Insight into the behaviour of futuristic low bulk resistivity Si sensors using device simulation

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Plan of the presentation

- **Introduction**
- **Comparison with Experimental Results**
- **Effect of Bulk Doping on CCE**
- **Summary**

Gain Variation with Fluence

The variation of gain (w.r.t. non-irradiated case) with fluence is due to two separate effects

a) The reduction of avg. path length of charge carriers

- Leads to trapping
- Double junction effect, may lead to negligible E field within the bulk
- Decreases the multiplication

➡ hence leads to lower collected charges

b) Change in charge collection volume with fluence

- Change in Neff may result in more depleted volume for low fluence (acceptor removal) and may be important in CMOS & LGAD devices

➡ hence leads to higher collected charge

The gain variation of CMOS has been attributed to "Acceptor Removal Mechanism" (A. Affolder et. al., JINST 11 P04007 (2016)).

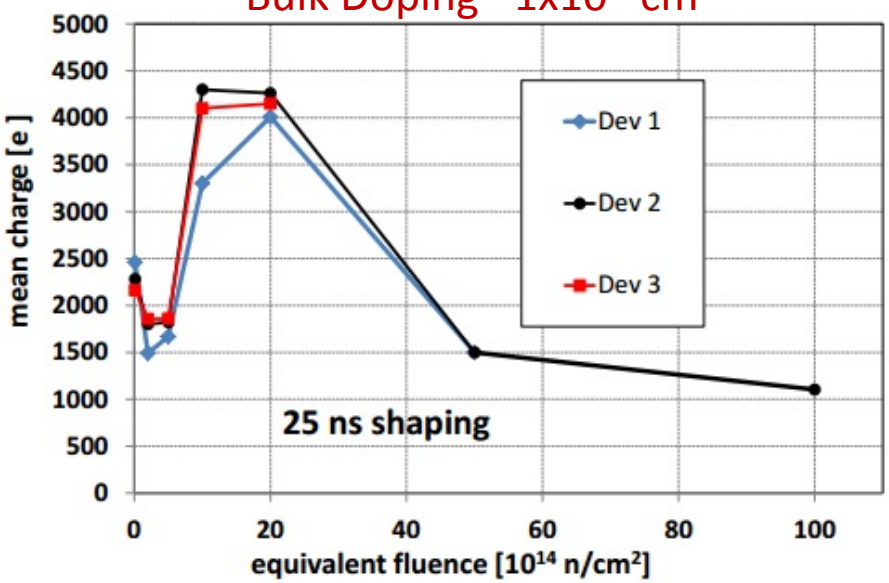
But, Can this behaviour be understood in terms of traps only (similar to LGAD devices)?

Sensors with high bulk doping (>5x10^{12}cm^{-3})

Much less investigated region (particularly, radiation damage)

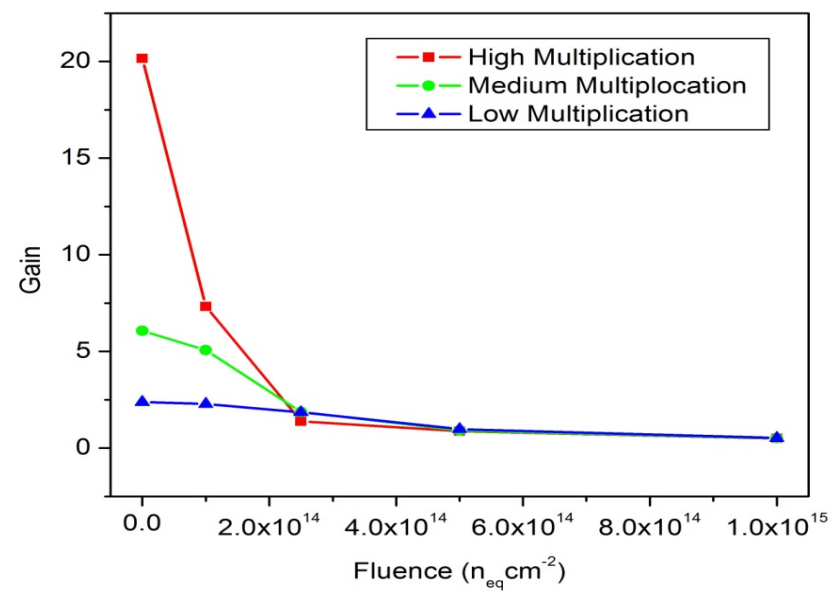
- No systematic investigation (simulation as well as measurements)
- Proper understanding of this (doping) region is critical for
  a) CMOS (~10^{14} cm^{-3} bulk)
  b) APD (~10^{14} cm^{-3} bulk)
  c) LGAD (High bulk doping may be more radiation hard)

Bulk Doping ~1x10^{14}cm^{-3}



Charge collection studies in irradiated HV-CMOS particle detectors, A. Affolder et. al., JINST 11 P04007 (2016)

Bulk Doping = 1x10^{12}cm^{-3}



Gain Vari)ation with fluence for LGAD, Simulation by DU group, R.Dalal, JINST 2016

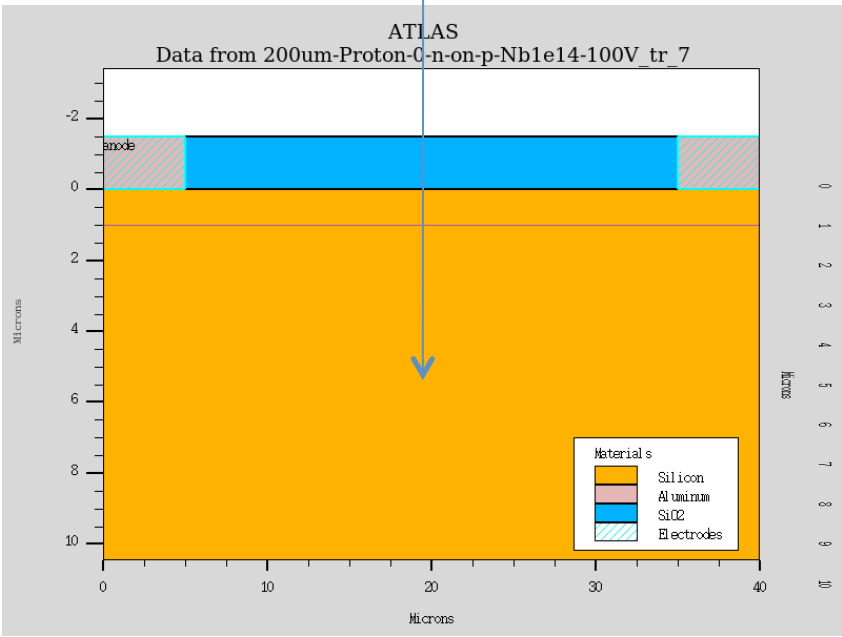
Simulation Structure

n-in-p and p-in-n 2-D diodes

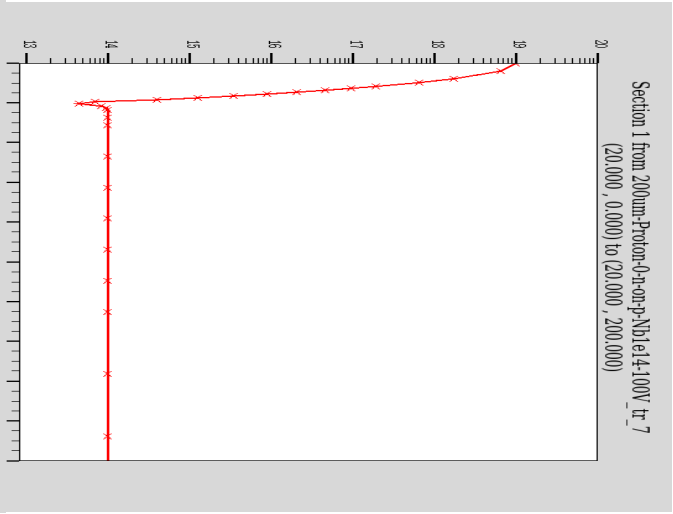
- 1 μm x 40 μm active area
- 300 μm, 200 μm diode thickness
- Front side n+/p+ doping depth = 1 μm
- Backside p+/n+ doping depth = 2 μm
- Bulk doping density $1x10^{12}cm^{-3}$ to $2x10^{14}$ cm^{-3}

