Isolation Characteristics of Silicon Sensors Using Simulation Approach

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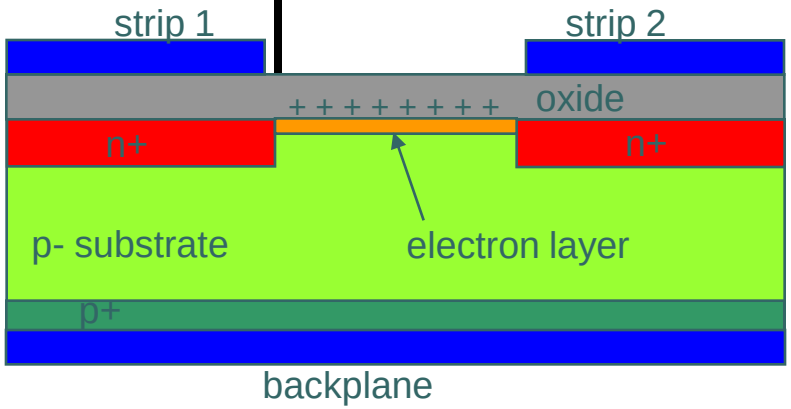
Overview

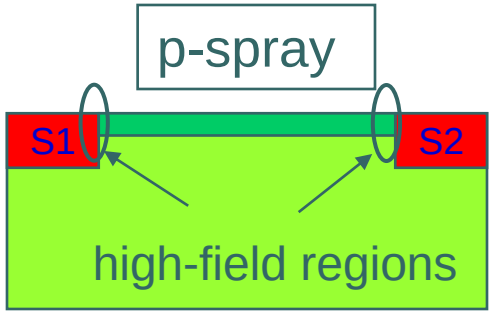
- **Isolation in Si sensors**
  - ✓ **R&D for the development of the double sided p^+-n^--n^+ Si detectors (DSSDs) for the proposed SiD detector.**
  - ✓ **The designs simulated in the present study are under fabrication at Bharat Electronics Limited (BEL), Bengaluru, India (same place which fabricated CMS Preshowe sensors)**
  - ✓ **Layout/Geometry**
  - ✓ **Results**
- **Double peak electric field profile simulation as part of the RD50 first simulation task**
- **Summary**

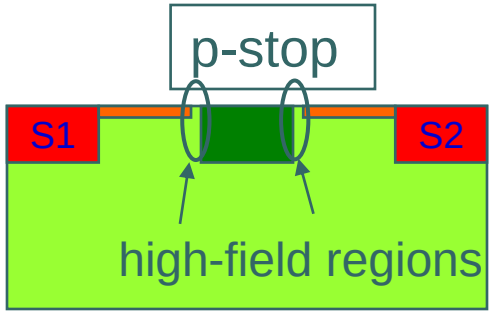
Isolation in Si sensors



- **Positive surface charge density (both fabrication and radiation induced).**
- **Shortening due to e- conduction layer in the n^+n^- (or n^+p^- sensors)**
  - **-- uniform spreading of signal over n^+ strips.**
  - **-- degradation of position resolution.**

- **Techniques to improve isolation (break conduction channel):P-spray & P-stop**





- **P-spray & P-stop also affect Interstrip Capacitance (C_{int}) & Breakdown voltage ($V_{BD.}$)**

Optimized electrical characteristics of the n^+-n^- sensors using 2-D TCAD simulation tool – ATLAS (Silvaco, not to confuse with the LHC expt.!) for following techniques: (a) combination of P-spray & P-stop; (b) multiple p-stops & (c) metal overhang over p-stops.

Performance parameters : Interstrip Conductance (G_{int}), C_{int} and V_{BD}

Cross-validation

- **Compared our results with the earlier work "*Device Simulations of Isolation Techniques for Silicon Microstrip Detectors Made on p-Type Substrates*" by Claudio Piemonte, IEEE TRANS. NUCL. SCI., VOL. 53, NO. 3, JUNE 2006. General Trends are same. Validation with some other papers on capacitance and breakdown are are also carried out.**

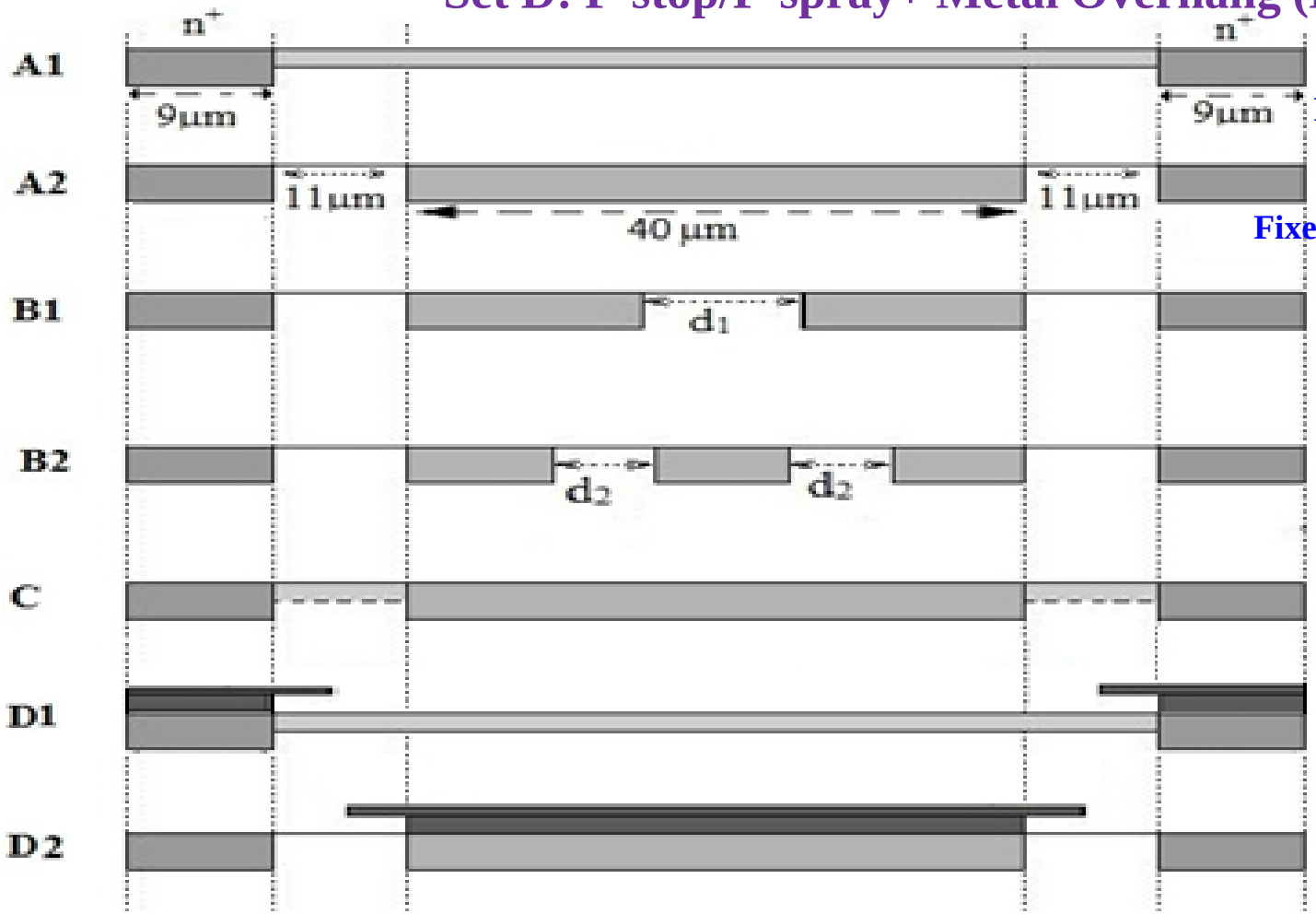
- **Working on CMS (Experiment of the LHC) and compared MSSD interstrip capacitance with Simulation => trends are similar (work is ongoing)**

