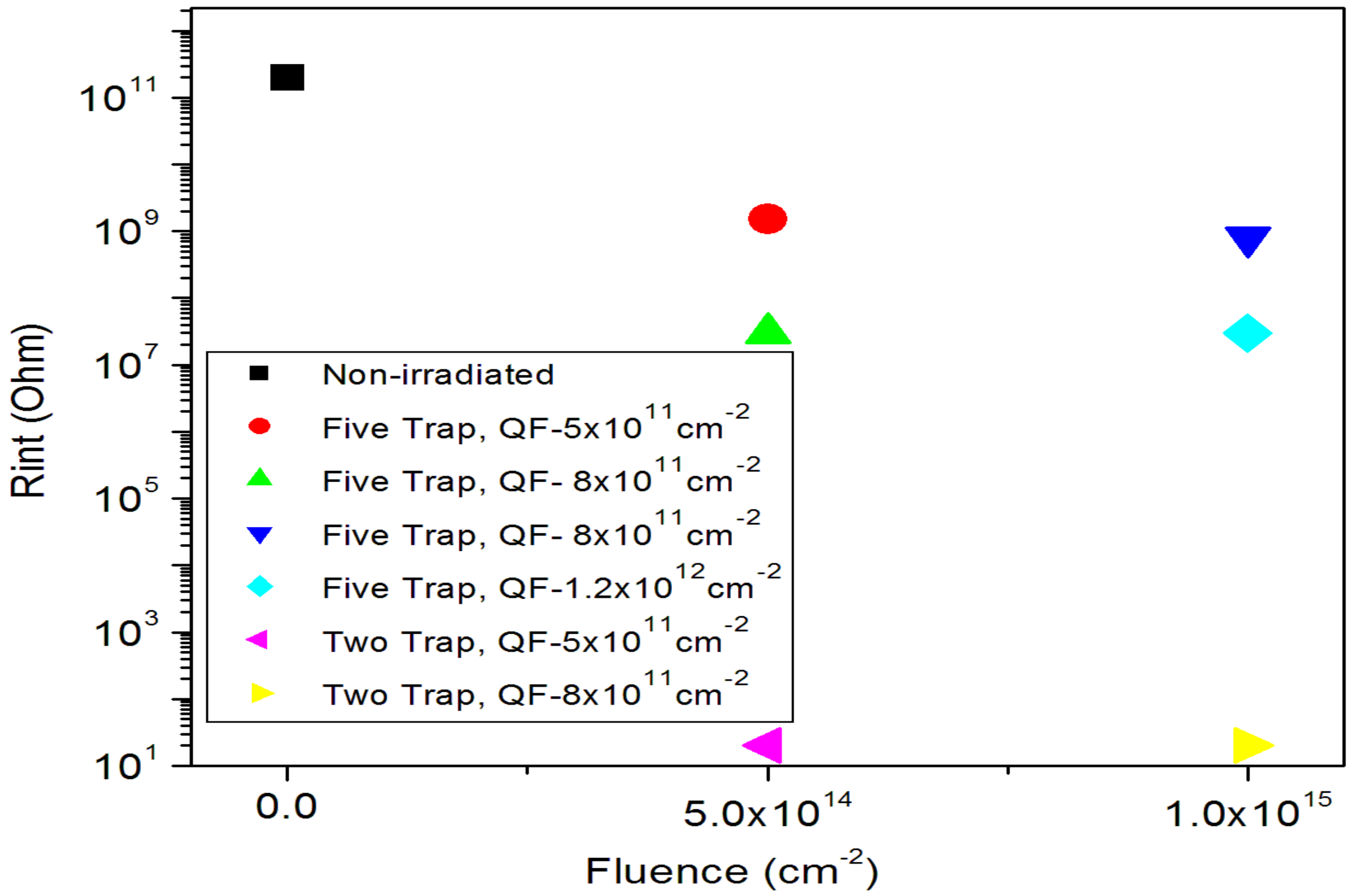
Surface damage

- Along with radiation damage, oxide charge density is a complex function of fabrication process, annealing steps, humidity, radiation particle type etc.
- Hence, instead of taking one value of Q_F, for a given flux of hadron irradiation, surface damage is incorporated in simulation by considering range of Q_F for a given fluence.

Ranges of Oxide charge density (Q_F) used :

Irradiation fluence (neq/cm^2)	Range of Q_F (cm^{-2})
0	5e10 to 5e11
$1\text{x}10^{14}$	1e11 to 8e11cm-2
$5\text{x}10^{14}$	5e11 to 1.2e12
$1\text{x}10^{15}$	8e11 to 2e12

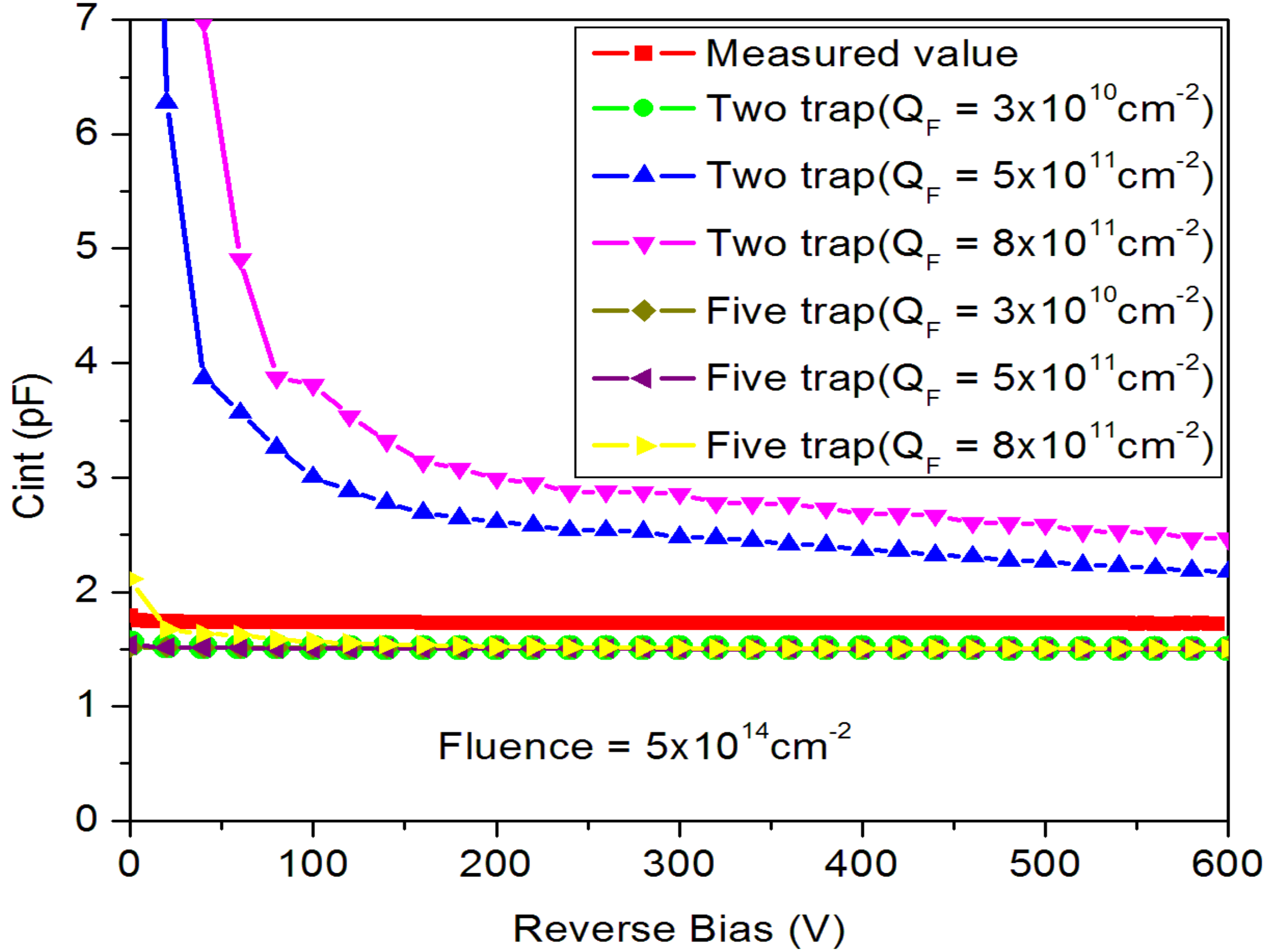
Two vs. Five trap model : Rint simulations



- ➢ Two trap models (in Silvaco [2] as well as in Synopsis [proton model of KIT] also) are not able to account the good Rint for irradiated sensors

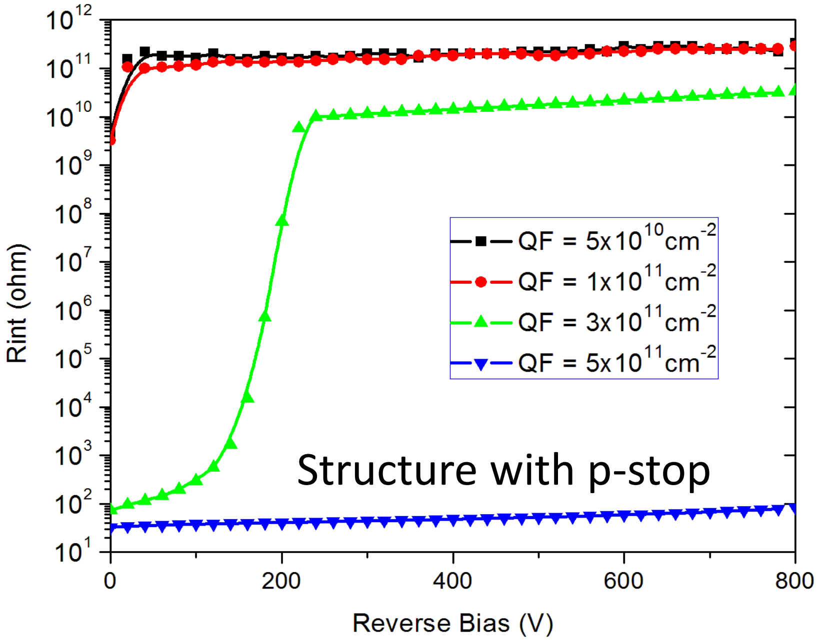
[2] Thomas Eichhorn, 2012 IEEE Nucl. Science Symp. and Medical Imaging Conf.(NSS/MIC) N2S-S

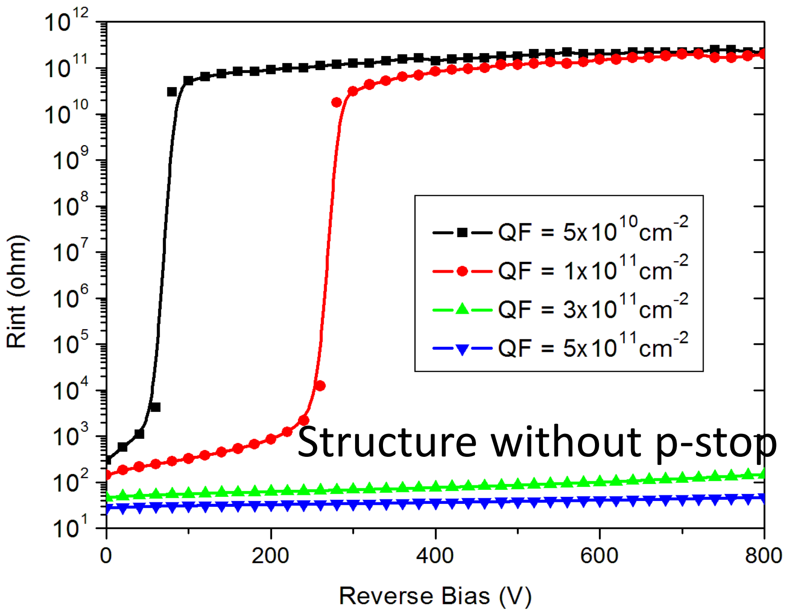
Two vs. Five trap model : Cint simulations



- For two trap model, Cint increases sharply with Q_F
- Five trap model is able to reproduce Cint for realistic Q_F values