- CCE Simulation at 500V and 1000V using Infrared laser TCT
- Fluence range from 0 to 1e16 $n_{eq}cm^{-2}$

Infrared laser



Doping profile
For bulk $1x10^{14}cm^{-3}$



Radiation Damage model

Radiation damage simulations are carried out using already published and tested two trap model (R. Dalal et al., Vertex-2014)

- It was developed during HPK campaign for proton irradiation
- It creates correct amount of leakage current, full depletion voltage (or CV), double peak electric field profile and CCE for fluence at least up to 2e15 $n_{eq}cm^{-2}$

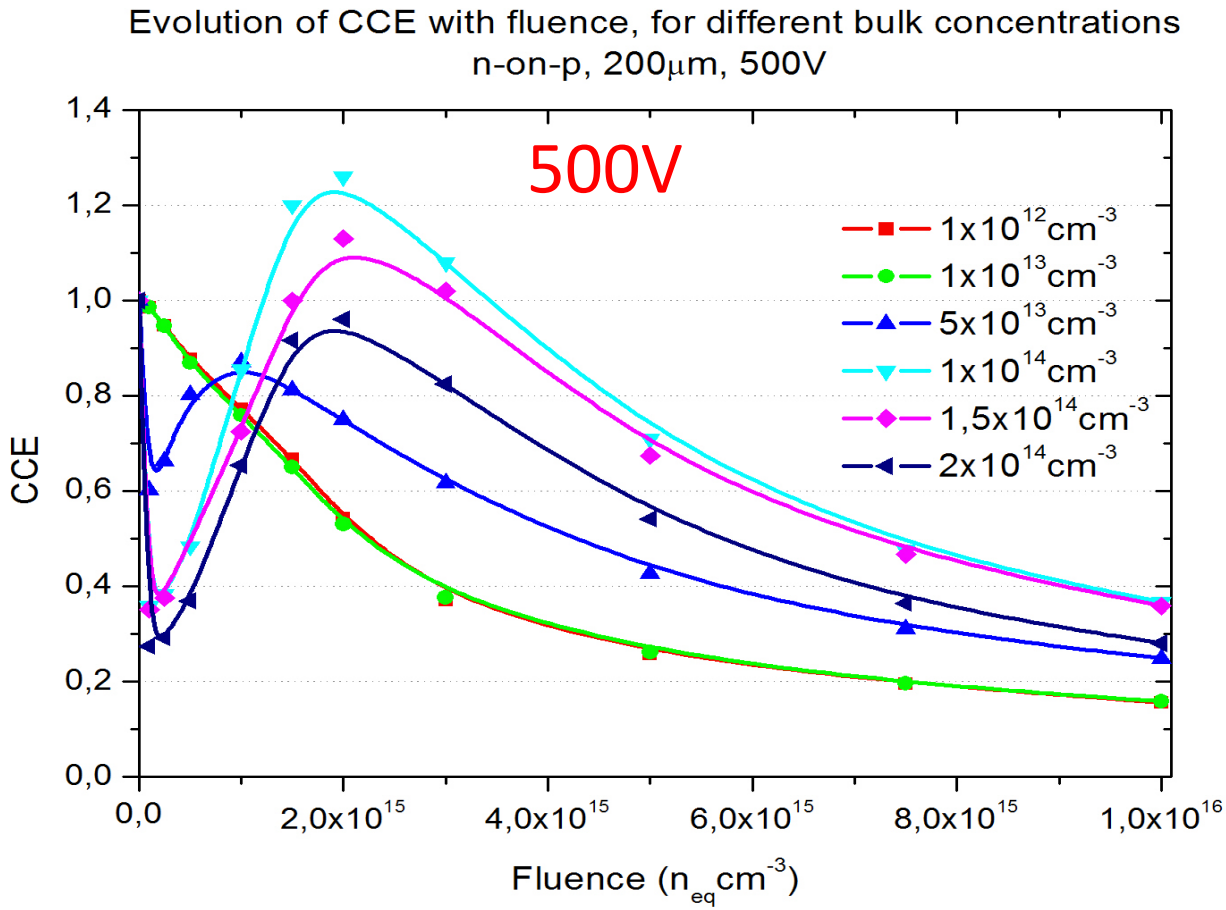
No acceptor removal term have been used in these simulations

- Simulations are carried out at 253K

No.	Trap	Energy Level	g_{int} (cm^{-1})	σ_e (cm^{-2})	σ_h(cm^{-2})
1.	Acceptor	E_c-0.51eV	4	$2x10^{-14}$	$3.8x10^{-14}$
2.	Donor	E_v+0.48eV	3	$2x10^{-15}$	$2x10^{-15}$

Parameter table for two trap model used in present simulations

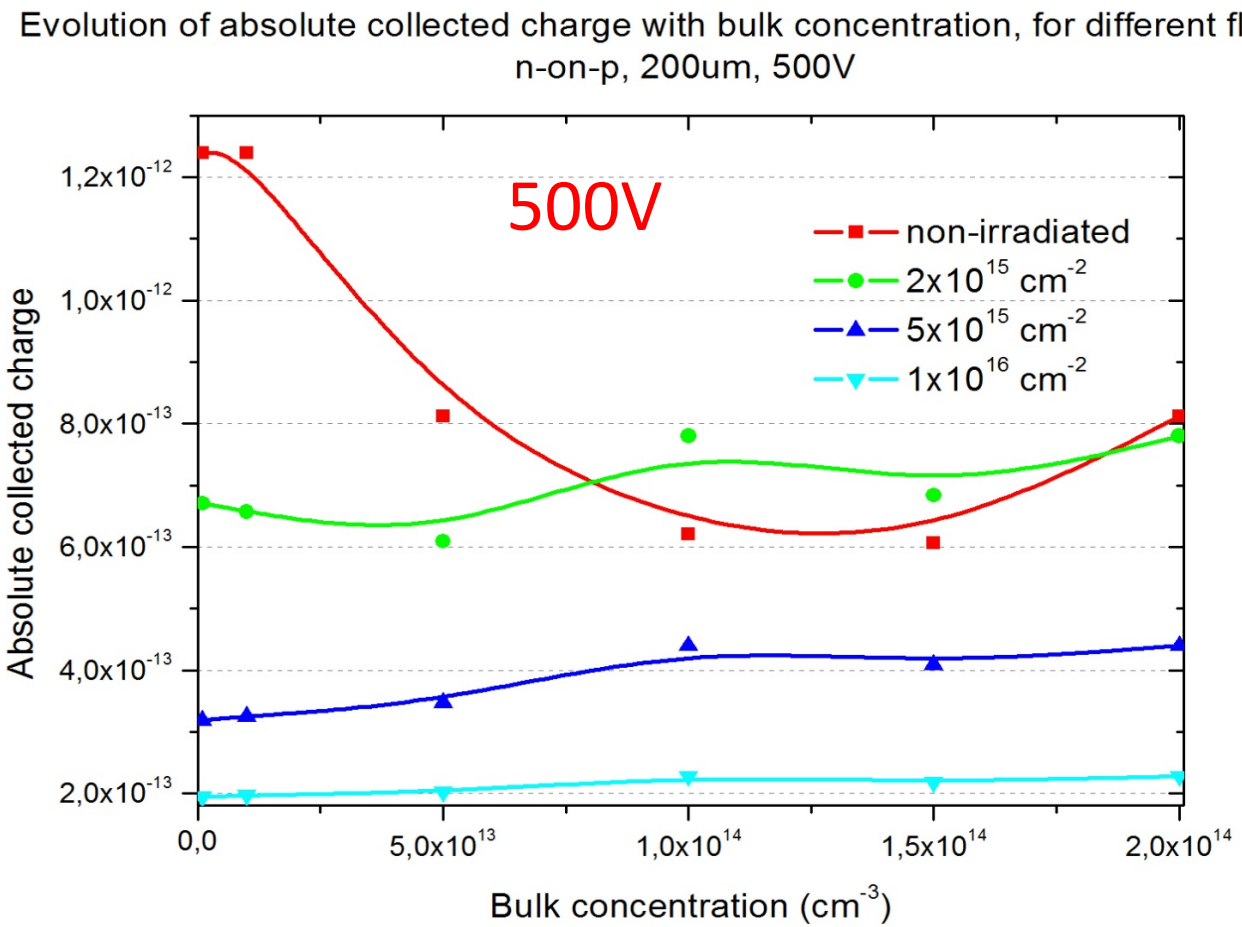
CCE variation for 200 μm n-on-p diode



- CCE at a given fluence is normalised by collected charge for non-irradiated cases for each bulk doping density.
- One could collect higher charges (than the non-irradiated case) after irradiation for high bulk doping densities , for example, CCE is highest at fluence of $2x10^{15}$ $n_{eq}cm^{-2}$ for bulk $1x10^{14}cm^{-3}$