Layout / Geometry

Set B: Multiple P-stops

Set C: P-stop + P-spray

Set D: P-stop/P-spray+ Metal Overhang (MO)



P-spray
Fixed dose and depth

P-stop : One
Fixed dose , depth and width

P-stop : Two

P-stop : Three

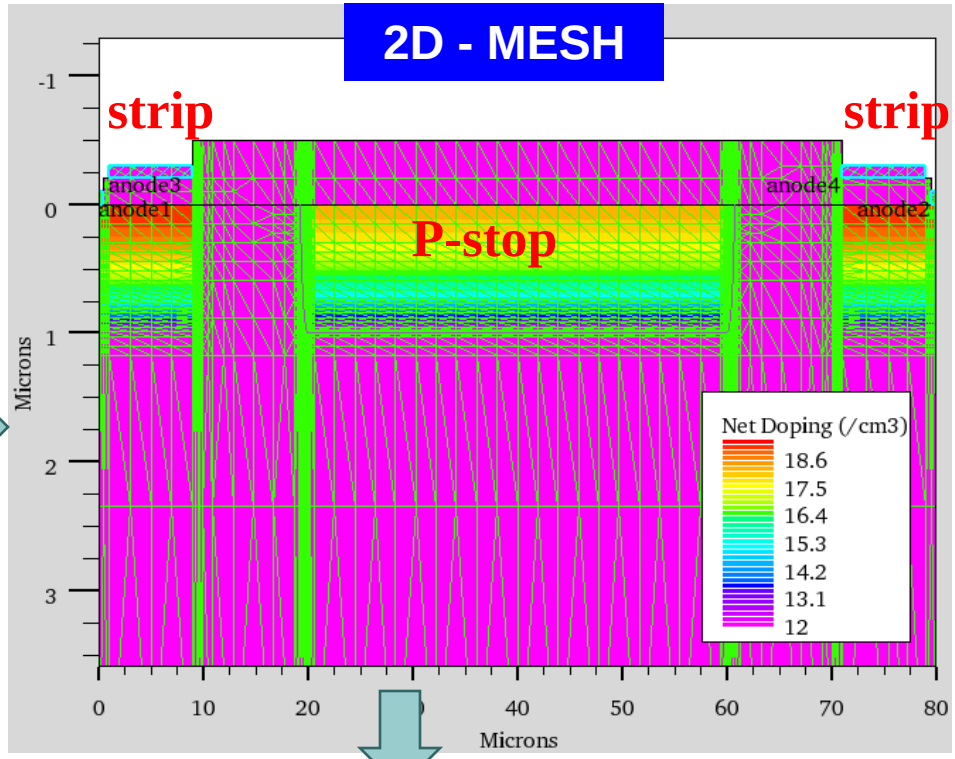
P-spray + P-stop

P-spray + MO

P-stop + MO

Layout / Geometry

Device Cross-section	300 x 80 μm^2
Junction depth (X_j)	1μm
Strip pitch	80μm
Strip width	18μm
n^+ conc.	$1x10^{19}$ cm^{-3}
n- Substrate conc.	$7x10^{11}$ cm^{-3}
Peak p-spray conc.	$2.8x10^{17}$ cm^{-3}
P-spray depth	0.5μm
Peak p-stop conc.	$1x10^{18}$ cm^{-3}
P-stop depth	1μm
P-stop width	40μm
Positive oxide charge density (Q_F)	Non-irrad: $1x10^{11}$ cm^{-2}
	Irrad: up to $3x10^{12}$ cm^{-2}



Boundary Conditions (BC)

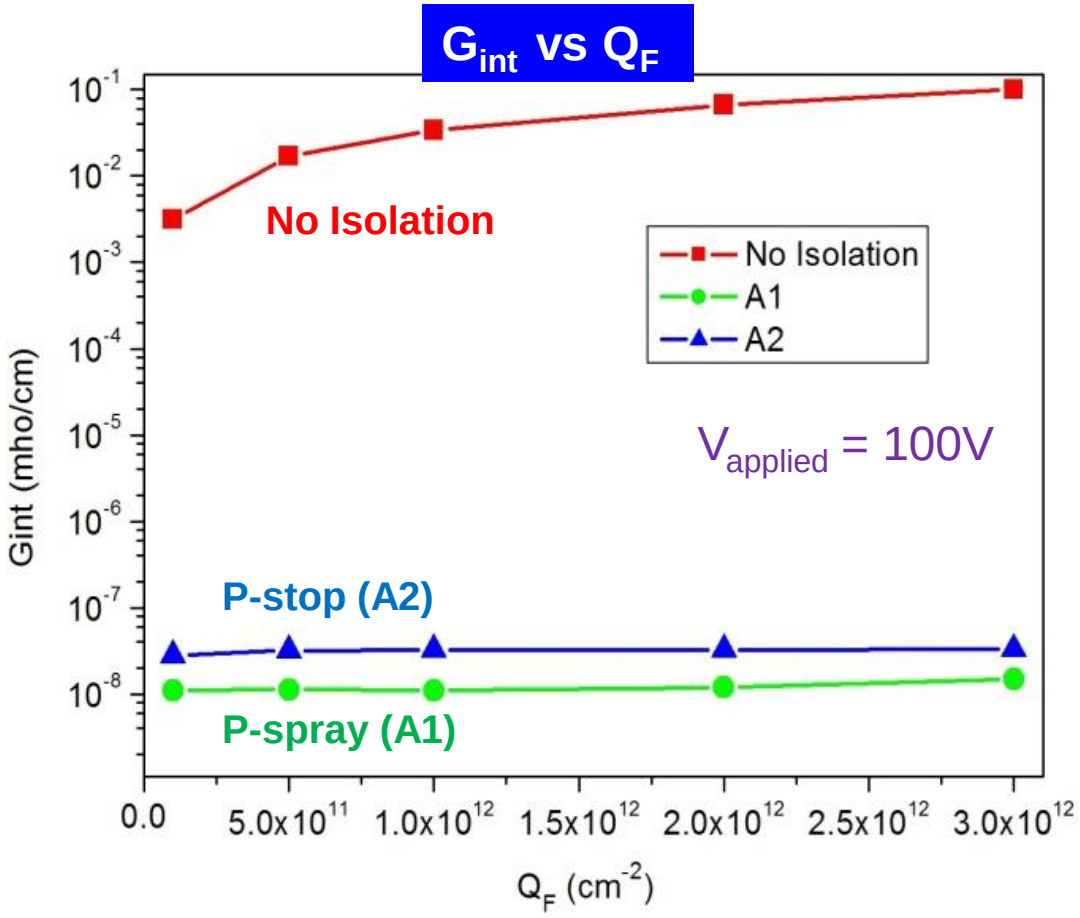
Ohmic BC: Implemented as Dirichlet BC.

Current BC: The floating contacts are implemented using current BC.

Neumann BC: Along the outer (non contact) edges of devices, homogeneous (reflecting) Neumann BC are imposed so that current only flows out of the device through the contacts.