Simulation of Rint without bulk damage

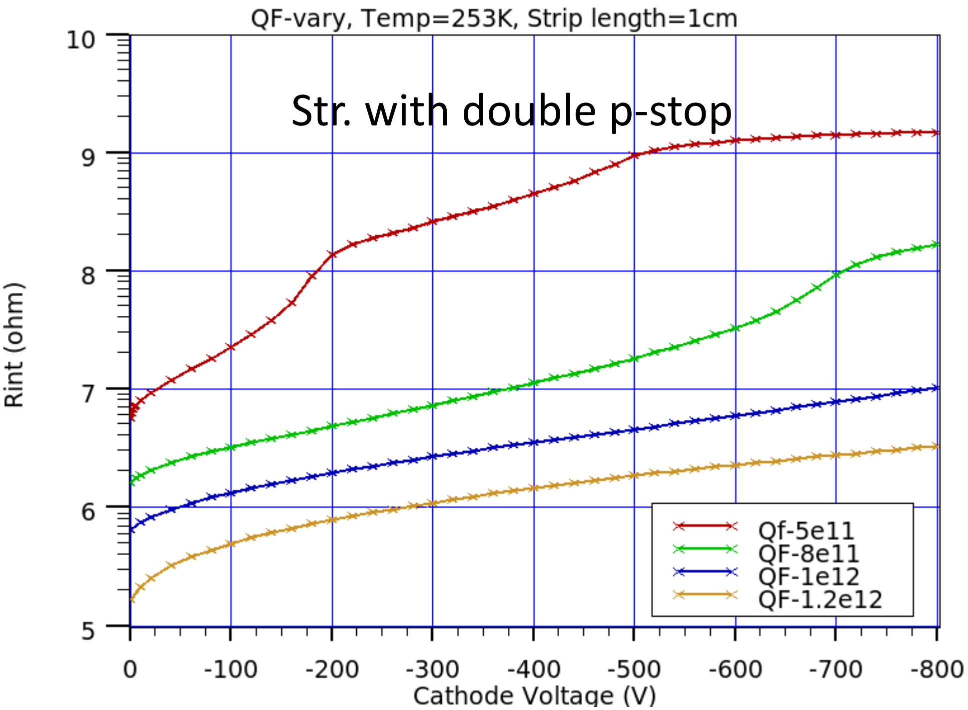


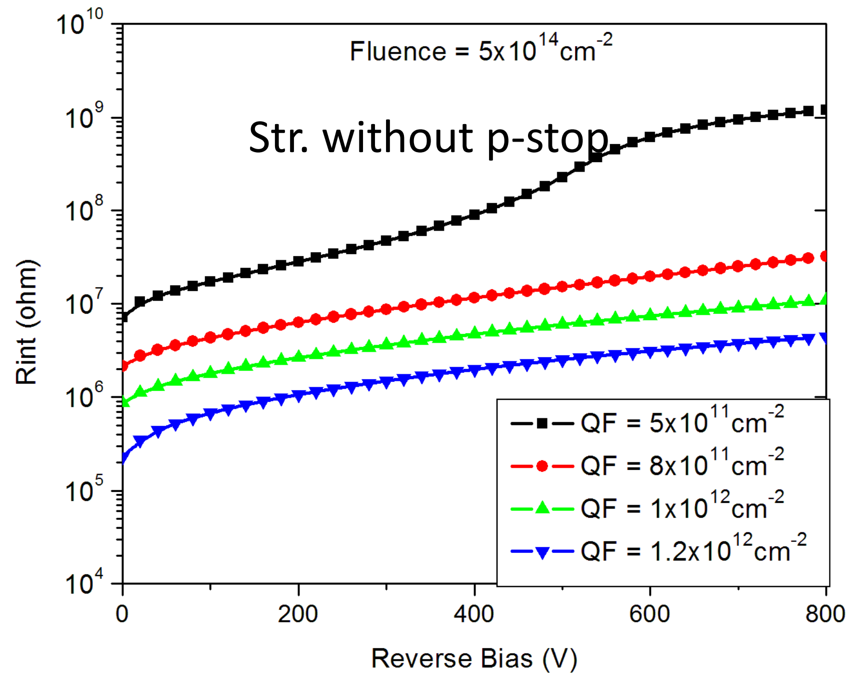


Three different Rint curves

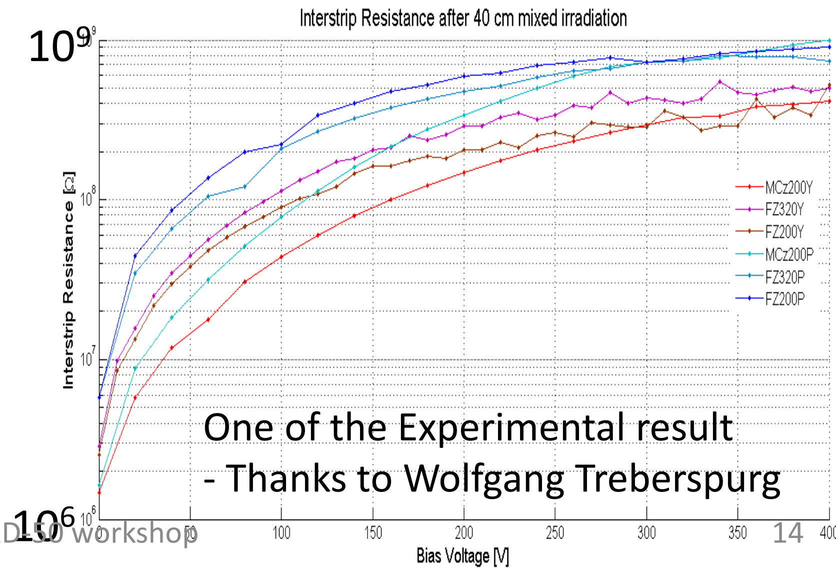
1. For low values of Q_F, good strip insulation is obtained even for low bias voltages.
2. For intermediate values of Q_F, strip insulation is very poor for low voltages, but improves with higher reverse biases, as the electrons from accumulation layer are progressively removed, resulting in a higher R_{int}.
3. But for higher values of Q_F, R_{int} remains very low up to 800 V.

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

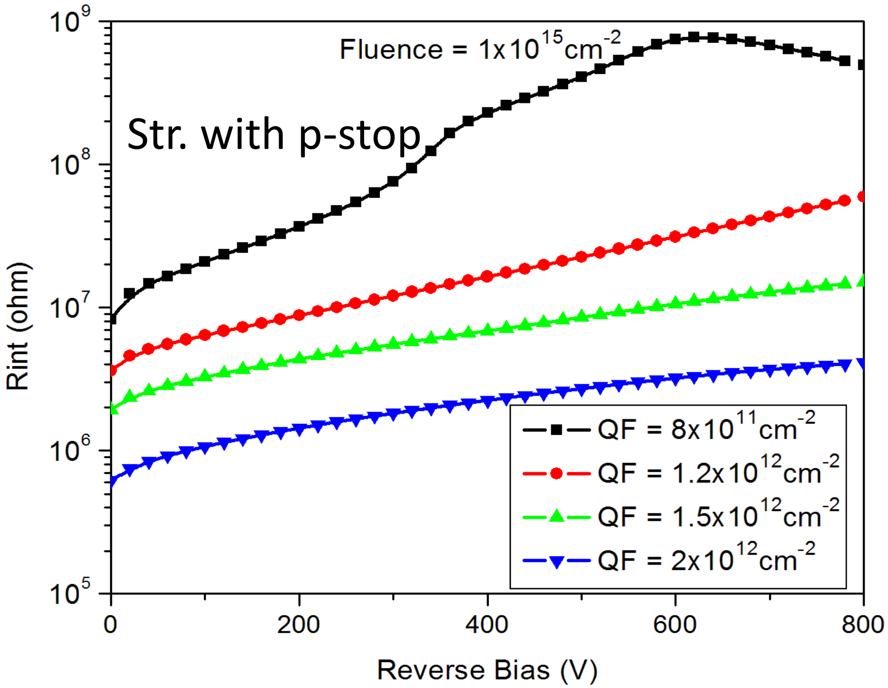


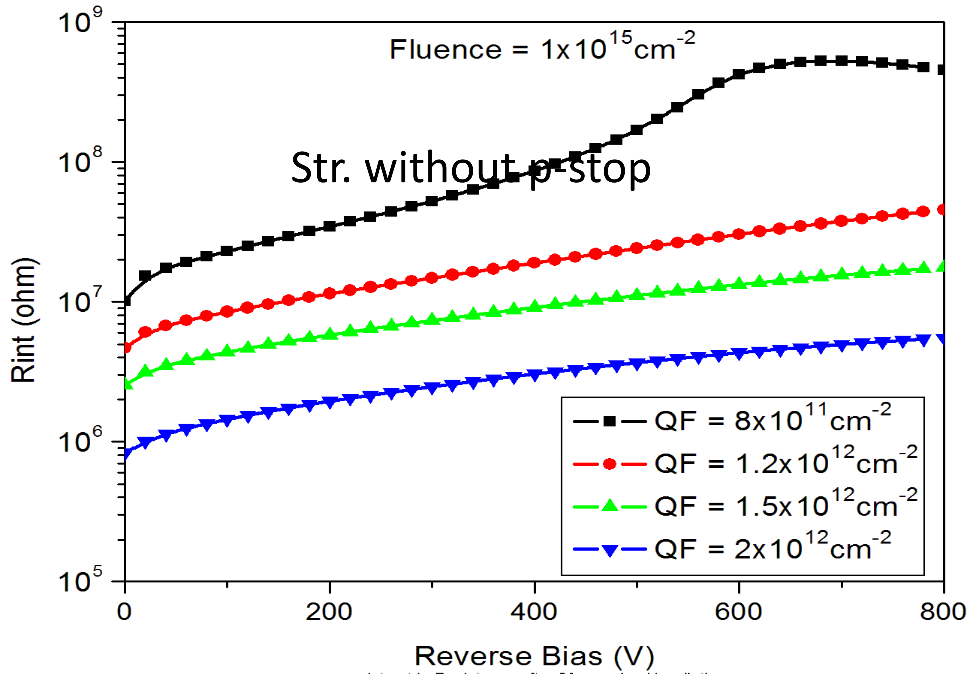


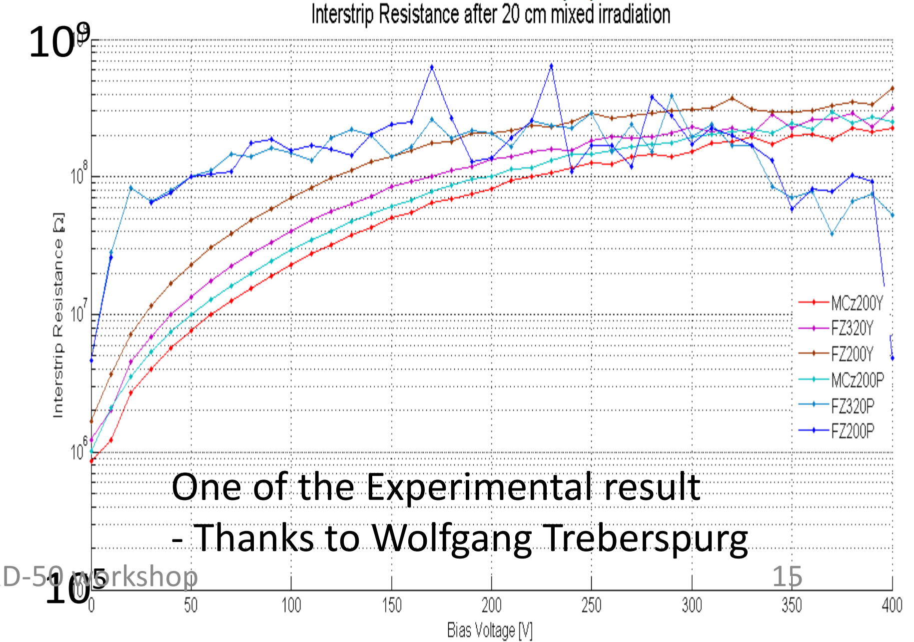
- ➢ Rint values of more then 100MOhm is possible for QF = 8e11cm-2
- ➢ Significant improvement in Rint values for higher values of Q_F
- ➢ Good strip insulation is possible even without any isolation structure!