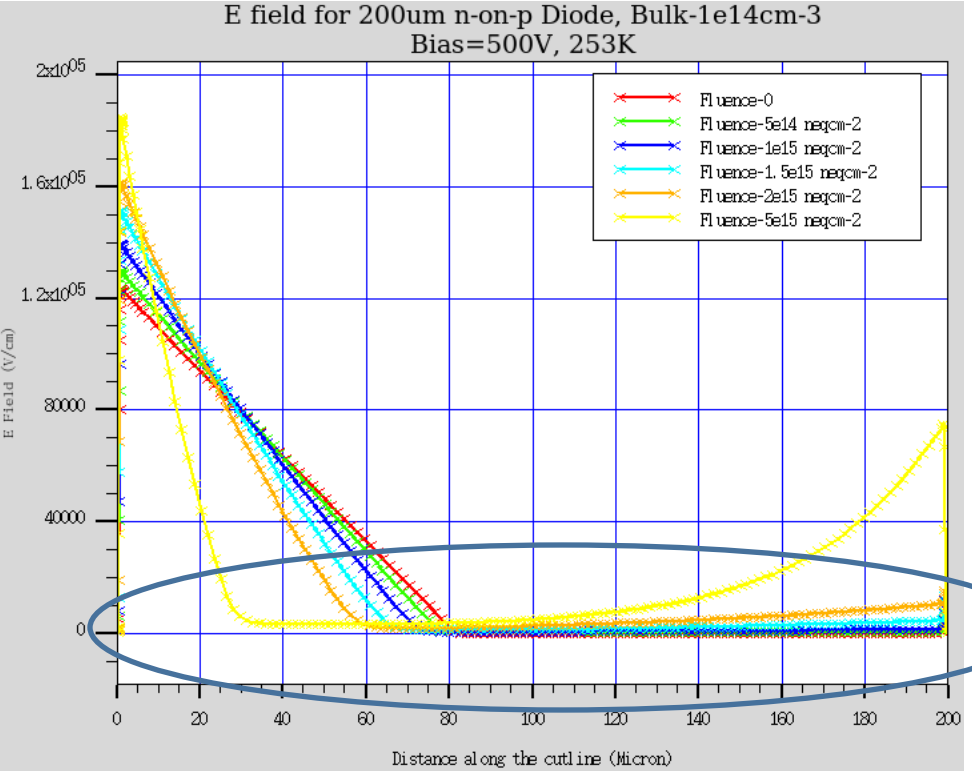
(Kindly, note that this is not absolute amount of charge, but relative !)

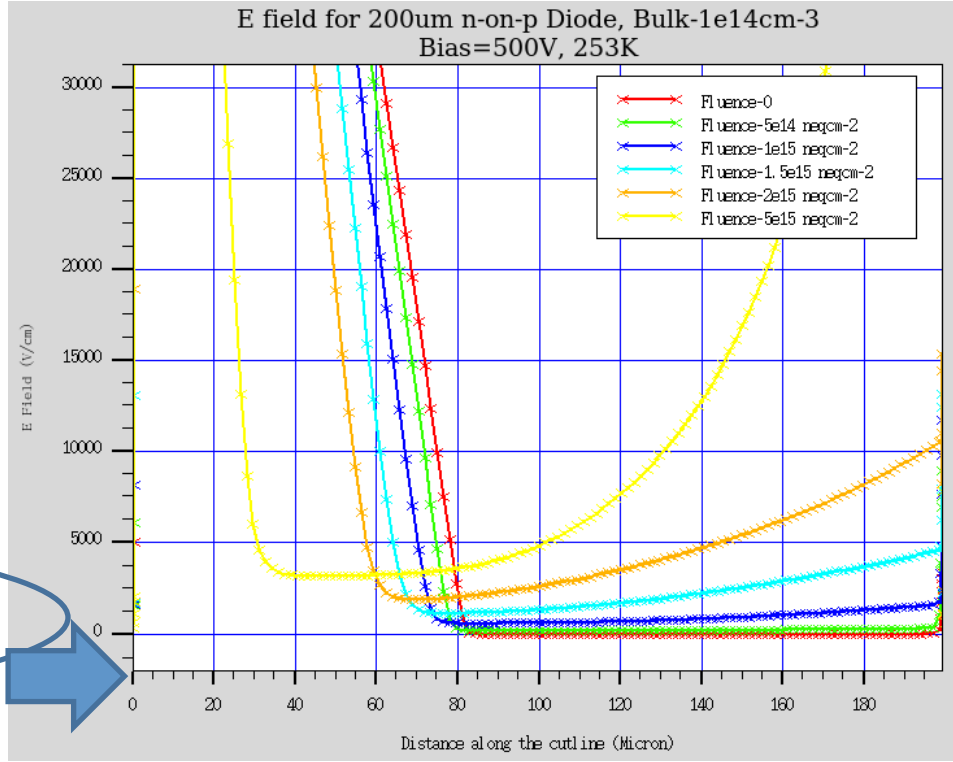
Absolute charge variation for 200μm n-on-p diode



- Higher bulk doping densities appears more radiation resilient
- Charge multiplication for high bulk doping ($2x10^{14}cm^{-3}$) for low/zero fluence
  e.g. Collected charge is higher for bulk $2x10^{14}$ cm^{-3} for non-irradiated case
- Same laser intensity (1060nm) is used for these cases

E Field Variation with Fluence





Zoomed view of left side plot

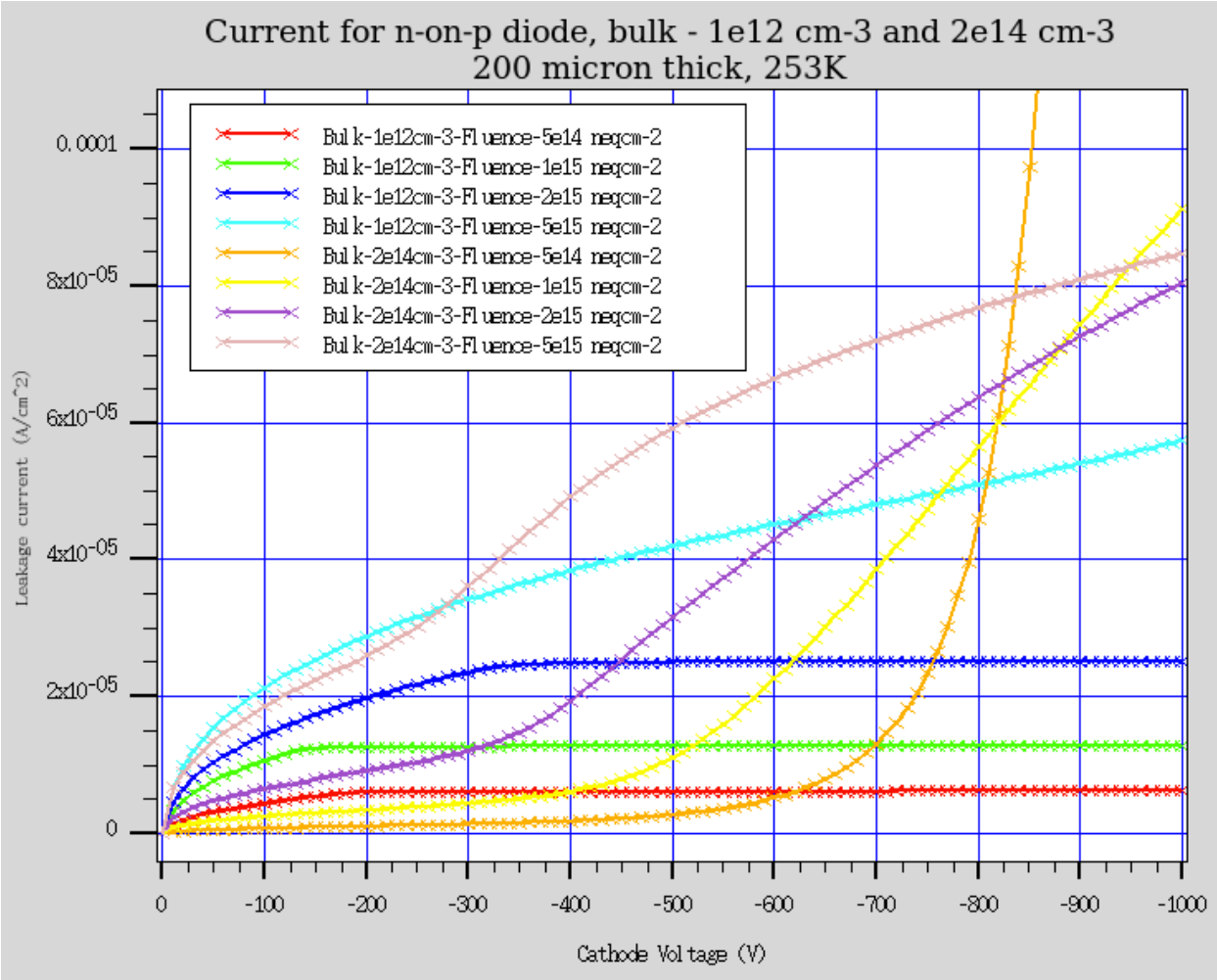
For high bulk density substrate (here it is $1x10^{14}$ cm^{-3}),