AC small signal analysis: performed as a post-processing operation to a DC solution. The results of AC simulations are the conductance and capacitance between each pair of electrodes @ f=1 MHz.

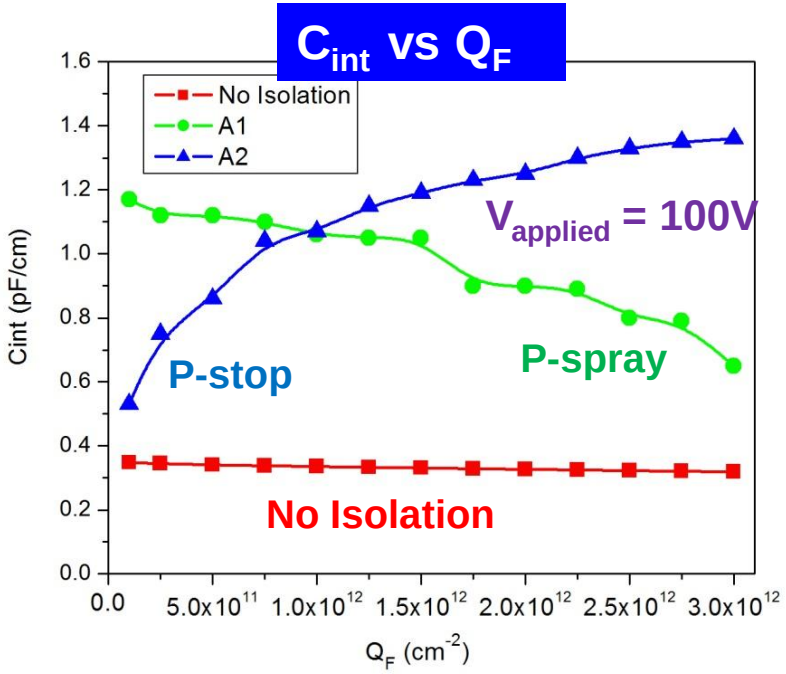
Set A: P-Spray and P-stop

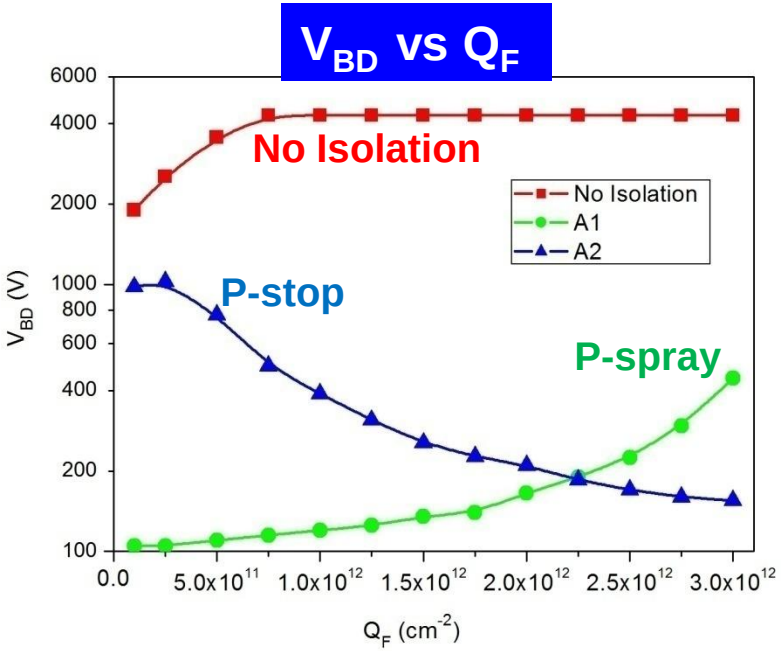


✓ **Sensor having no isolation structure has large G_{int} (indicating poor isolation) even at the low values of Q_F**

✓ **A1 (p-spray) and A2 (p-stop) with the chosen parameters provide isolation at all values of Q_F**

Set A: P-Spray and P-stop





For No isolation structure: G_{int} C_{int} V_{BD}

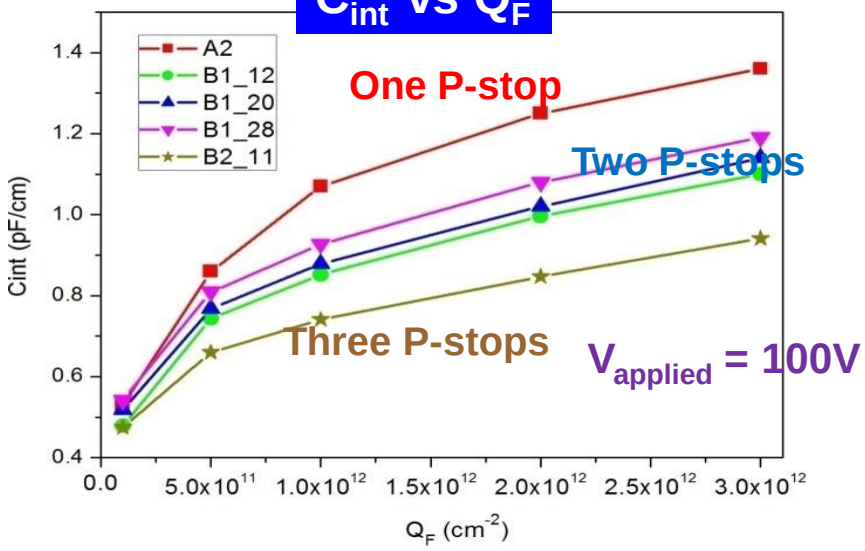
- For P-spray, C_{int} is high & V_{BD} is low for small Q_F & improve w/ increase in Q_F.
- For P-stop, C_{int} is low & V_{BD} is high for small Q_F & deteriorate w/ increase in Q_F.

C_{int} and V_{BD} degrade for both as compared to a structure without isolation. Investigate sensors equipped with isolation techniques, which, while ensuring isolation at all Q_F, should ensure better performance of V_{BD} and C_{int}.

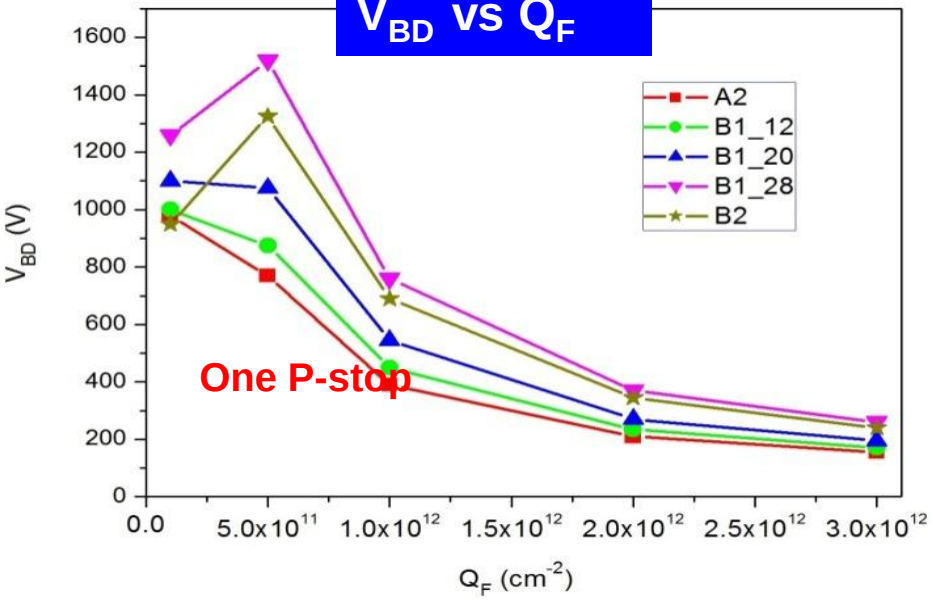
Set B: Multiple P-stops

- 3 configurations of **two p-stops** (B1) w/ different gap (12, 20 & 28 μm)
- 1 configuration of the **three p-stops** (B2) w/ gap = 11 μm .