Simulations of Rint for Fluence = $1x10^{15}$neq/cm^2



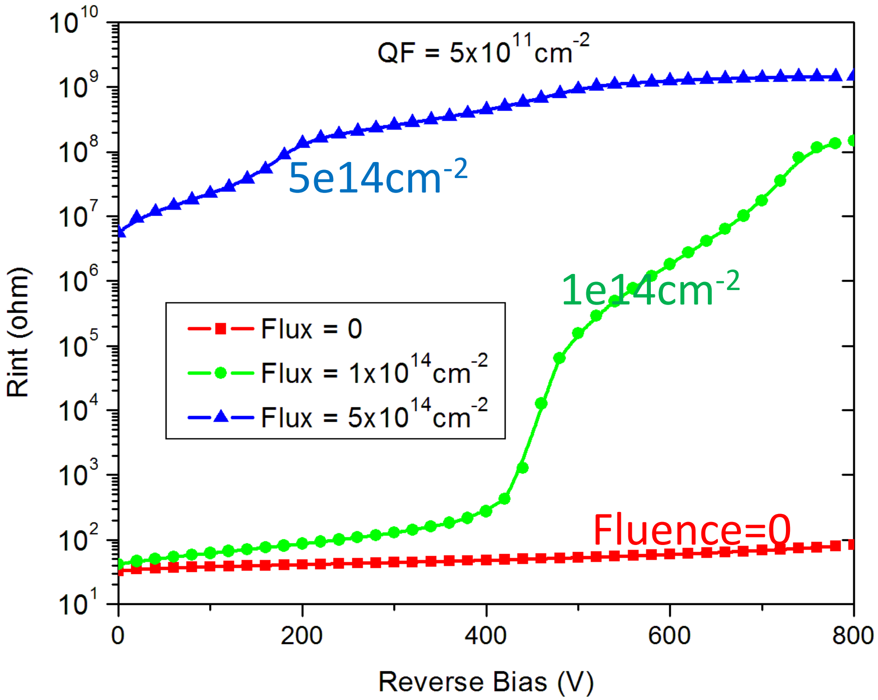


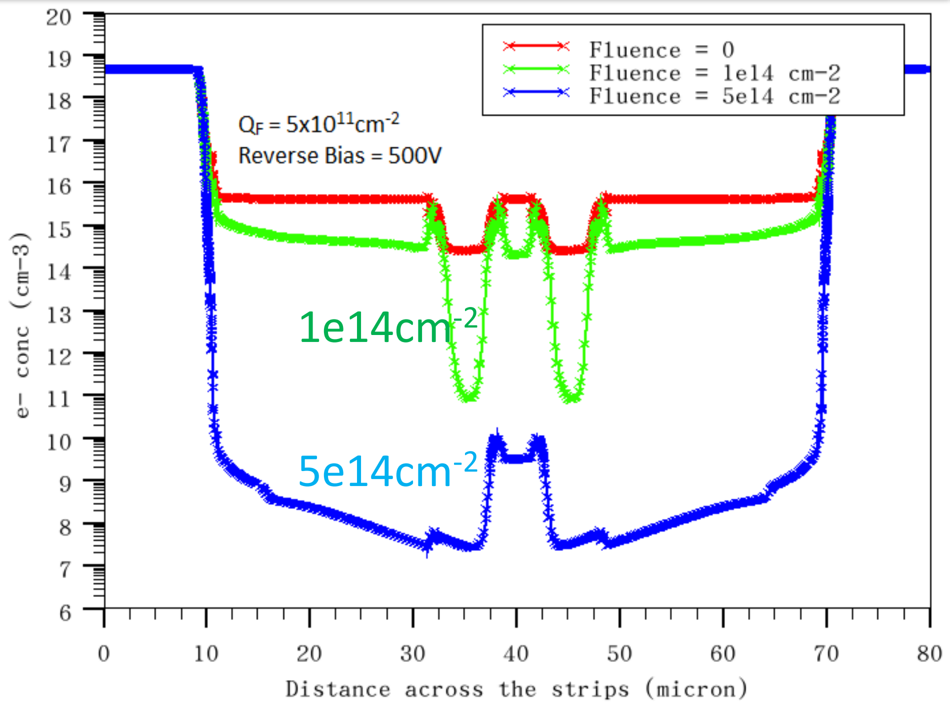


One of the Experimental result
- Thanks to Wolfgang Treberspurg

- ➢ Rint values of more then 100MOhm is possible for QF = 8e11cm-2
- ➢Significant improvement in Rint values for higher values of Q_F
- ➢ Good strip insulation is possible even without any isolation structure!

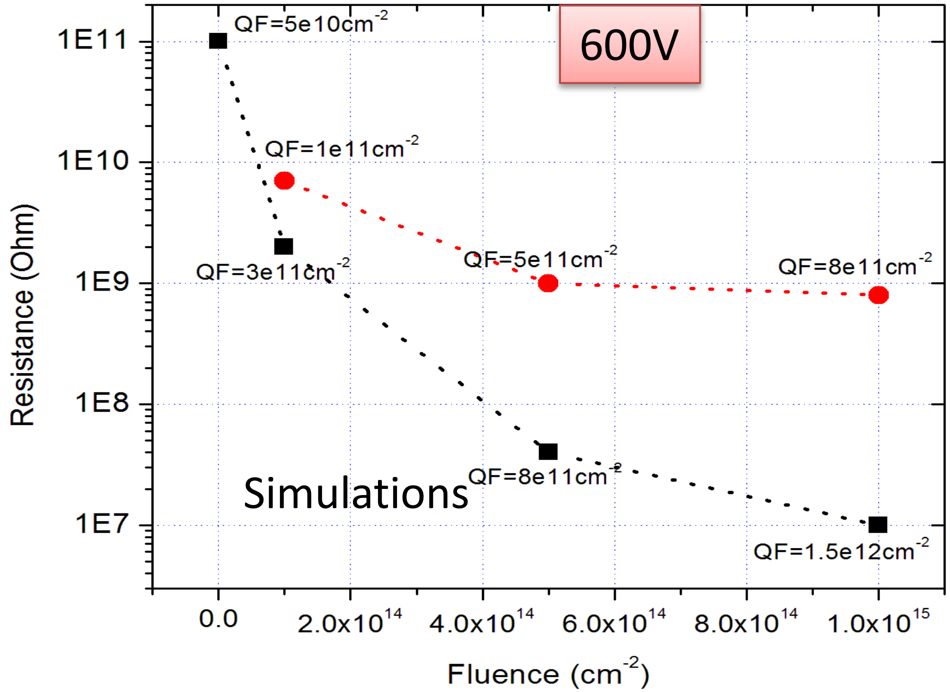
Effect of bulk damage on electron accumulation layer

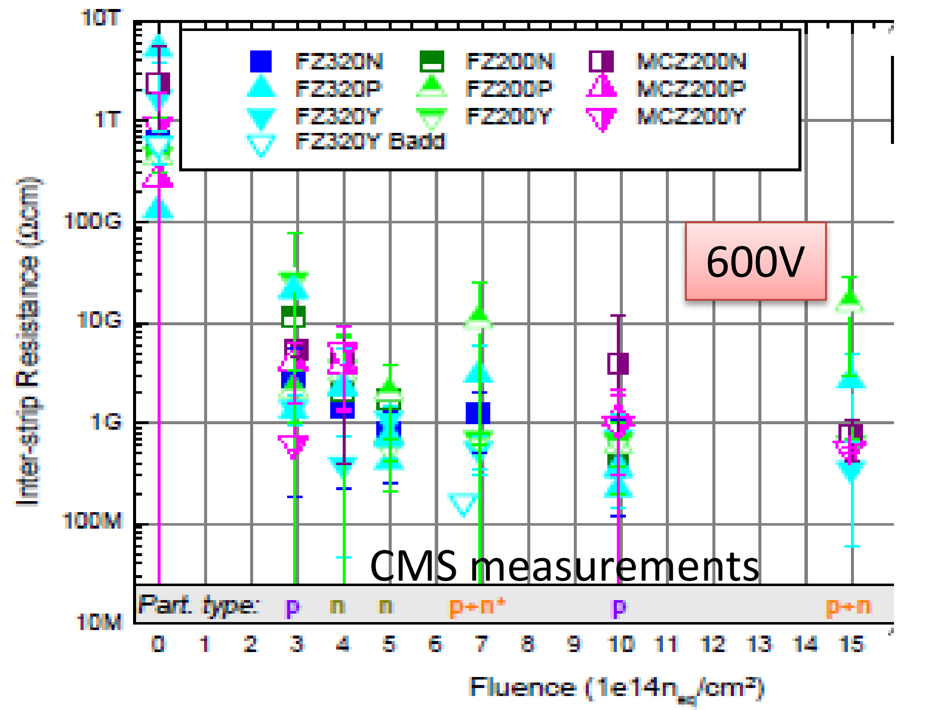




- For a given Oxide charge density value, Rint increases with bulk damage
- Bulk damage suppress the electron accumulation layer

R_{int} variation with Irradiation flux



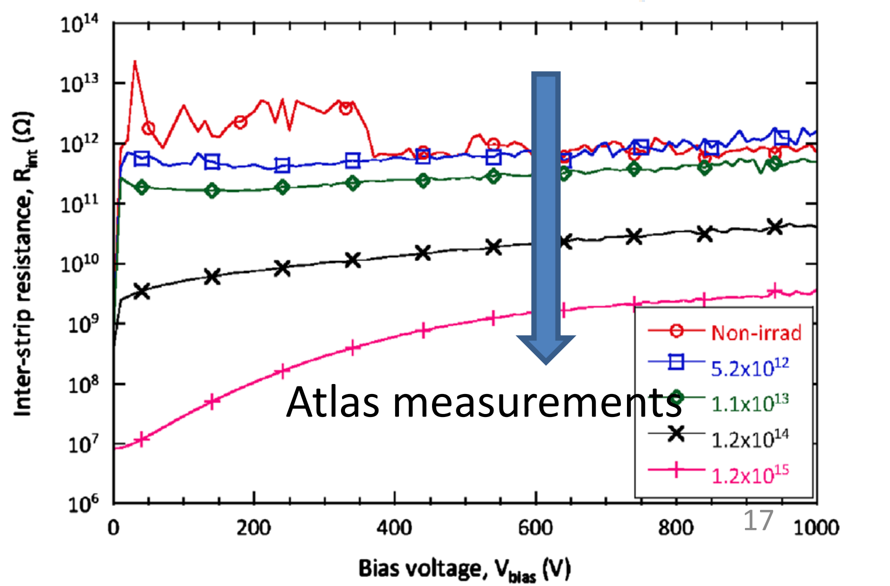


-Rint decreases with increase in fluence

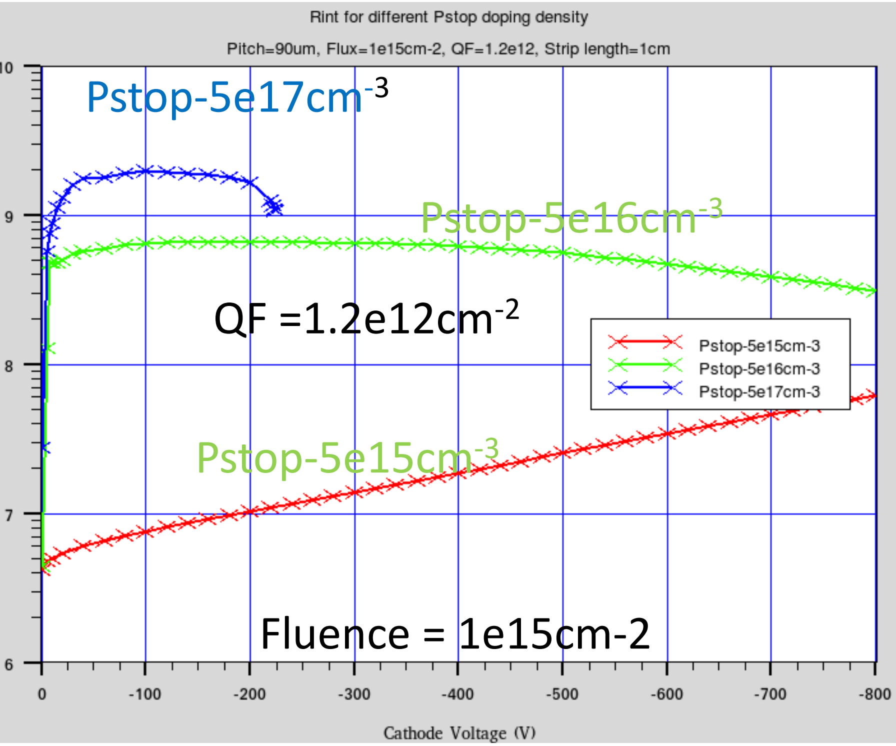
-Similar trends in CMS tracker upgrade measurements (A. Dierlamm, PoS paper, Vertex 2012, 016)