(a) For initial irradiation (~ $1x10^{14}$ $n_{eq}cm^{-2}$), both acceptor/donor traps are created but the E field in most of bulk is not sufficiently strong enough to collect the generated charge carriers & leads to initial drop in CCE

(b) Fluence > $5x10^{14}$ $n_{eq}cm^{-2}$, active sensor volume increases due change in effective doping conc. leading to increase in CCE by compensating the trapping charge losses.

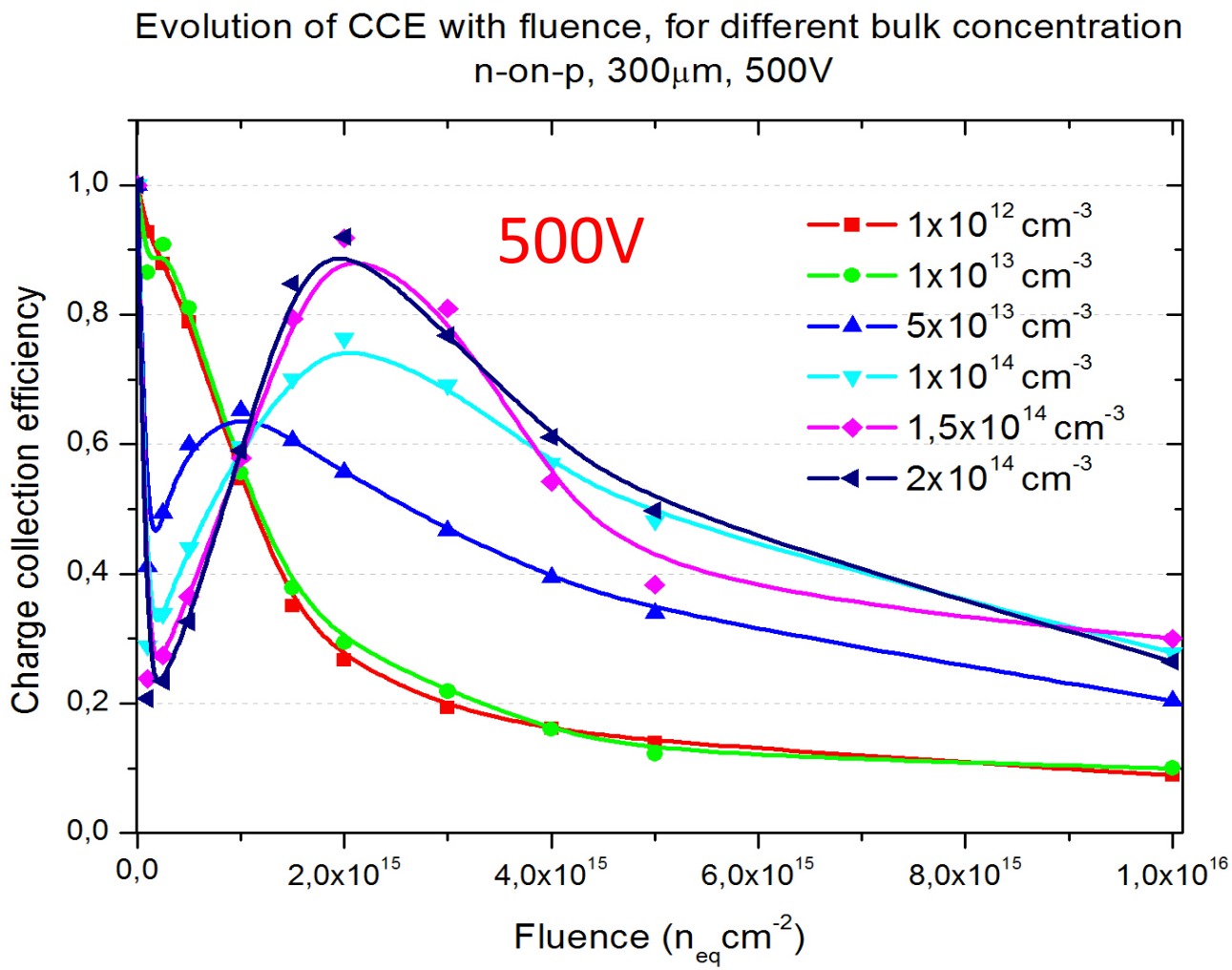
(c) For very high fluence > $2x10^{15}$ $n_{eq}cm^{-2}$, trapping becomes more dominant (as active sensor volume has already reached maximum) and field is peaking near the sensor back