C_{int} vs Q_F



V_{BD} vs Q_F



- **C_{int}: An increase in Q_F results in an increase in the C_{int}.**
  Single p-stop (A2) has highest C_{int} & B2 with triple p-stops has lowest C_{int}.

- **V_{BD}: Single p-stop has lowest V_{BD}.**
  For B1, wider p-stop (B1_12) has lower V_{BD} than narrower p-stop (B1_28).
  V_{BD} of the triple p-stop (B2) is almost same as that of B1_28.

Triple p-stop structure gives better parameter values under investigation.

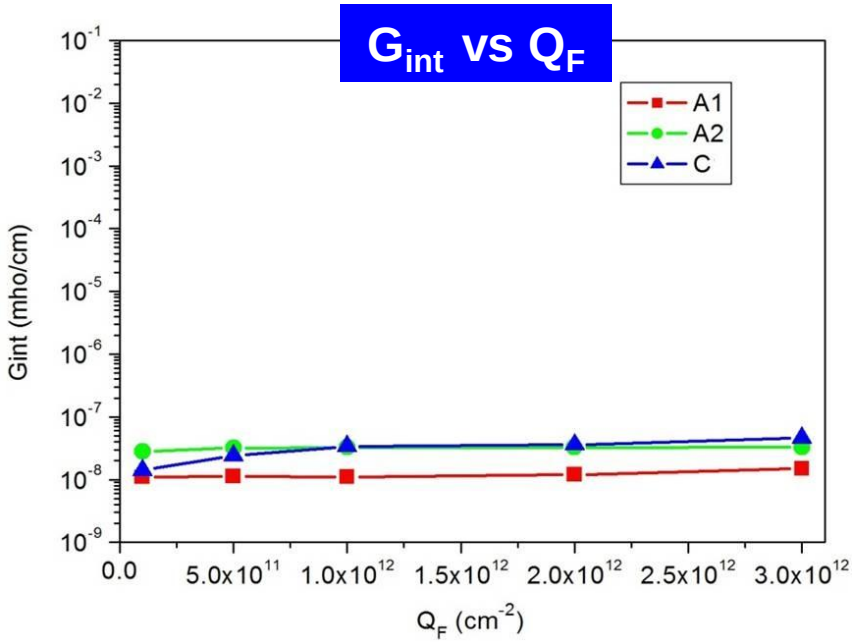
Set C: P-spray + P-stop

- Simulation was performed for various values of the peak doping conc. of the p-spray (N_{pspray}) and p-stop (N_{pstop}).

- Results vary between two extremes such that in one case p-spray guides the result and in another p-stop.

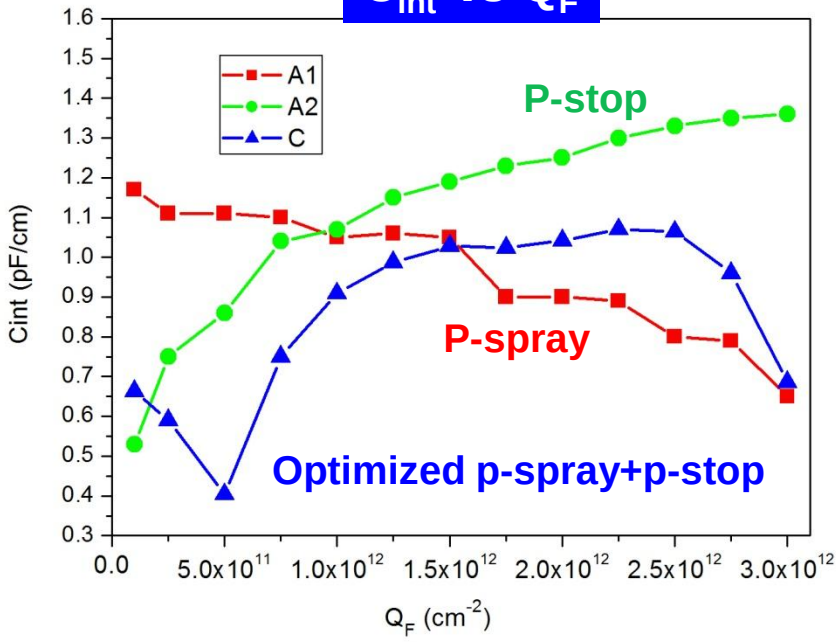
- Aim was to optimize these conc. - optimized results are achieved for N_{pspray} = $4x10^{16}$ cm^{-3} and N_{pstop} = $1x10^{17}$ cm^{-3} (Set C).

Set C is able to preserve isolation for all values of Q_F.