- 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



Rint variation for different p-stop doping



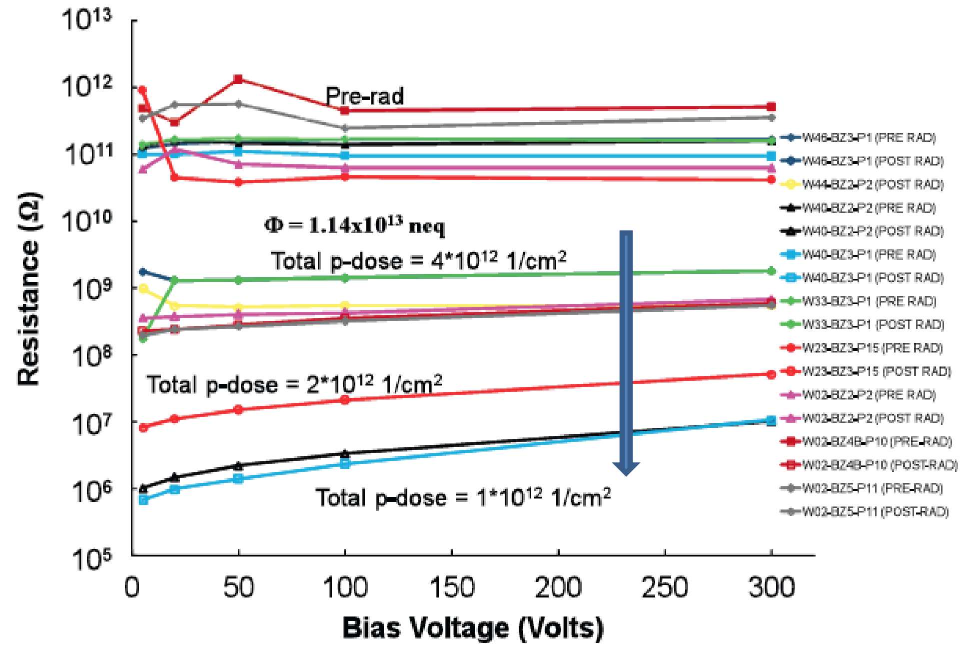
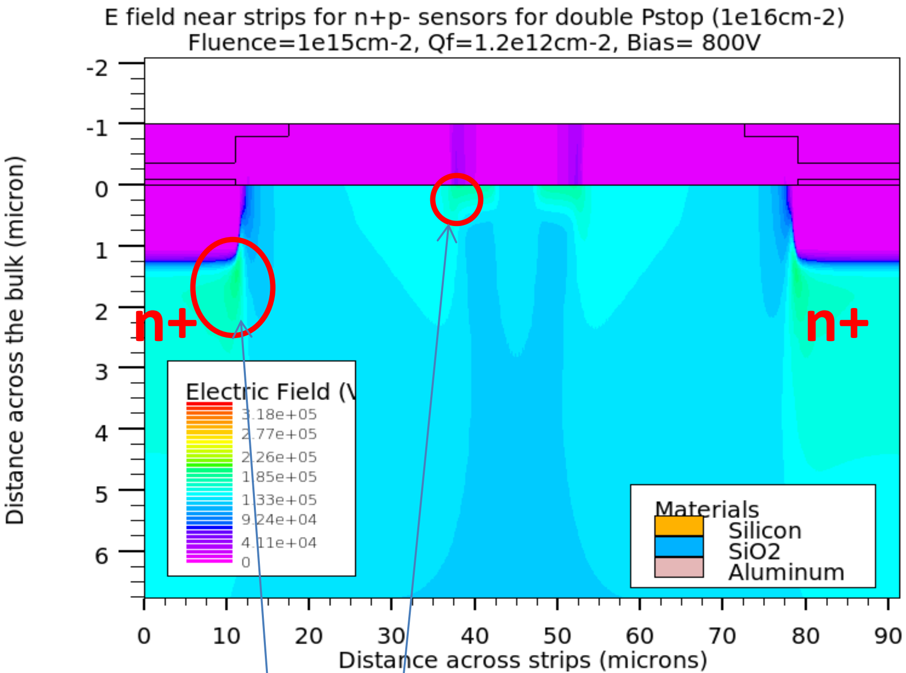


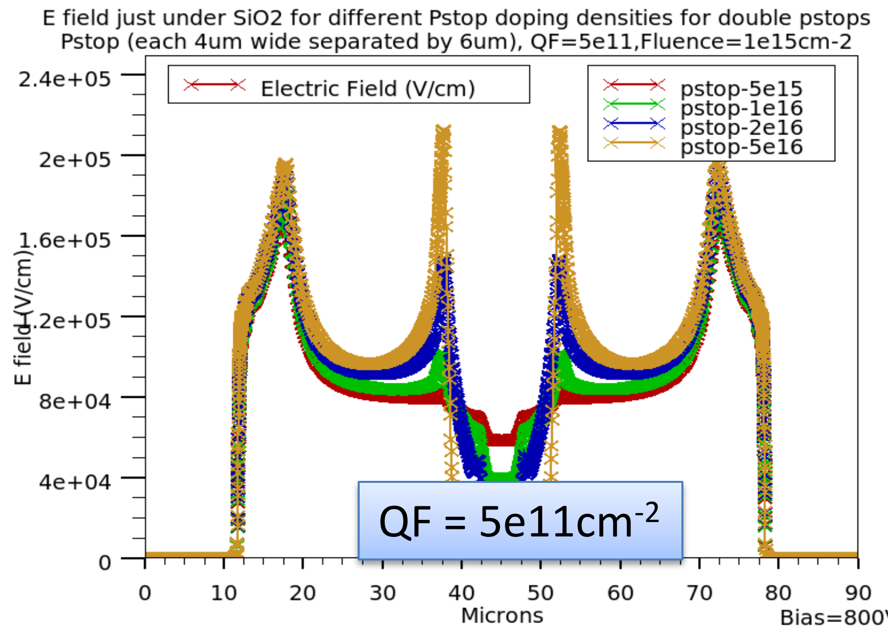
Fig. 6. Interstrip resistance for irradiated series 3 detectors. There is a clear dependence on the total p-dose applied after irradiation.

S. Lingren et al., Nucl. Instr. Meth. A636 (2011) S111

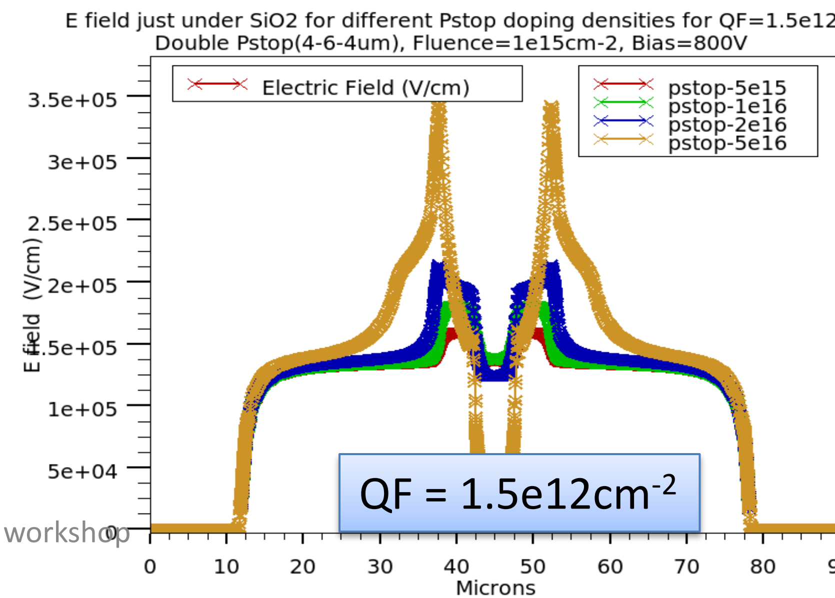
-Higher Pstop doping density leads to better Rint
- similar trends seen in measurements also
- But very high p-stop doping density may leads to breakdown near p-stop curvature region

E field 0.1μm below SiO2/Si interface for different p-stop doping



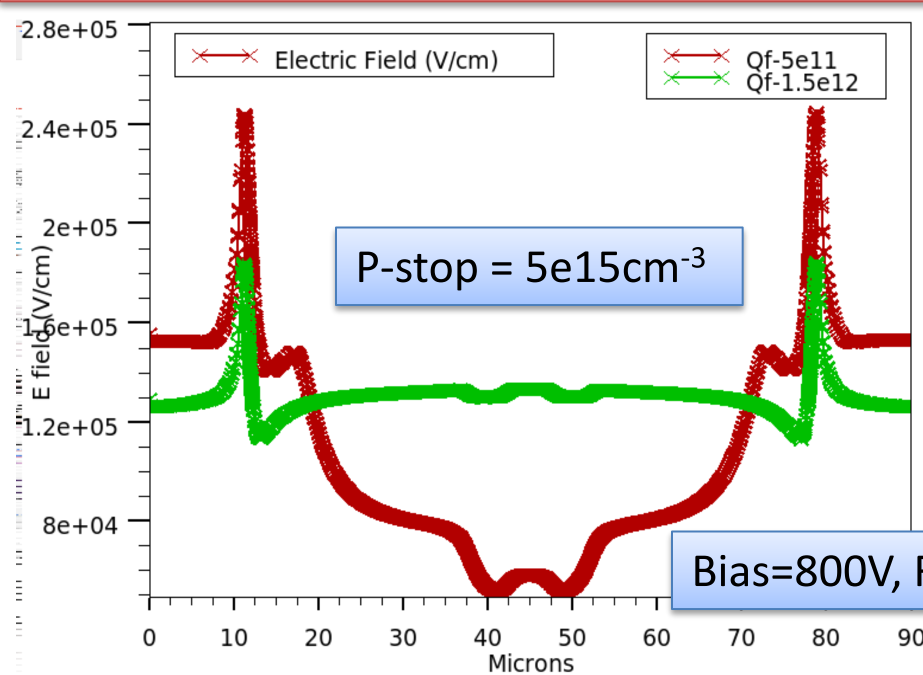


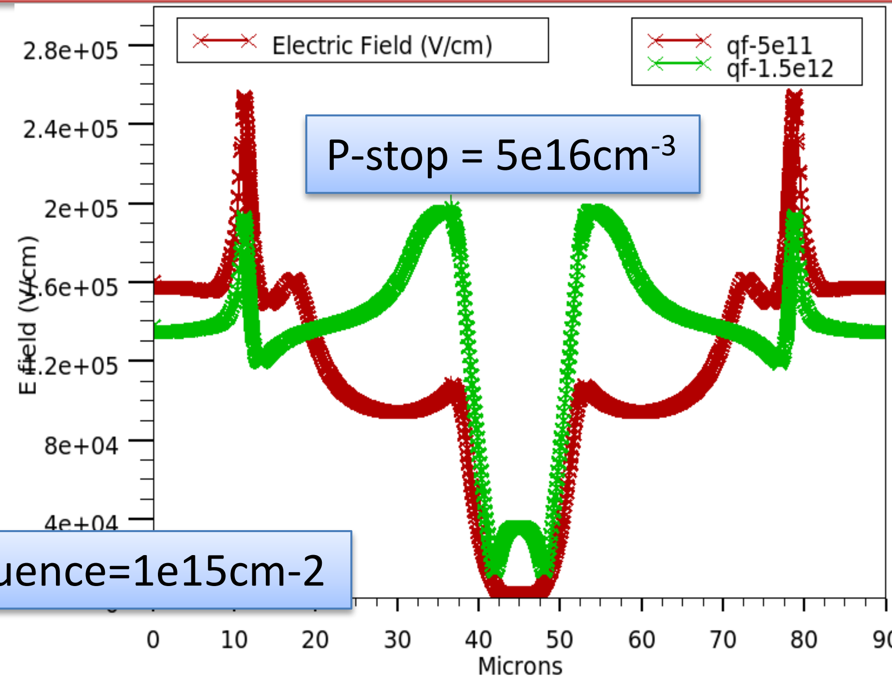
Max. E field for n+p- MSSD is near the curvature region of n+ strip Or near p-stop, just below SiO2/Si interface
- Need two cutlines : 0.1μm and 1.4μm below interface



- For Pstop upto 2e16cm^{-3}, highest E field is near n+ strip curvature (next slide)
- For higher Pstop concentration (5e16cm^{-3}), maximum E field is near p-stop

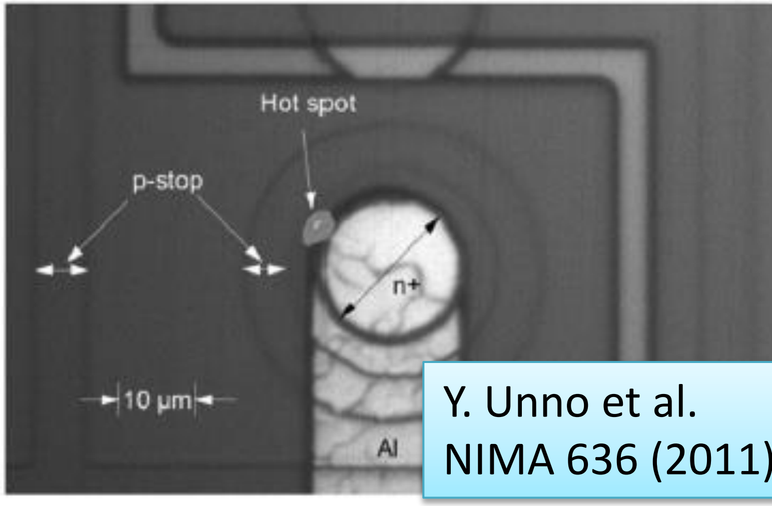
E field 1.4µm below SiO2/Si interface for diff. p-stop dopings