Leakage current variation with bulk doping-1



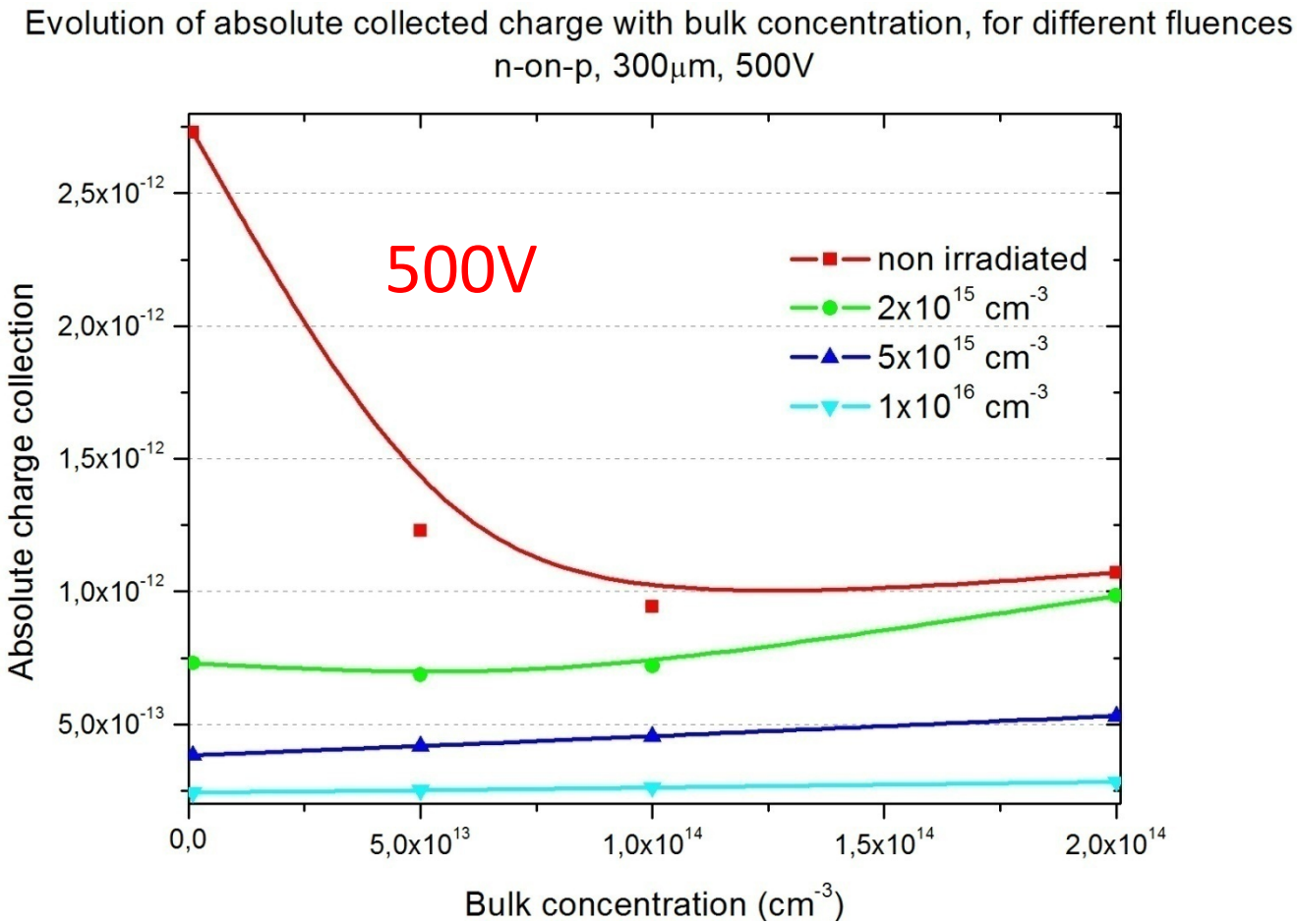
- For bulk 1e12 cm^{-3}, I_{leak} first increases but saturates after full depletion upto fluence of $2x10^{15}$ cm^{-2}
- For bulk doping 1e14cm^{-3}, I_{leak} increases and shows breakdown behaviour at 5e14cm^{-2} & 1e15cm^{-2} fluence. At higher fluence current is monotonously increasing (Leakage current has been normalized for the 1cm x 1cm active area)

CCE variation for 300μm n-on-p diode



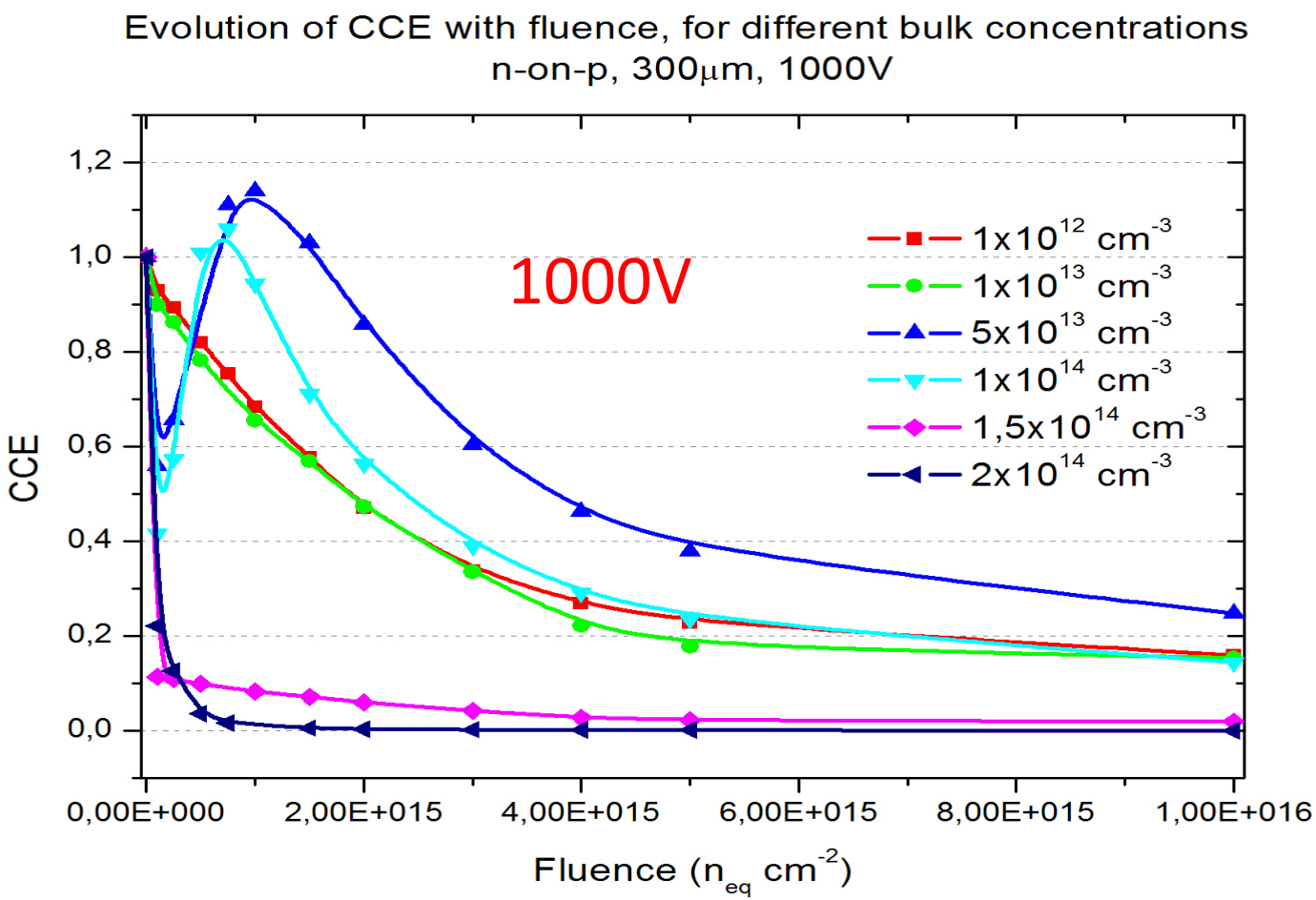
- Similar trends are observed for the 300 μm diodes (500V)