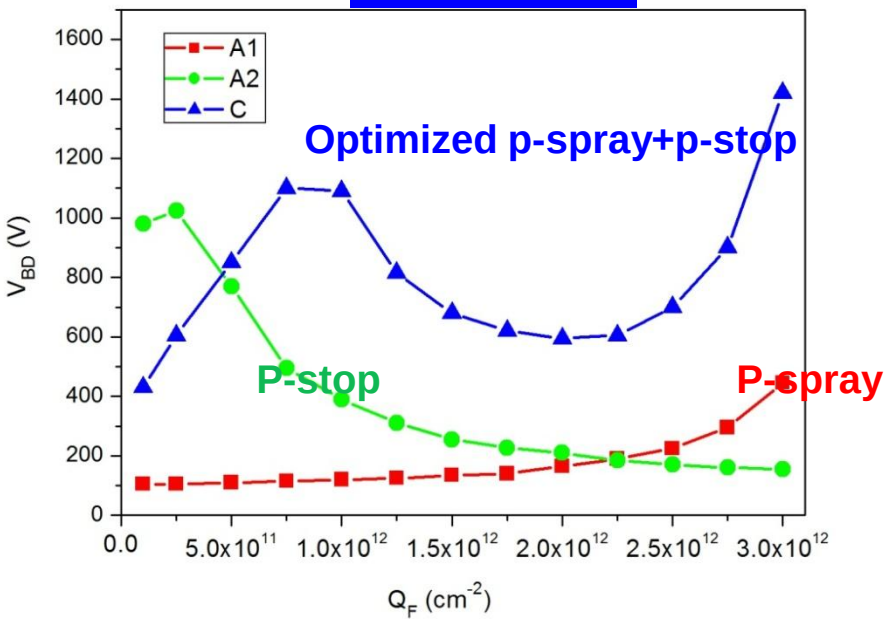


Set C: P-spray + P-stop

C_{int} vs Q_F



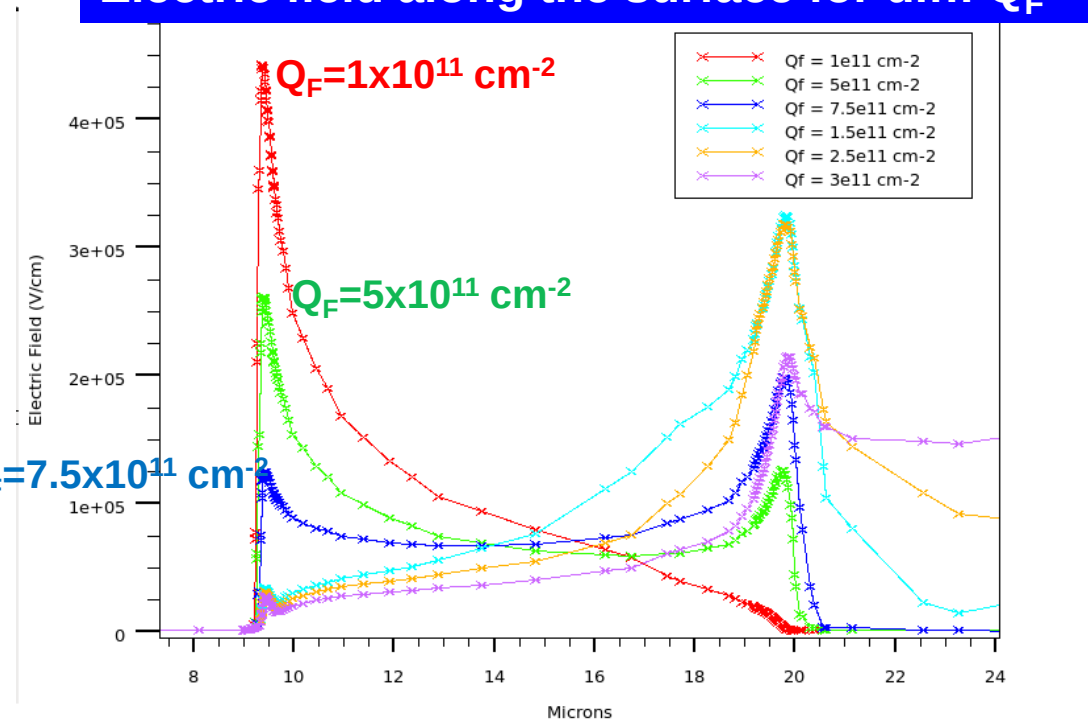
V_{BD} vs Q_F



- For $Q_F = 1x10^{11}cm^{-2}$, C_{int} and V_{BD} fall in between the two extremes of A1 and A2.
- An initial increase in Q_F results in a behaviour similar to that of p-spray (A1)
- However, for $Q_F = 5x10^{11}cm^{-2}$, the effect of p-spray starts getting neutralized and then p-stop (A2) guides the behaviour of C_{int} and V_{BD}.
- For sufficiently high values of Q_F, i.e. after $Q_F \sim 2x10^{12}cm^{-2}$, the p-stop also starts getting compensated. But, the structure is still able to support good isolation while improving the breakdown and capacitance performance.

Set C: P-spray + Pstop

Electric field along the surface for diff. Q_F

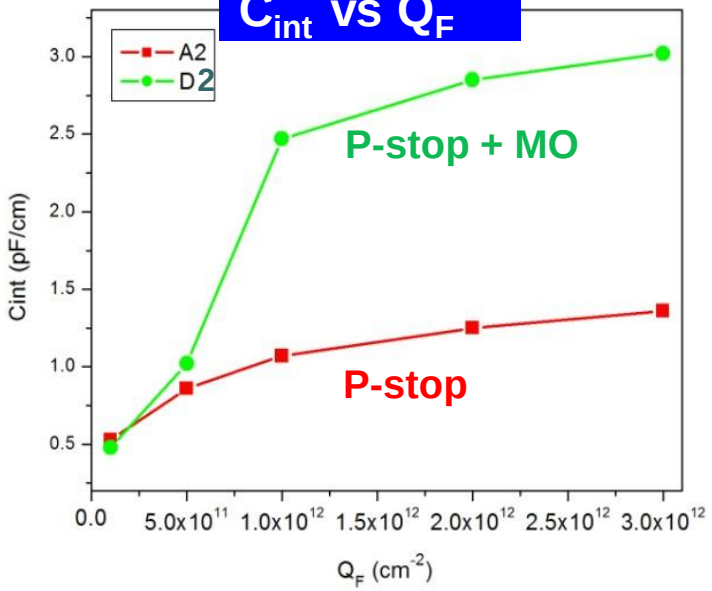


- For small values of Q_F, the breakdown takes place at the p-spray-n+ junction, i.e. when p-spray guides the results.
- An increase in Q_F results in a shift of peak electric field from p-spray-n^+ junction to the curvature of p-stop, p^+-n^- junction.
- For very large values of Q_F peak electric field starts reducing at the p-stop junction and becomes higher all along the surface.

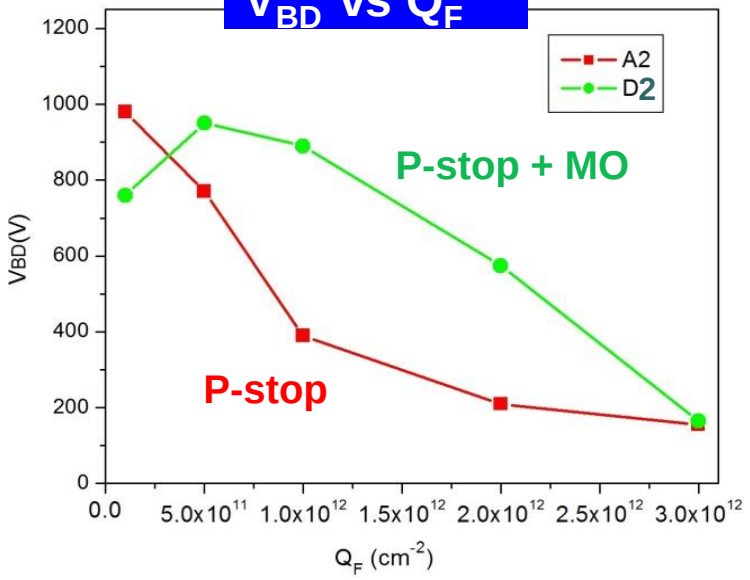
Set D: P-stop+ MO

- Structure D1 defines a metal overhang of length 5μm over n^+ (with p-spray) with SiO_2 thickness below metal overhang equal to 0.2μm.
- Structure D2 defines a metal overhang of length 5μm over p-stop with SiO_2 thickness below metal overhang equal to 0.5μm.

C_{int} vs Q_F



V_{BD} vs Q_F



- **The use of metal overhang is able to increase the V_{BD}, however, deteriorates the C_{int}**

Summary (1)

- P-stop/p-spray are commonly used tech. to ensure isolation of Si sensors, but, none of these techniques provide optimized electrical characteristics for p^+-n^--n^+ sensors separately.

- Investigated the sensors equipped with other possible strategies which include multiple p-stops isolation, p-spray & p-stop combined isolation and use of metal overhang over p-spray/p-stop.

- Multiple p-stops isolation improve C_{int} as well as V_{BD} without degrading G_{int}.

- Combined isolation is best among all the techniques investigated for all scenarios of surface damage provided doses are optimized.

- Use of MO over p-stop to improve V_{BD} is not an attractive option as it contributes significantly to C_{int}.