Bias=800V, Fluence=1e15cm-2

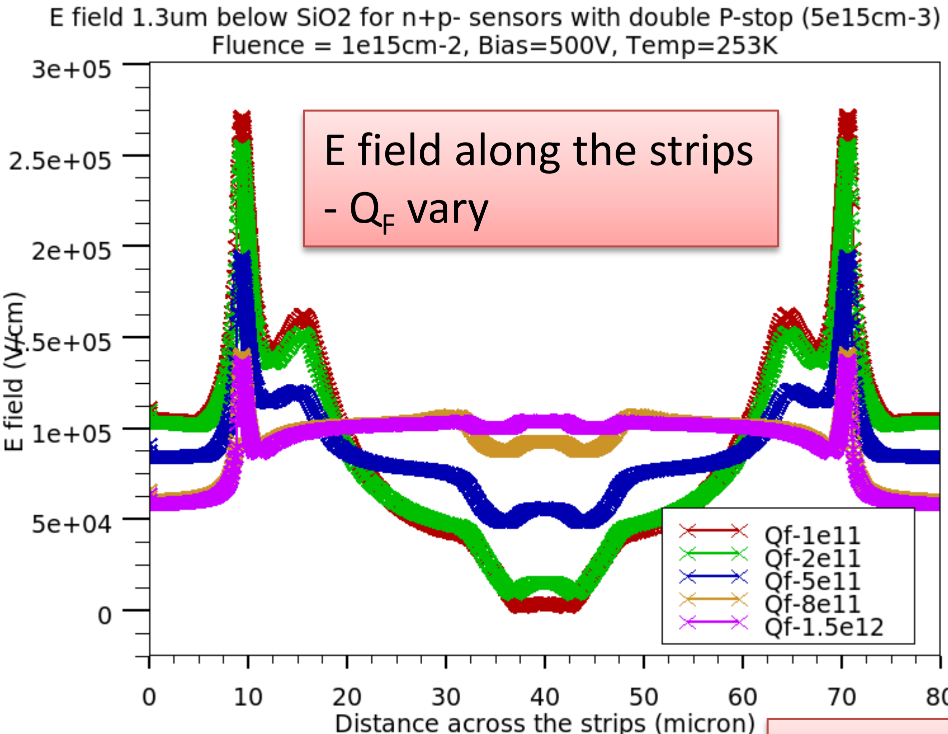
- **For p-stop (at least) up to 2e16cm-3, highest E field is near n+ strip curvature**
- **For low and intermediate p-stops, it is quite possible, that microdischarges are taking place at n+ curvature.**

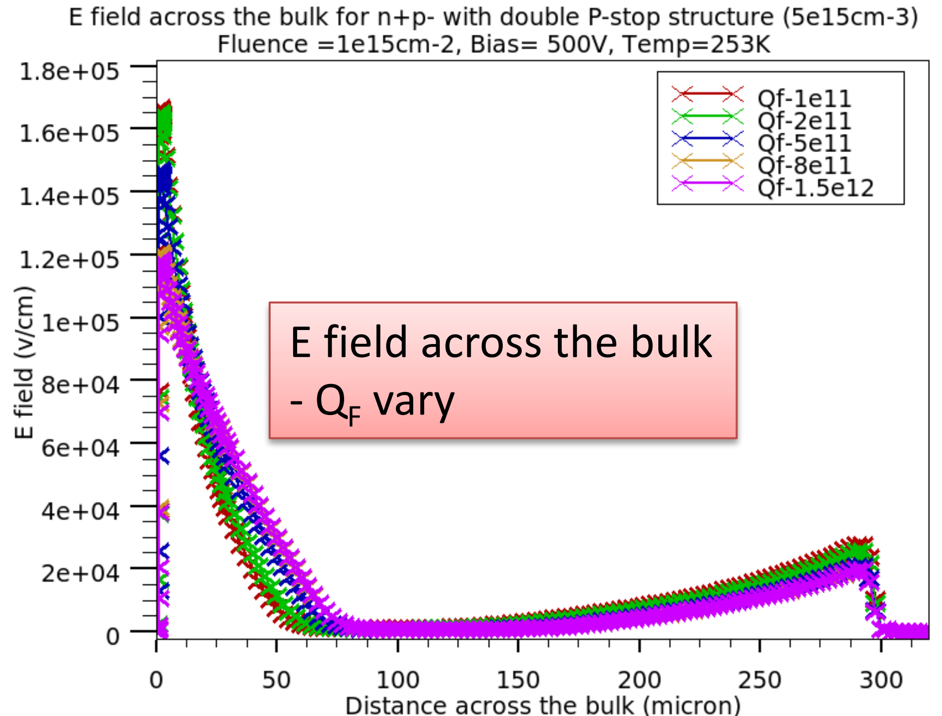


Y. Unno et al. NIMA 636 (2011)

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.

E field 1.3µm below SiO2/Si interface for n+p- strip sensor





Flux=1×10^{15}cm^{-2} Bias = 500 V

- **E field near n+ strips strongly decrease with increase in Oxide charge density**
- **Higher E field near strips, for neutron irradiation compare to proton irradiation**
- **More charge multiplication for neutron irradiation then proton irradiation !**

(See C. Betancourt`s Yeasterday talk)

- **Different amount of surface damage can be very useful in understanding different effects of n & p irradiations**

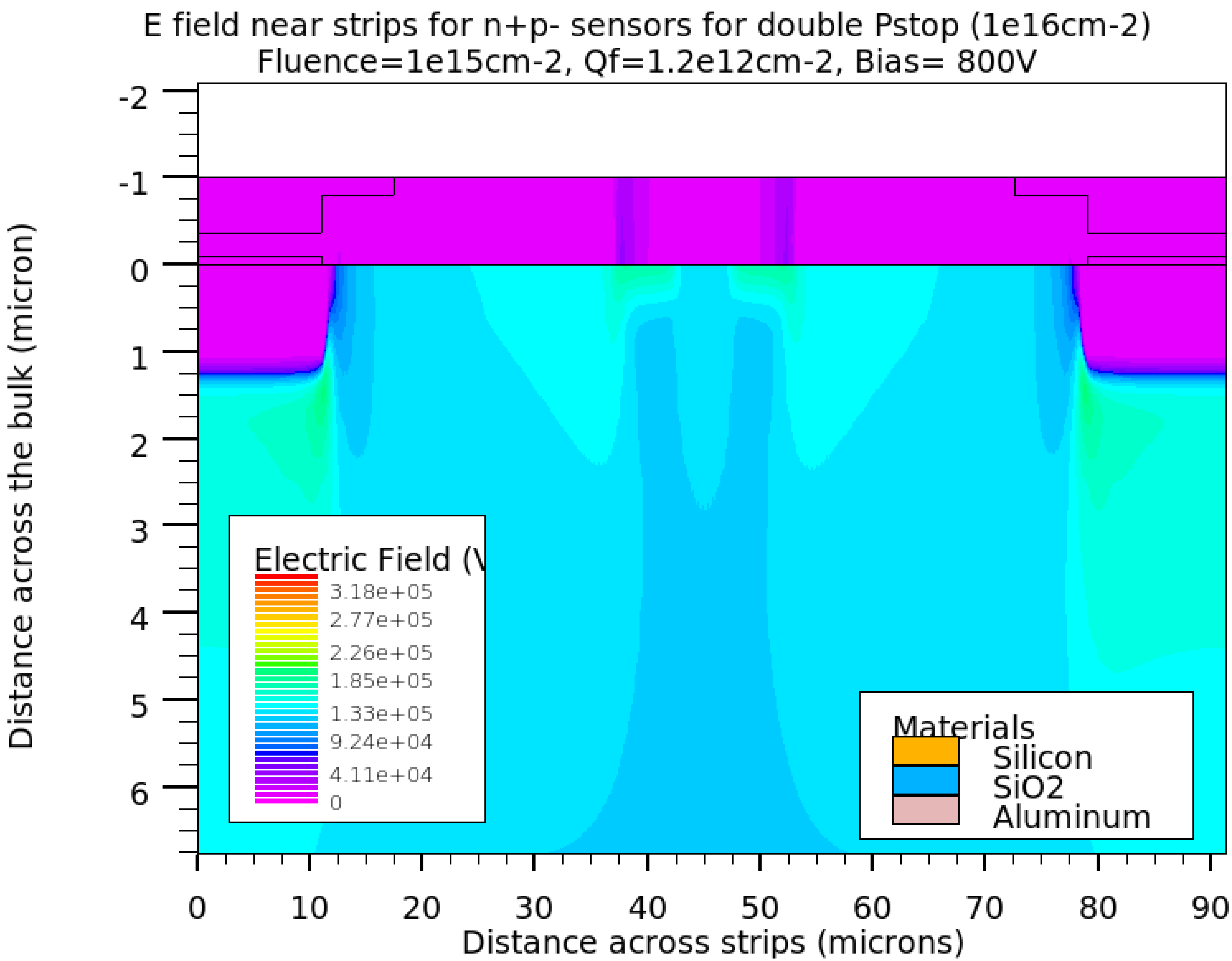
Summary and future directions

- Measurements clearly indicate good Rint values for low very p-stop/p-spray isolation structure or even without any isolation structure, after hadron irradiation
- Similarly, other observables like Cint, Rint trends & position of microdischarge for p-type sensor etc., indicate the combined effects of surface and bulk damage.
- Bulk damage appear to suppress the electron accumulation layer due to surface damage
- Surface + Bulk damage considered simultaneously in simulations
- Good agreements between Rint , Cint trends were obtained
- Rint increases with p-stop doping but very high value of p-stop doping can lead to low value of breakdown
- Position of critical field for hadron irradiated sensors can be understood
- Electric field near the strips for n+p- sensors strongly decrease with increase in oxide charge density. This indicate that charge multiplication may be more for neutron irradiated sensors

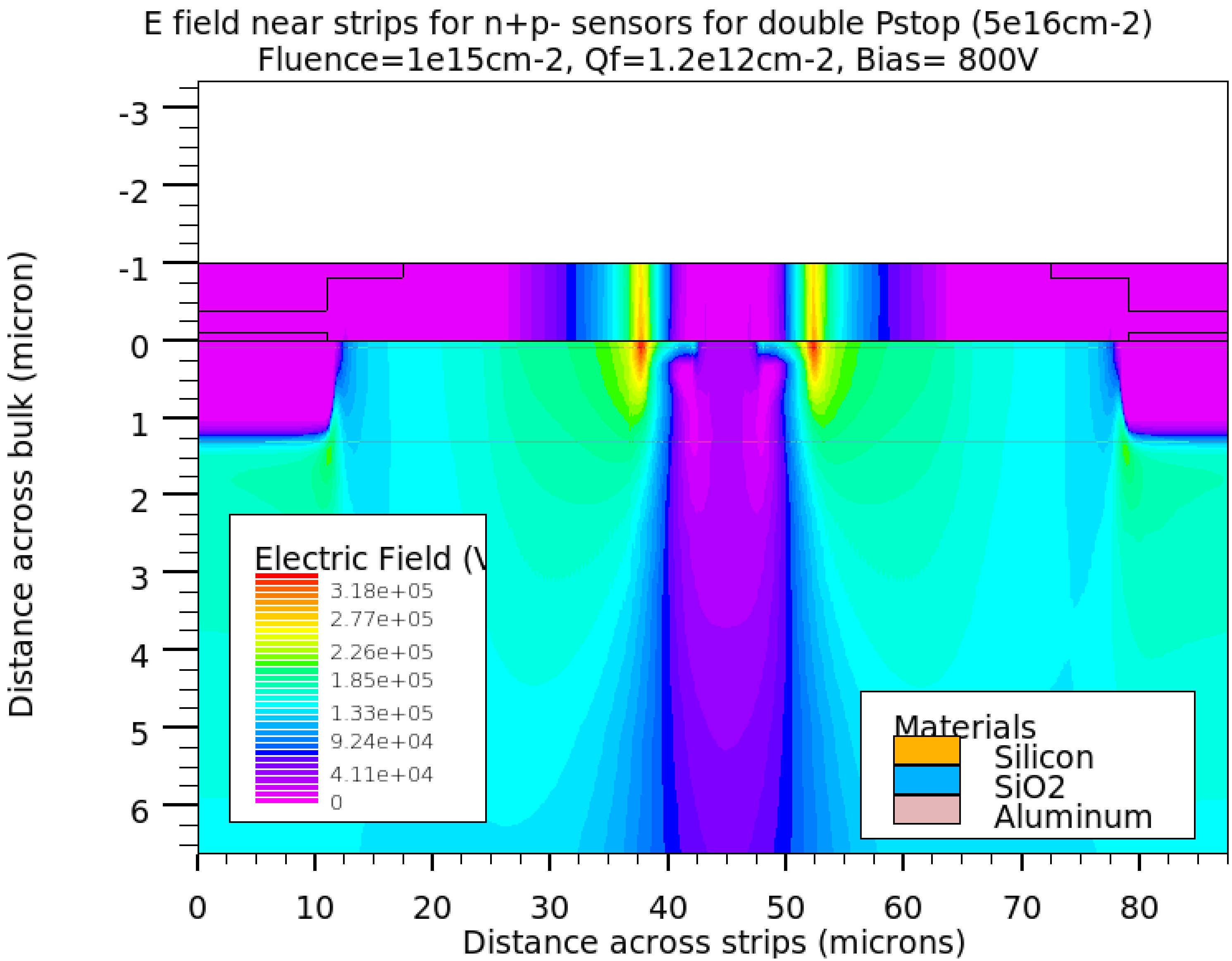
- No. of traps in the bulk damage model
- Interface traps incorporation into simulations
- Comparison of E field in the bulk with results of eTCT (Marcos, Kramberger)
- Simulation study of E field difference for proton and neutron irradiation

Thanks for your attention!