Absolute charge variation for 300μm n-on-p diode



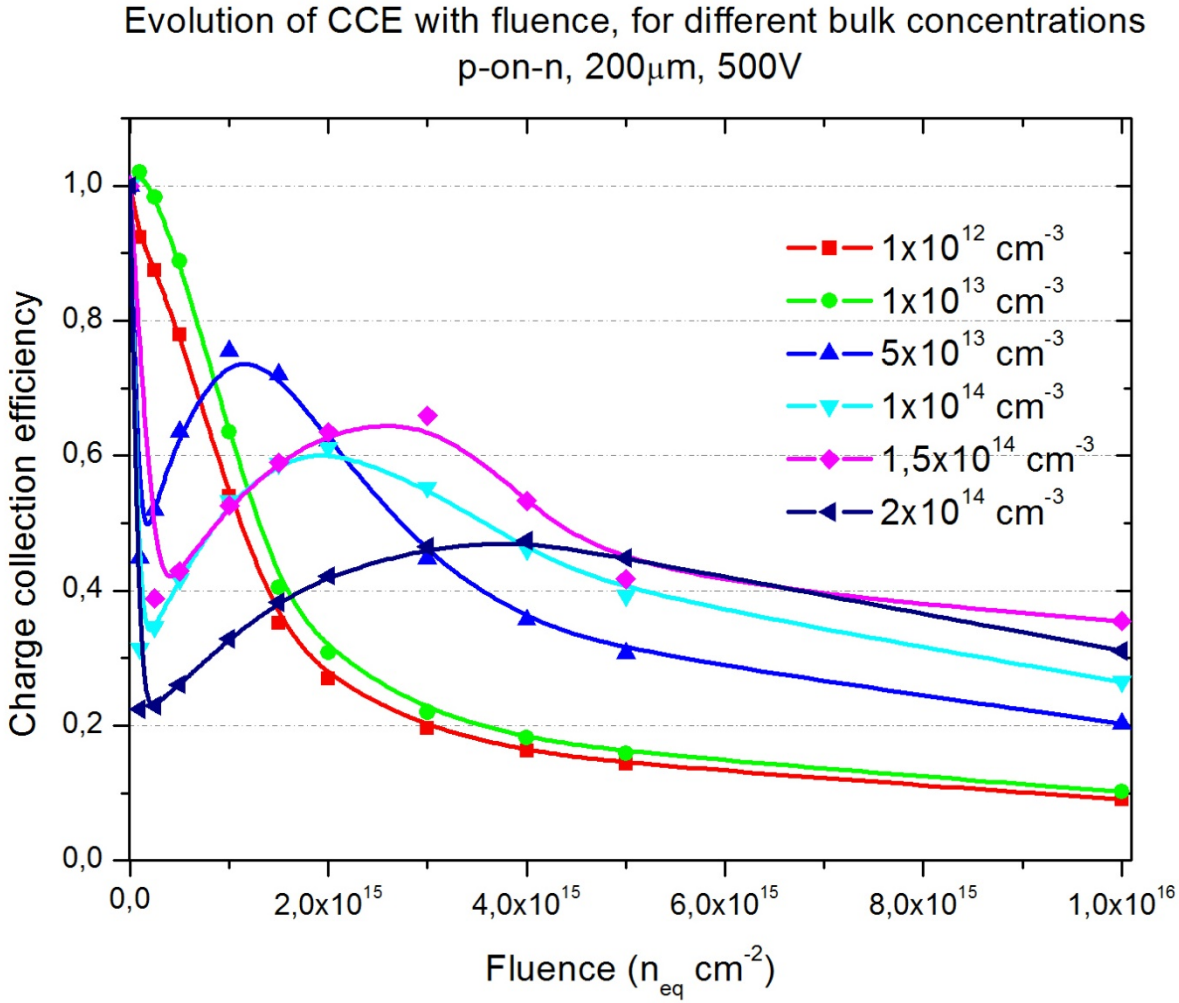
-Charge multiplication for high bulk doping (~$2x10^{14}cm^{-3}$) for low/zero fluence
e.g. Collected charge is higher for bulk $2x10^{14}$ cm^{-3} for non-irradiated case
- Same laser intensity (1060nm) is used for these cases

CCE variation for 300μm n-on-p diode



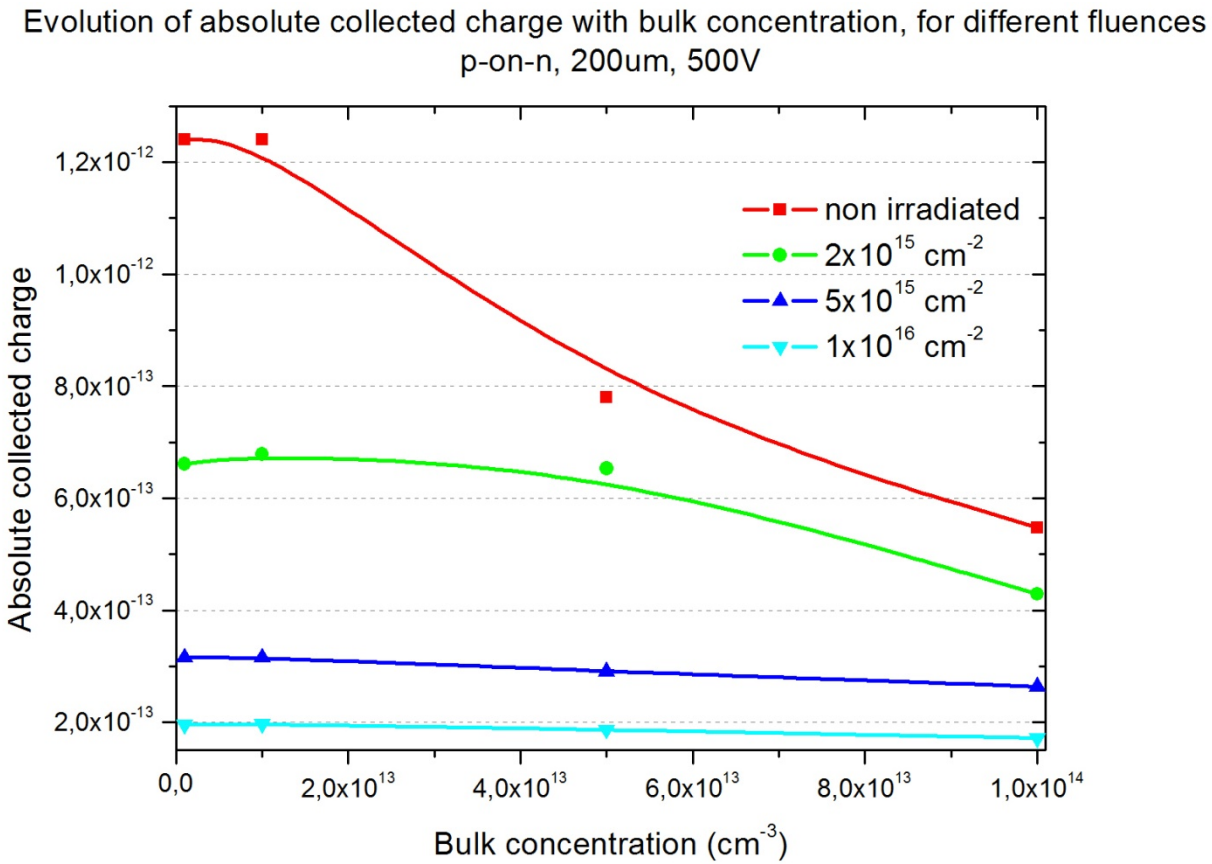
- For bulk doping density $2x10^{14}$ cm^{-3} and $1.5x10^{14}$ cm^{-3} at 1000V, very high E field near n-p junction leads to a significant signal multiplication. This charge multiplication is strongly suppressed by traps leading to very low relative CCE for higher fluences.