(thanks to IUSSTF for financial assistance)

RD50 Simulation Activity – First Task

from Vladimir Eremin

The set of parameters for cross-test of modeling software:

Detector thickness ---------- d=0.03 cm

Concentration of shallow donors (phosphorus) ----------N_{SD} = 6e11 cm^{-3}

Bulk generated current calculated from

- Single level model
- Effective energy of current generating level---------- E_i – 0.65 eV
- Effective cross-section of current generating level --------- σ_j = 1e-13cm^2
- Introduction rate of current generating level ---------- G_i = 1 cm^{-1}

Radiation induced deep levels

Type of defect	Activation energy, eV	Trapping cross section, cm^2	Introduction rate, cm^{-1}
Deep donor	E_{DD} - E_V = 0.48	σ_e = σ_h = 1e-15	G_{DD} = 1
Deep acceptor	E_{DA} - E_V = 0.595	σ_e = σ_h = 1e-15	G_{DA} = 1

We will compare the results of simulation for the following set of parameters:

T = 290K and 260K ⟸ **TEMP. variation**

V= 200V, 300V, 500V, 1000V at F = 1e15cm^{-2} ⟸ **BIAS variation**

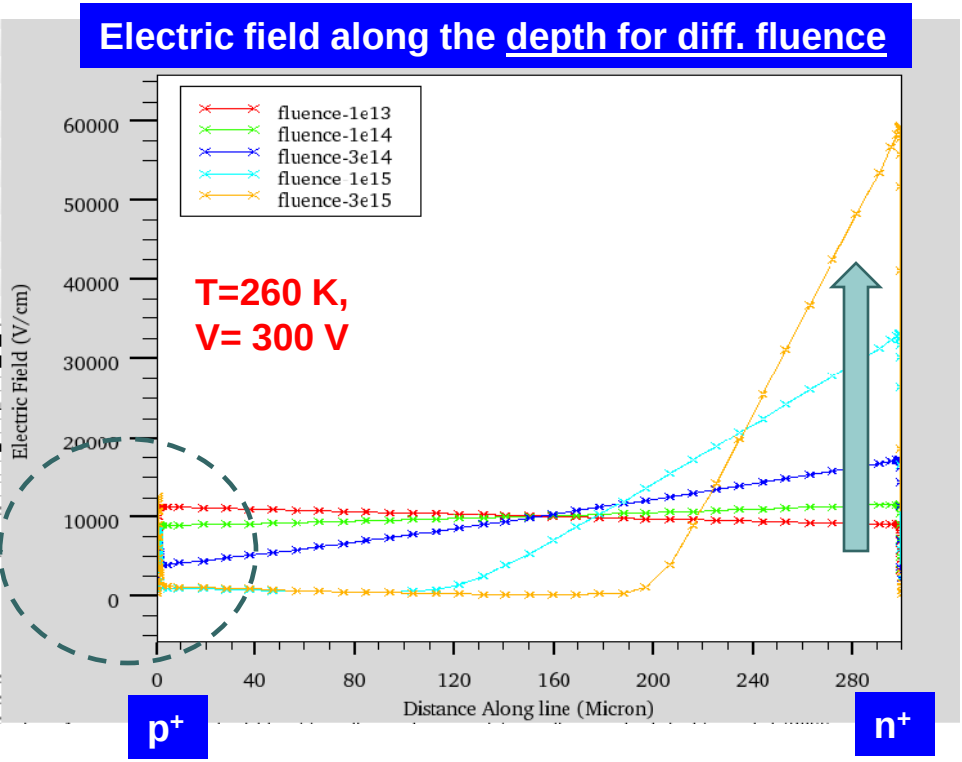
F= 1e13, 1e14, 3e14, 1e15, 3e15 cm^{-2} at V=300V ⟸ **FLUENCE variation**

Device structure: Plane parallel 2-D, p^+-n^--n^+ diode, with 100µm width & 300 µm depth
1-D electric field is seen at the middle of the diode (i.e. at 50µm) along the device depth.

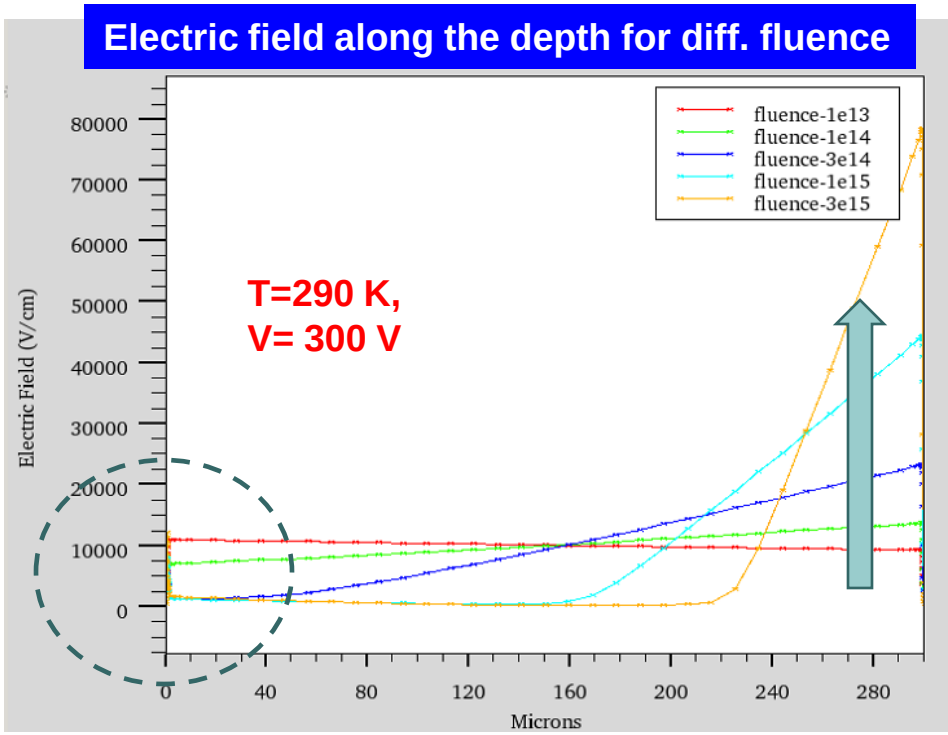
RD50 Simulation Activity – First Task

- **Since ATLAS (Silvaco) doesn't have a way of incorporating "Bulk Generation Current level" so the first results were obtained without it.**

Electric field along the depth for diff. fluence



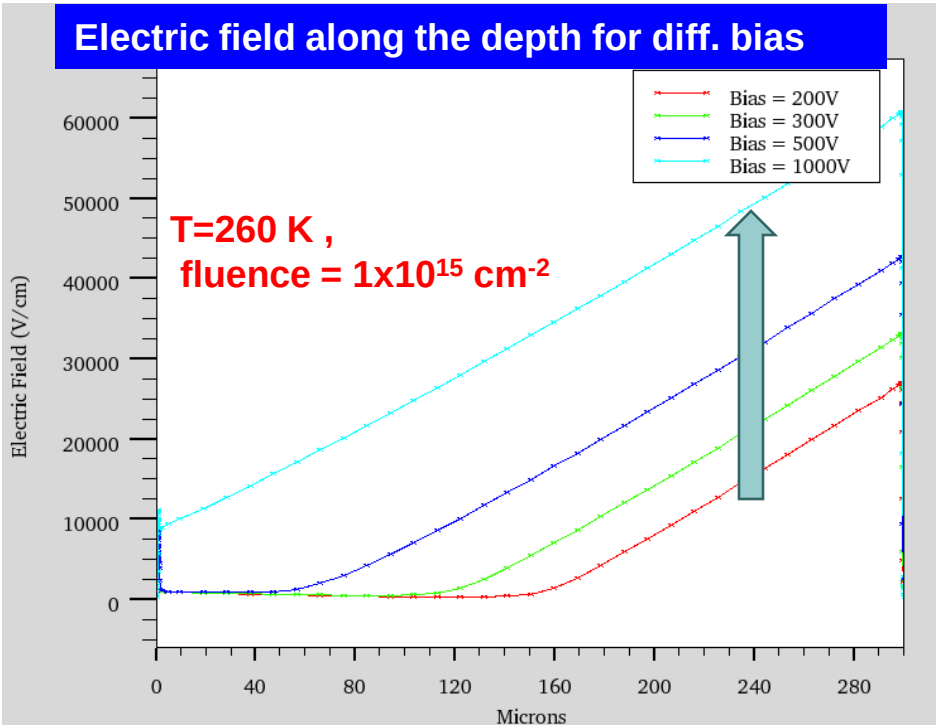
Electric field along the depth for diff. fluence