E field contours for double p-stops doping = 1e16cm^{-3}



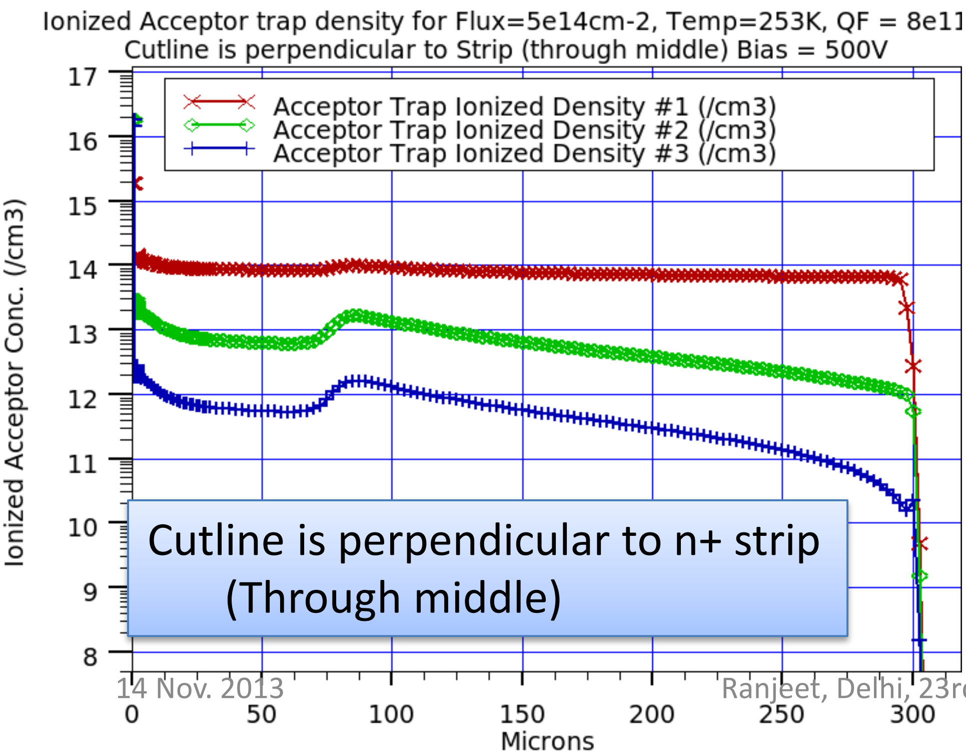
E field contours for double p-stops doping = 5e16cm^{-3}

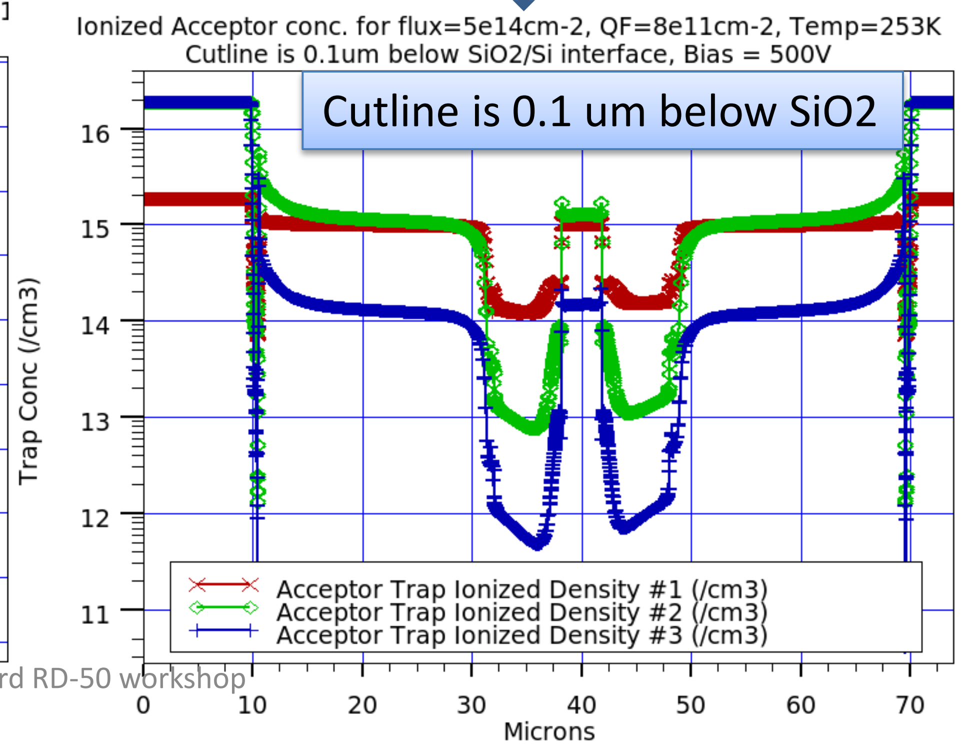


Why two more acceptors with higher introduction rates ? – continue…

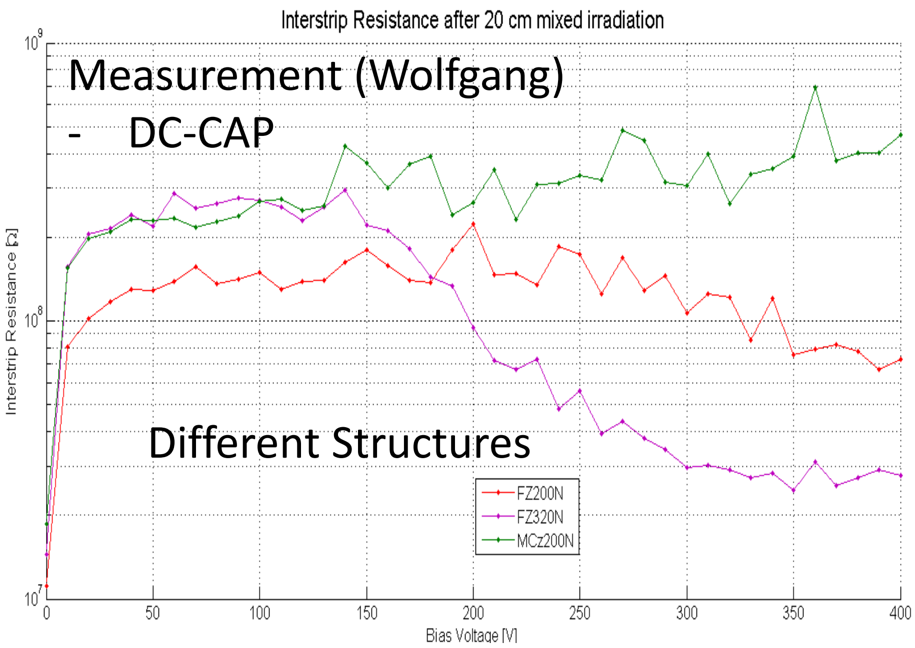
Ionized Acceptor trap density inside Si sensor
-Ionized Shallow levels (green and blue) are much less compare to deep levels (Red color).

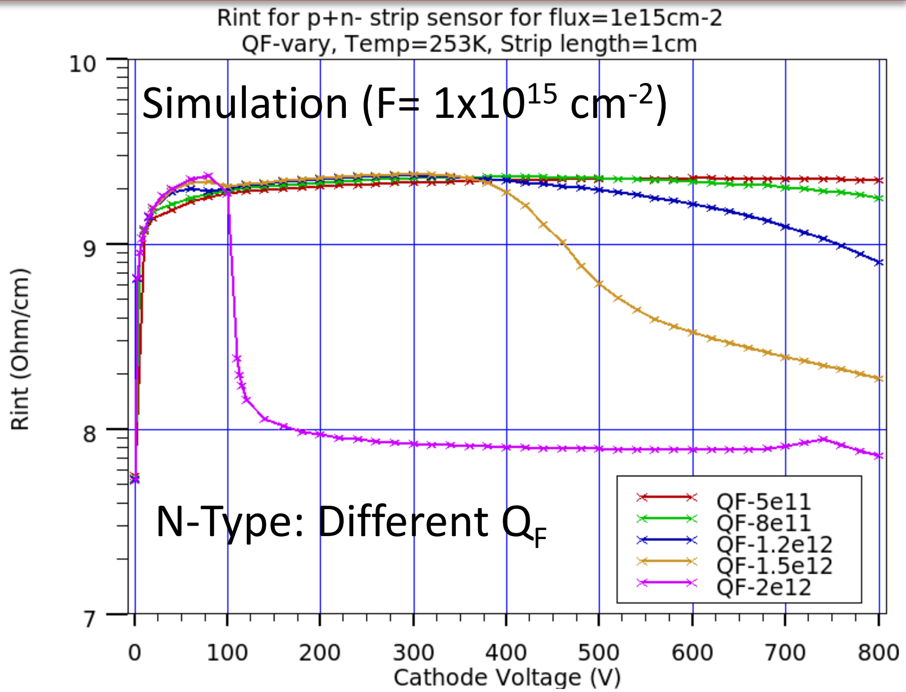
Ionized Acceptors just below SiO2/Si Interface
-In some of the region, Ionized shallow traps (green and blue) are much more compare to deep one





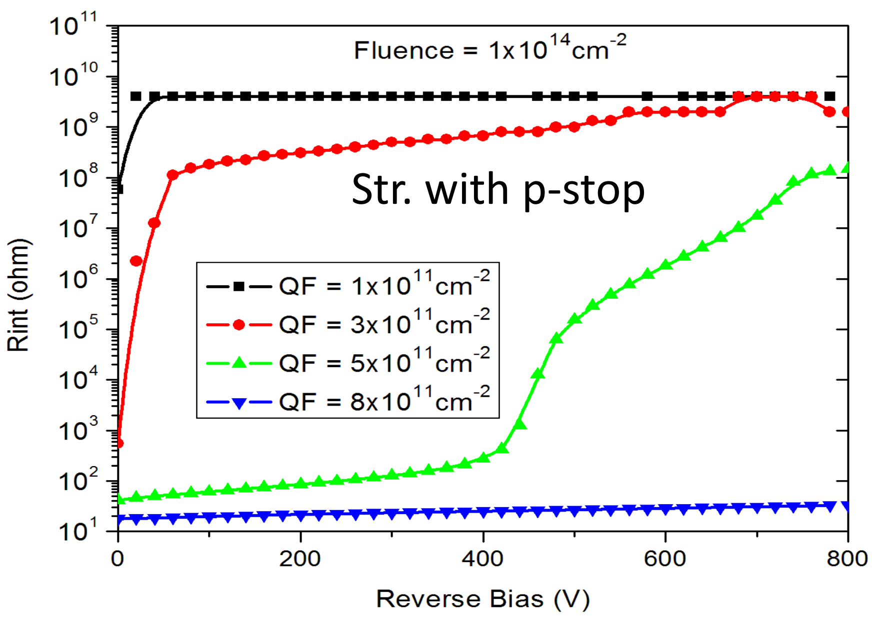
R_{int} vs. V_{bias} (Irradiated) : p+n- strip sensor

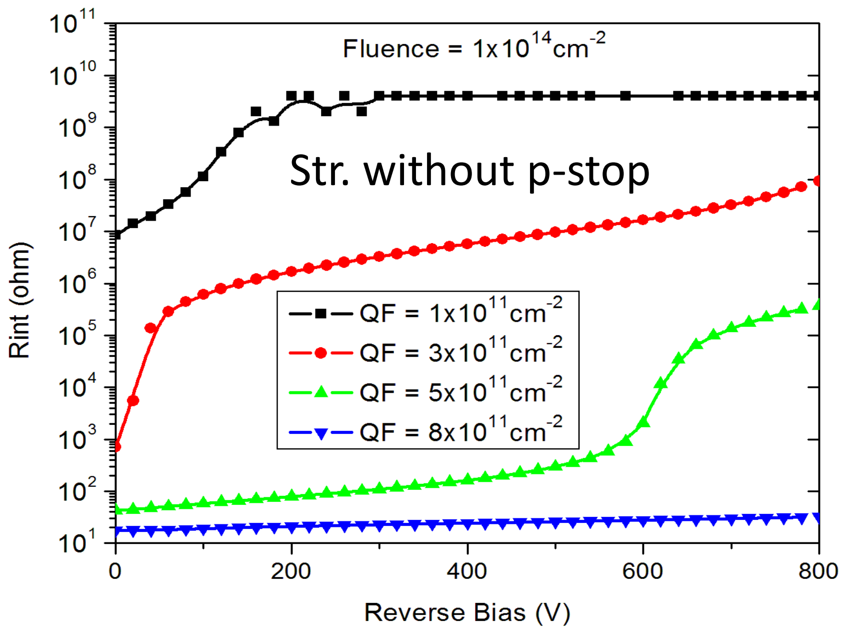




- Isolation remains good for all values of Q_F.
- Simulation shows decrease in R_{int} for high values of Q_F at high Bias values. Experimentally different structures show similar behavior.
  - Electric field near the curvature of p+ strip is quite high & increases with Q_F . This high E field can initiate a localized avalanche & can decrease R_{int}

Simulations of Rint for Fluence = $1x10^{14}$neq/cm^2





- Saturation value of Rint decreases (compare to unirradiated case) with irradiation
- Significant improvement in Rint values for higher values of Q_F

What is going inside hadron irradiated sensors !