CCE variation for 200μm p-on-n diode

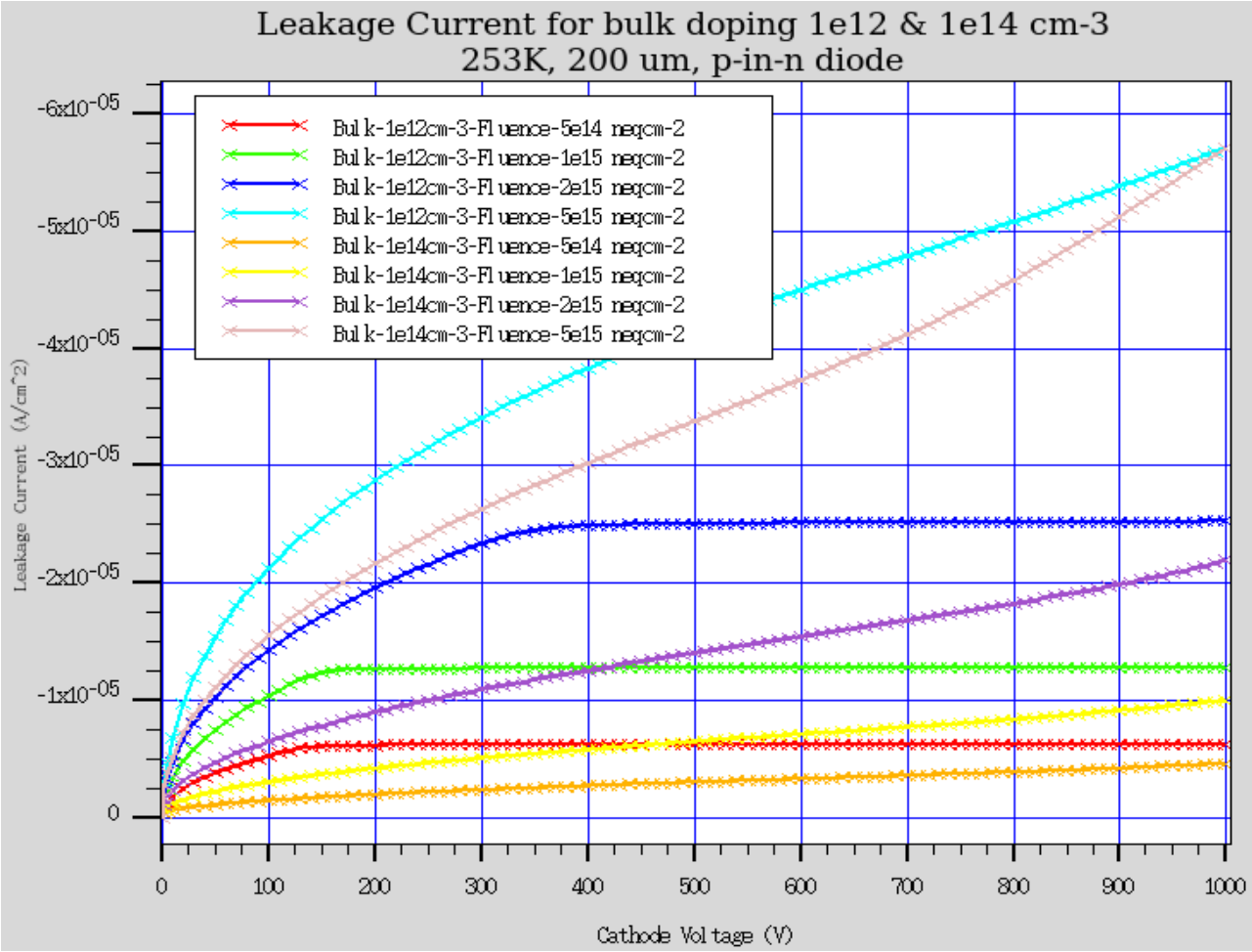


- CCE rebound is somewhat less in n type bulk (compared to p-type bulk)

Absolute charge variation for 200μm p-on-n diode



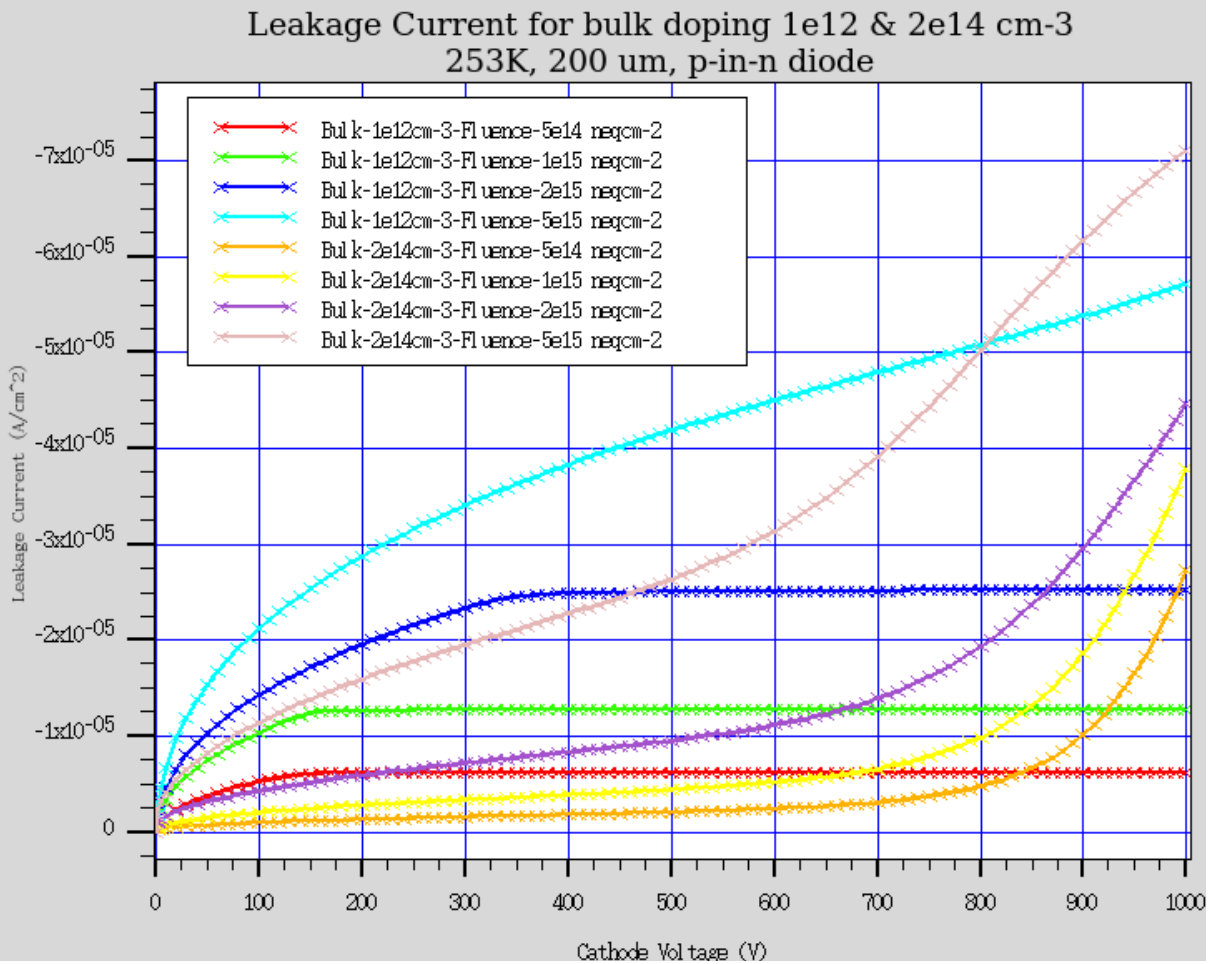
Leakage current variation with bulk doping-1



- For bulk 1e12 cm^{-3}, I_{leak} first increases but saturates after full depletion upto fluence of $2x10^{15}$ cm^{-2}
- For bulk doping 1e14cm^{-3}, I_{leak} increases with bias monotonously and saturation is not observed up to 1000V

(Leakage current has been normalized for the 1cm x 1cm active area)

Leakage current variation with bulk doping-2



- For bulk 1e12 cm-3, I_{leak} first increases but saturates after full depletion
- For bulk doping 2e14cm^{-3}, initially I_{leak} increases with bias slowly but it starts to increase rapidly for higher reverse bias.

For example, for diode irradiated with fluence 2e15 n_{eq}cm^{-2}, I_{leak} increases steeply after 700V

Summary and future outlook

- Si sensors having low resistivity bulk (10-1000 ohm -cm) are increasingly used in different type of sensor designs.
- Need a systematic investigation of radiation damage effects using simulation based approach on simple structures (and measurement approach too!)
- Radiation damage effect on different sensor bulk doping densities up to $2x10^{14}$ cm^{-3} is simulated
- Simulated CCE for the high bulk doping densities
    a) First decreases with fluence (minimum at ~ few time 10^{14} $n_{eq}cm^{-2}$) at a given voltage
    b) Then, increases with fluence (maximum at about $2x10^{15}$ $n_{eq}cm^{-2}$)
    c) For higher fluences, it again gradually decreases
- From E field plots, it appears that the CCE variation can be understood as interplay of trapping and increase in the active sensor volume due to traps.