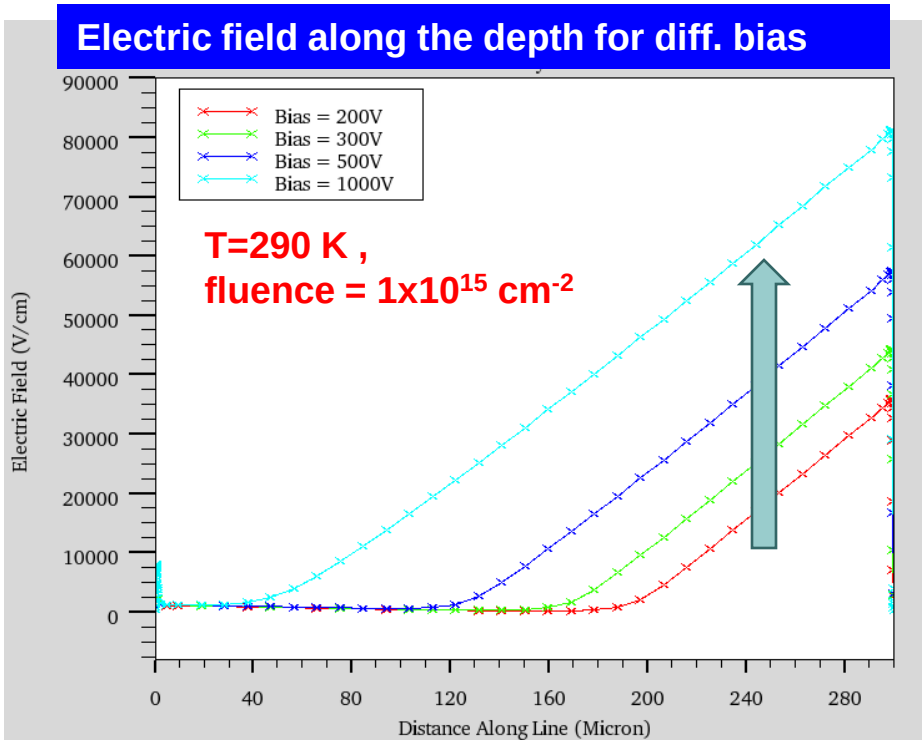


- **Temperature & Fluence dependence**
- **In the absence of bulk current level => double peak structure is rather suppressed.**

RD50 Simulation Activity – First Task

- **No "Bulk Generation Current level"**





- **Temperature & Bias dependence**
- **In the absence of bulk current level => double peak structure is rather suppressed.**

RD50 Simulation Activity – First Task

- **To increase current, two possibilities exist:**
  - **Change Carrier Life-times**
  - **Change Capture Cross-sections of electron and hole**
  - ***("Simulation of Heavily Irradiated Silicon Pixel Sensors and Comparison With Test Beam Measurements", by V. Chiochia et al., IEEE Trans. Nucl. Sci., Vol. 52, No. 4, Aug.2005)*** - ISE TCAD package, Integrated System Engineering AG, Zurich, Swiss.

    - "It is possible to implement the EVL model in TCAD simply **by setting and by varying the size of the common cross section** until the generation current is equal to the observed or expected leakage current.
      - The trap occupancies are not affected in zeroth order by the rescaling, but the leakage current and the free carrier densities are affected by it.
      - The carrier densities have a first-order effect on the occupancies so that varying does alter the effective carrier density.
      - This approach uses the same trapping states to produce space charge and leakage current

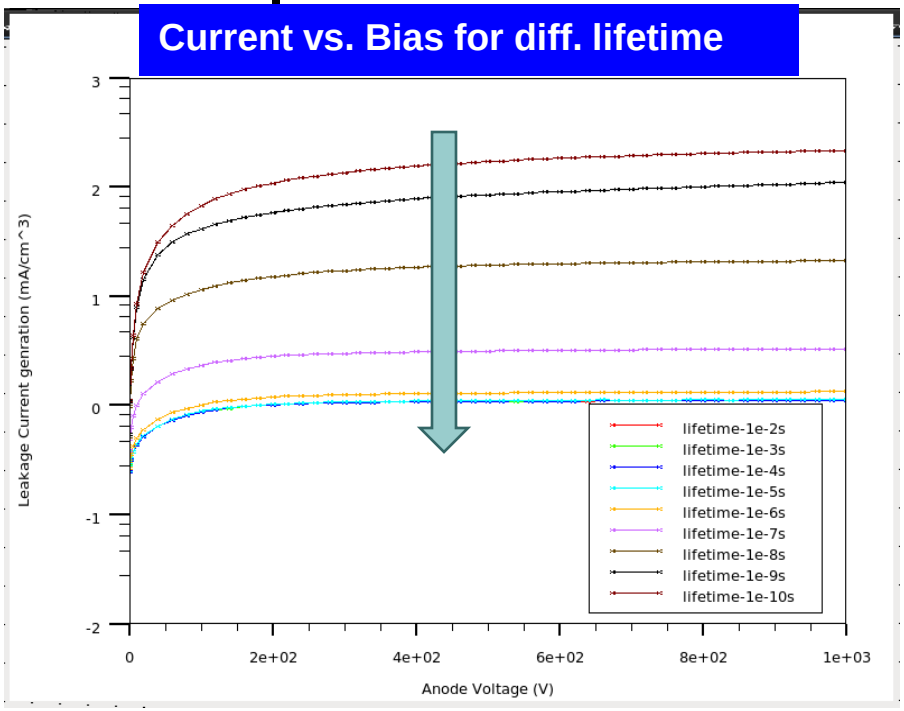
      "It is not necessary to introduce current-generating states"