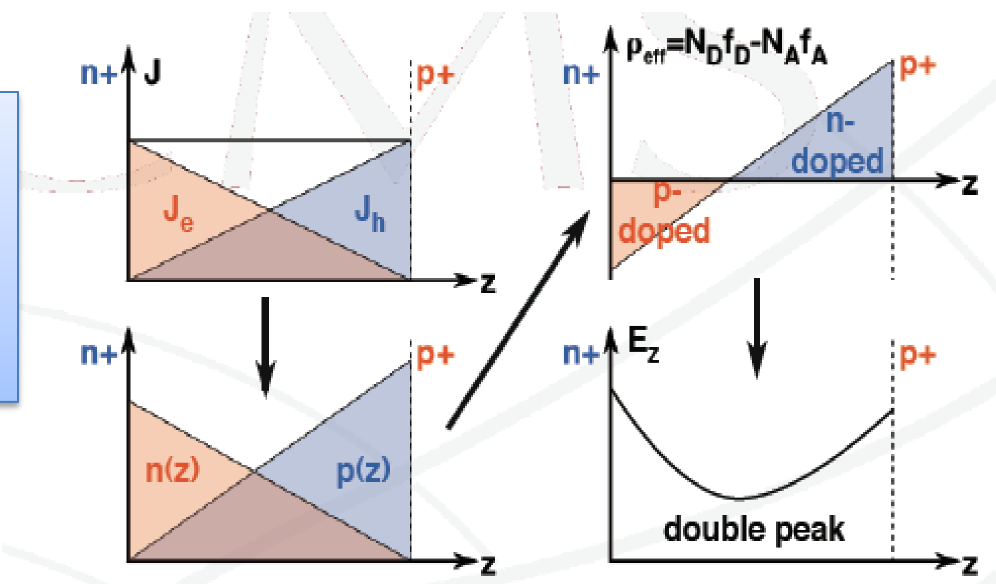
Irradiation of n+p-p+ Si sensor by hadrons :

- 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….?

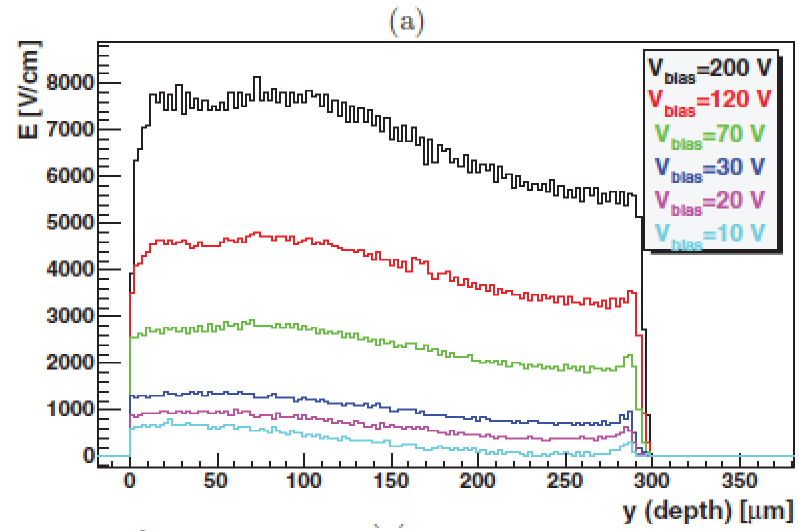
Yes by eTCT



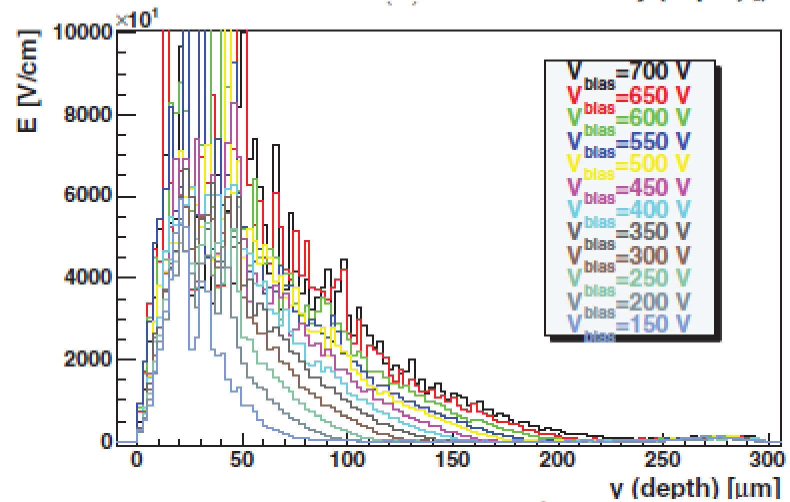
Measurement of E-field in a irradiated Si strip sensor (n+p-)

G. Kramberger et all , 2009, IEEE conference

E field profile for a non-irradiated sensors <8000V/cm for reverse bias = 200V



- **E field profile for a irradiated sensors**
Can be as high as 80000V/cm, near the strips for reverse bias = 200V !
- ***Formation of high density negative space charge near n+ strips***



(flux=5e14cm^{-2})

- The negative space charge will act as Pspray and increases with irradiation !
Hence, we never had much problem of strip isolations in hadron irradiation expt!

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

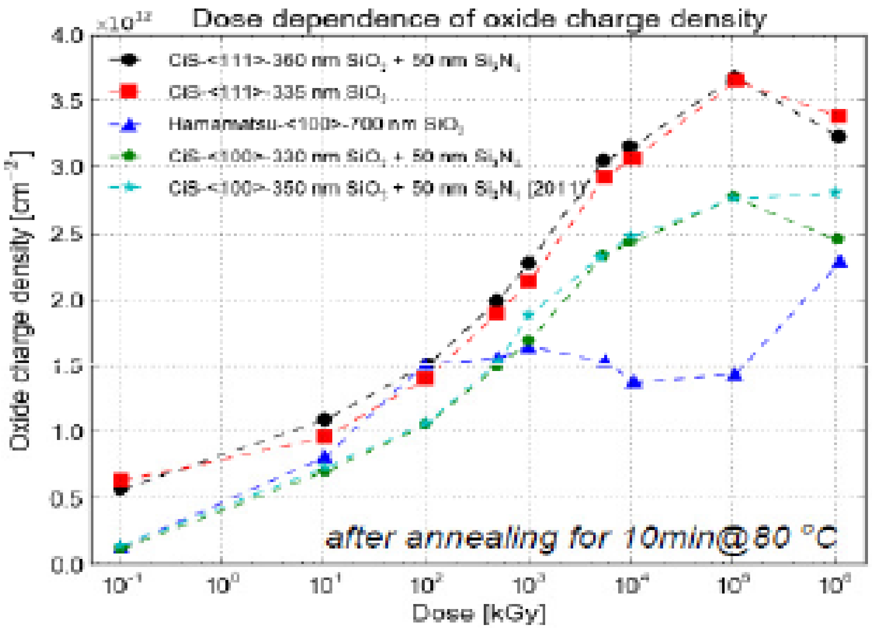
- Oxide charge density ~ 2-3x10^{12} cm^{-2} after irradiation ~ 1MGy (in MOS as well as in strips and pixel sensors), leading to very serious problems for isolation, Cint & breakdown.

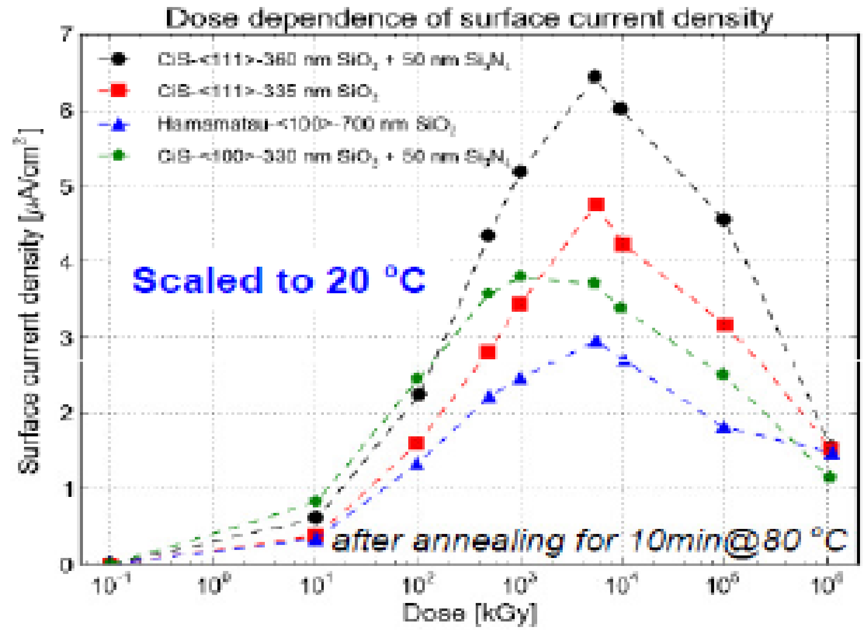
❖ **Irradiations with Hadrons (p,n or pions irradiations)**

- 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 !!!

Universität Hamburg

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Analytical Model for the Ohmic-Side Interstrip Resistance of Double-Sided Silicon Microstrip Detectors

Giovanni Verzellesi, Gian-Franco Dalla Betta, and Giorgio U. Pignatel

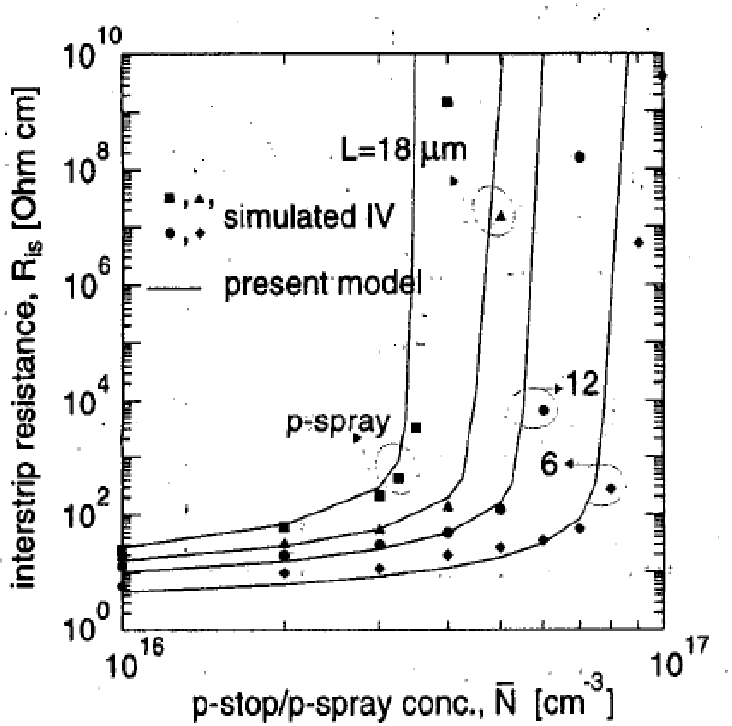


Figure 4: Interstrip resistance values as a function of the p-stop(p-spray) average doping concentration, as obtained from the proposed analytical model and from simulated $I_2(V_1)$ curves. A positive charge density of 2×10^{12} cm^{-2} is assumed in the oxide.