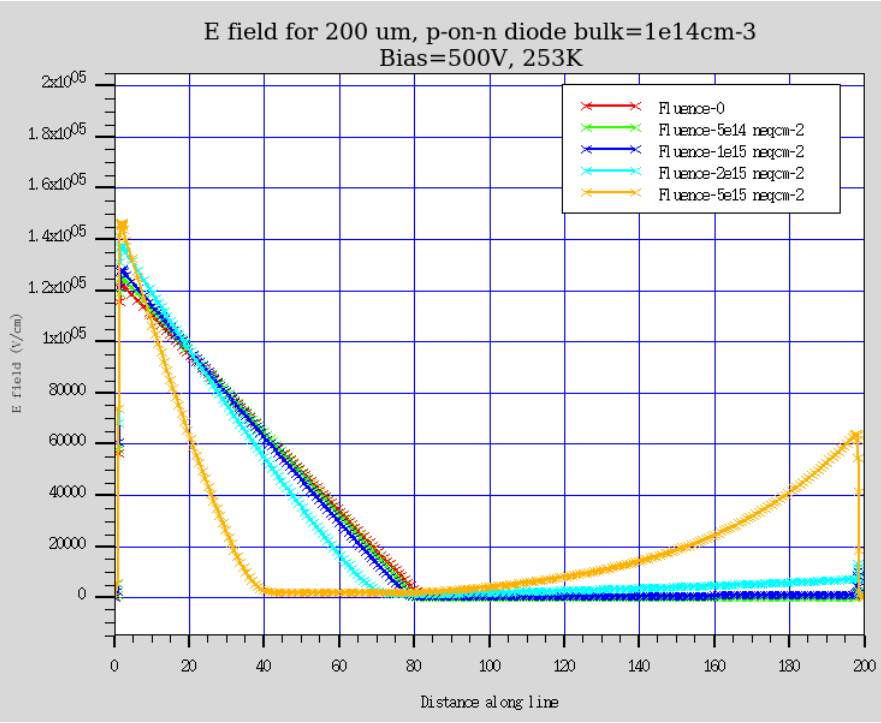
Further work

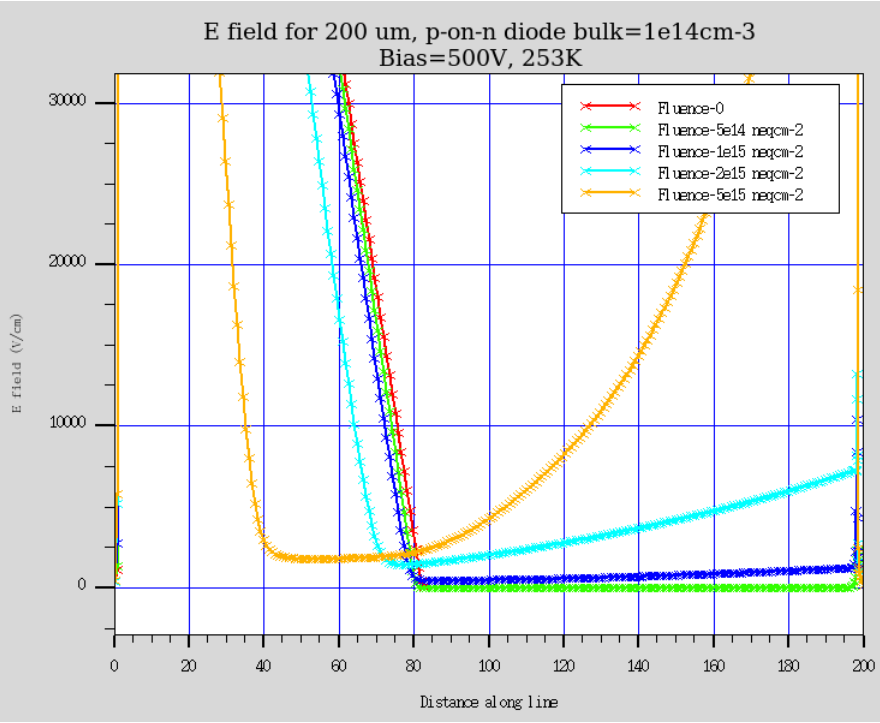
- Study Neff within the device as a function of fluence
- Understand variation of other parameters of interest like, sensor leakage current, Capacitance, and breakdown voltage.
- Moreover, surface damage effects for the high bulk doping density sensors
- Simulation of HV-CMOS sensor geometry with more realistic parameter values

Thanks
&
Suggestions, Comments from the Collaboration

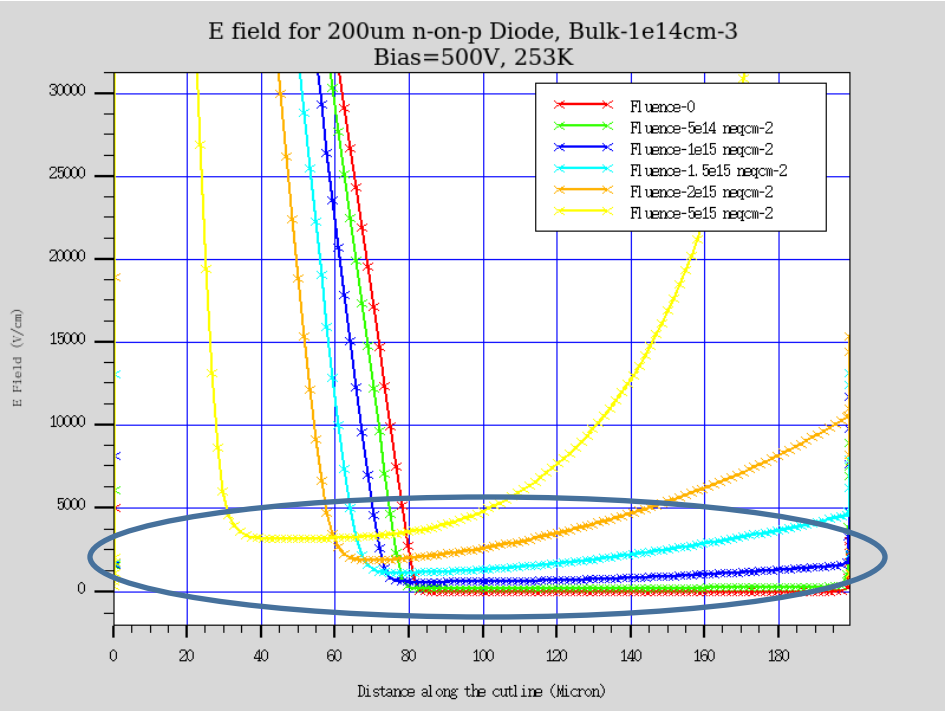
Backup slides

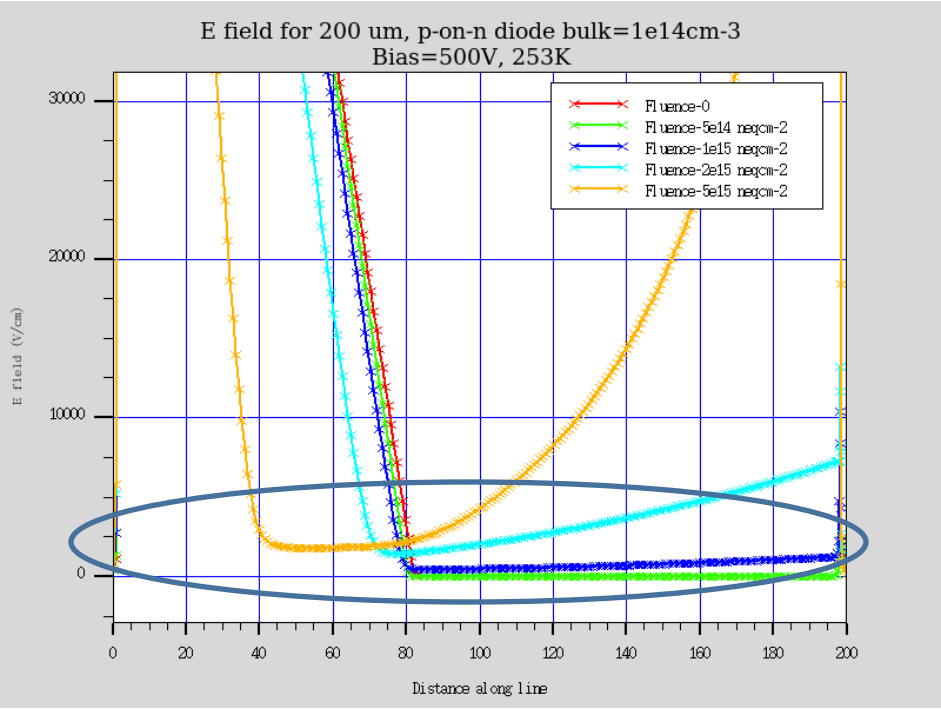
p-on-n diode 200 micron, 500V





p-on-n and n-on-p diode 200 micron, 500V





- Slightly higher E field in mid region for irradiated n-on-p would be helpful