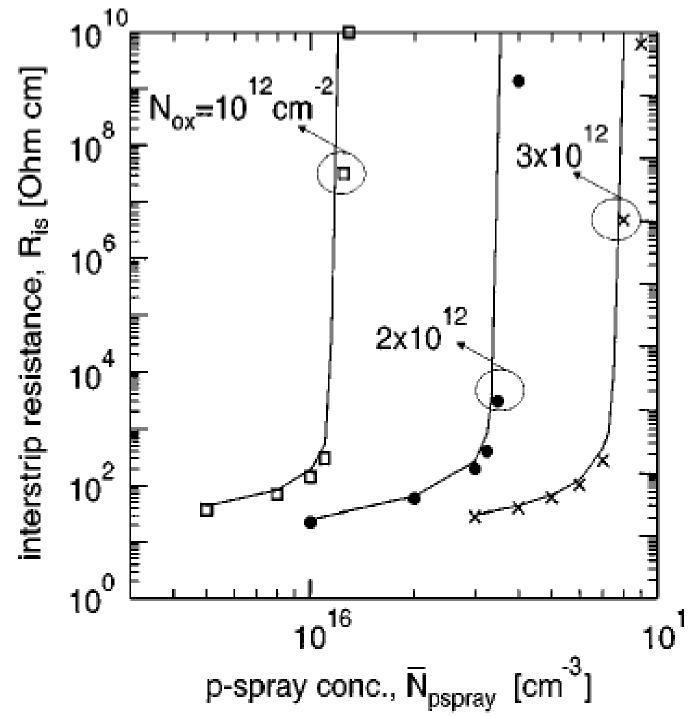
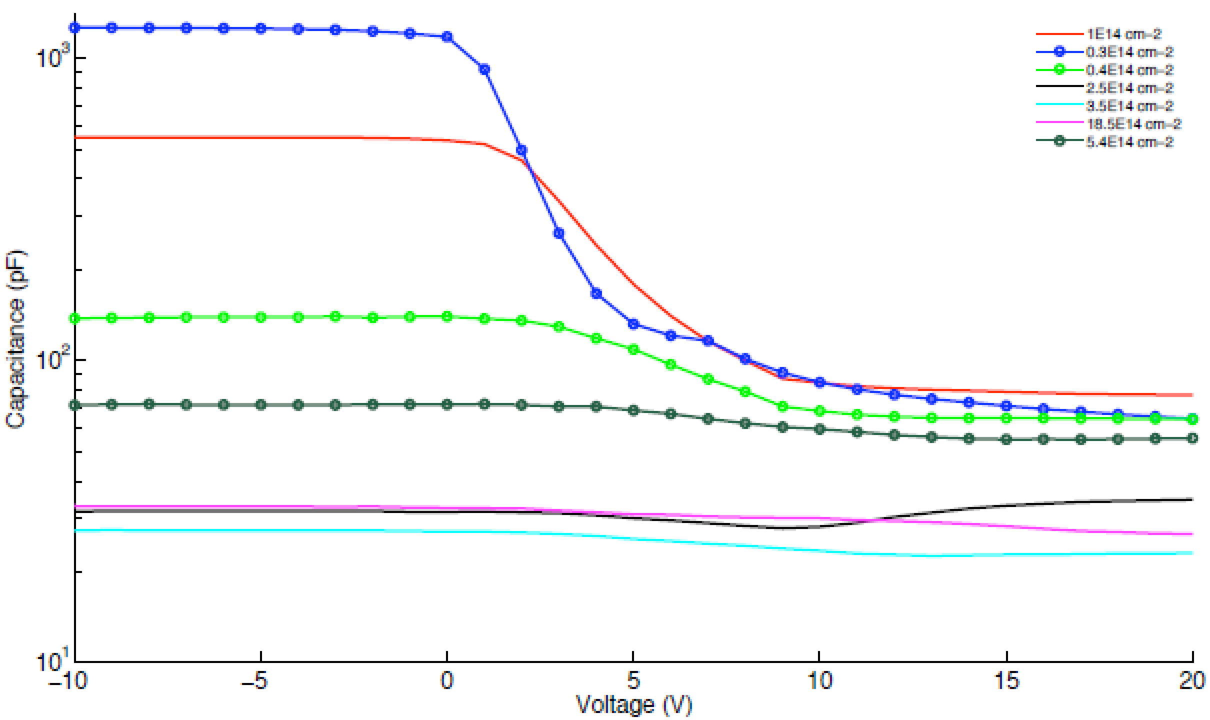


Fig. 6. R_{is} as a function of p-spray doping concentration for different N_{ox} values, as obtained from the present model (solid lines) and from device simulations (symbols). For all curves, $L = 28\ \mu$m and $V_{rev} = 100$ V.

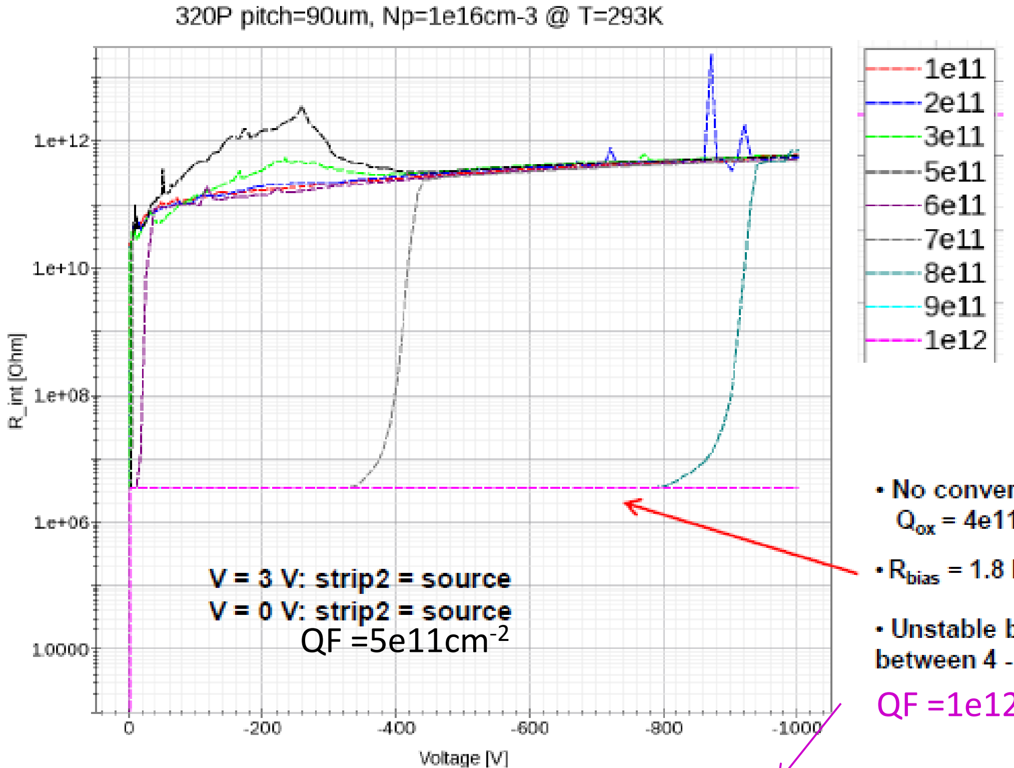
From Maria thesis, MOS measurement

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.



■

Rint simulations (Timo Peltola)
-Pspray doping (1e16cm^{-3}) is one order of magnitude higher then HPK
-For QF = 5e11cm^{-2}, Strip isolation Was not possible (upto reverse bias = 400V)
-For QF = 1e12 cm^{-2}, No strip isolation Even upto 1000V (Though pspray is 10 times denser then HPK pspray)

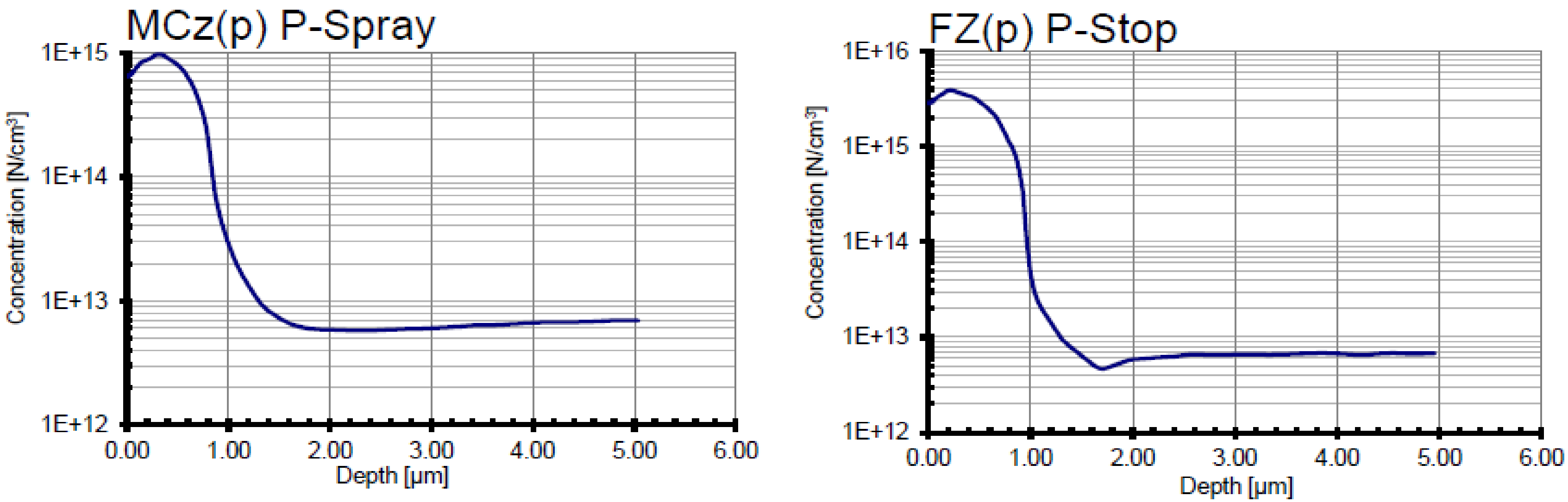


- No convergence at Q_{ox} = 4e11 cm^{-2}
- R_{bias} = 1.8 MΩ
- Unstable behaviour between 4 - 5e11 cm^{-2}

QF =1e12cm^{-2}

Pspray/Pstop doping profile measurement

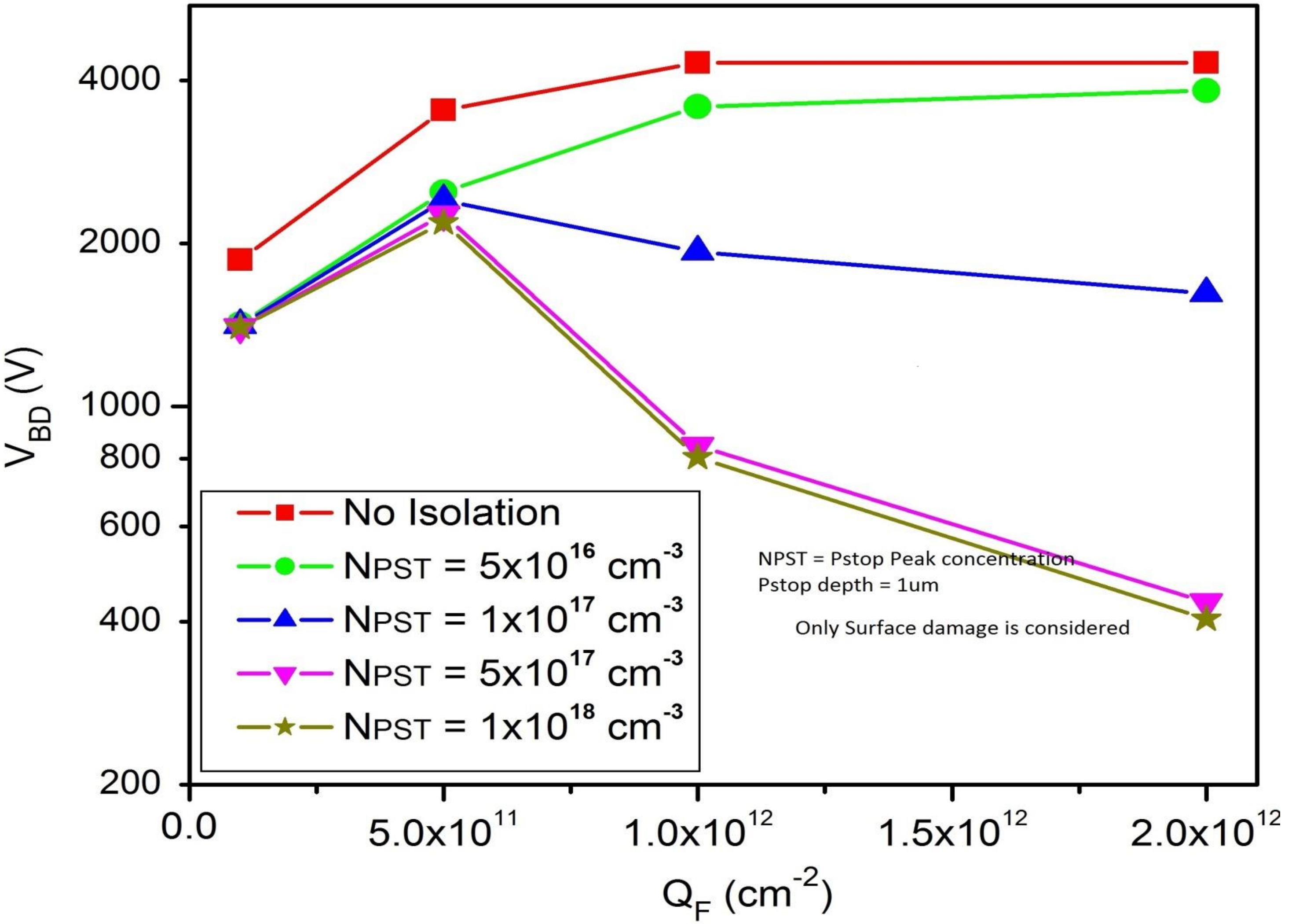
2. Doping Profiles: P Spray/Stop Implant



- **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

21.02.2013 Wolfgang Treberspurg (HEPHY Vienna) 10

Trend for Vbd for different P-stop doping density



For slightly different $n^+ p^-$ structure