RD50 Simulation Activity – First Task

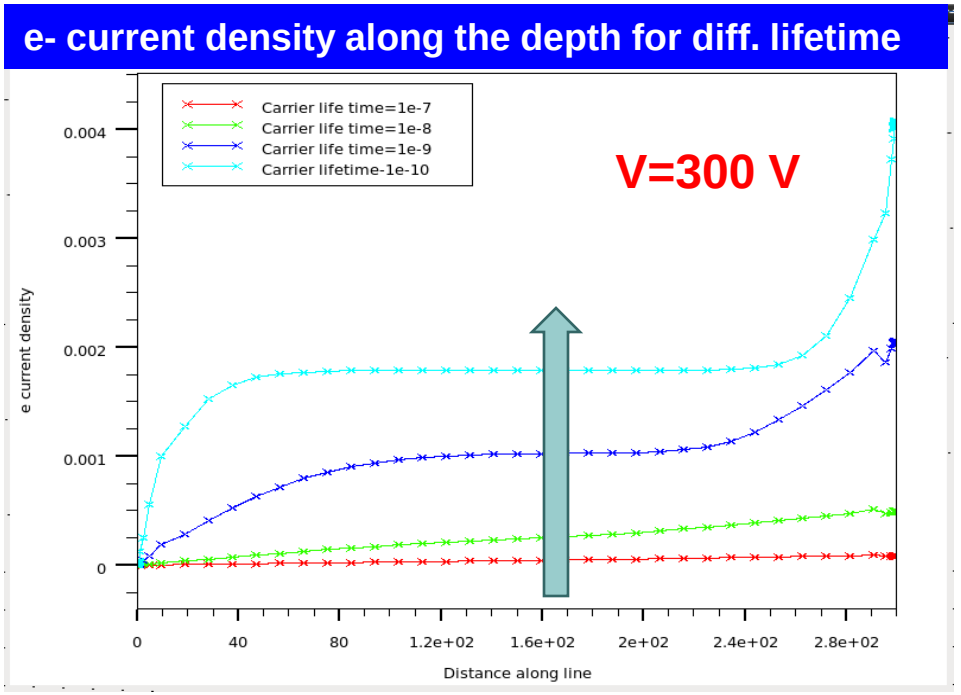
Varying carrier lifetime

T=290 K , fluence = $1x10^{15}$ cm^{-2}

Current vs. Bias for diff. lifetime



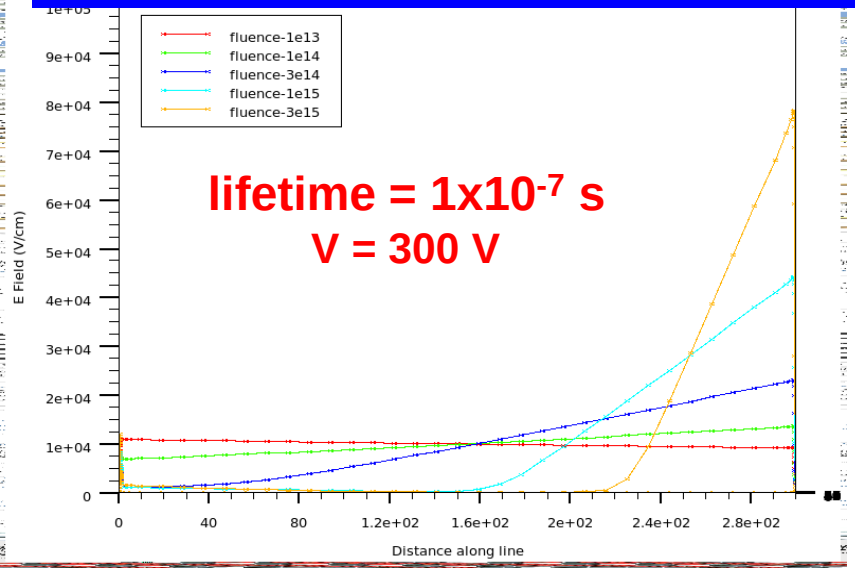
e- current density along the depth for diff. lifetime



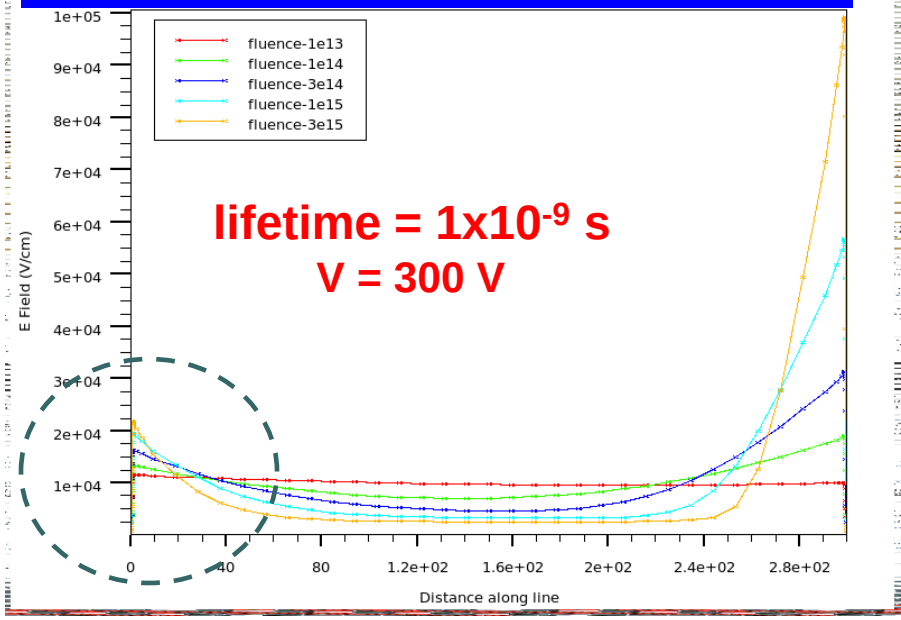
- **Current decreases as carrier lifetime increases**
- **Electron current density profile changes with changing carrier lifetime**

RD50 Simulation Activity – First Task

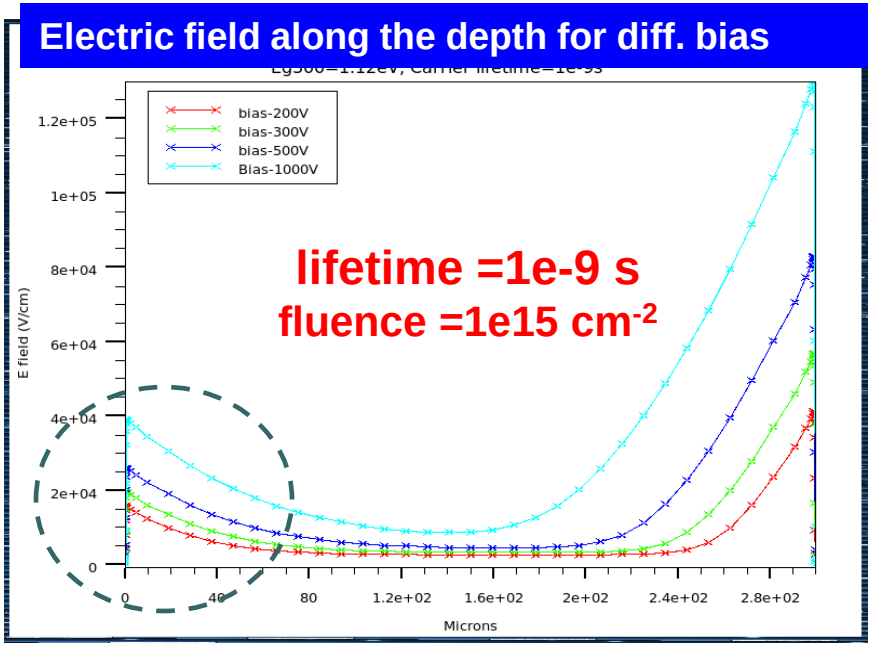
Electric field along the depth for diff. fluence



Electric field along the depth for diff. fluence



Electric field along the depth for diff. bias



- **Electric field profile changes with change in lifetime**

  => shows signature of double peak for reduced lifetime.

RD50 Simulation Activity – First Task

Varying carrier cross-sections

("Simulation of Heavily Irradiated Silicon Pixel Sensors and Comparison With Test Beam Measurements", by V. Chiochia et al. (IEEE Trans. Nucl. Sci., Vol. 52, No. 4, Aug.2005)

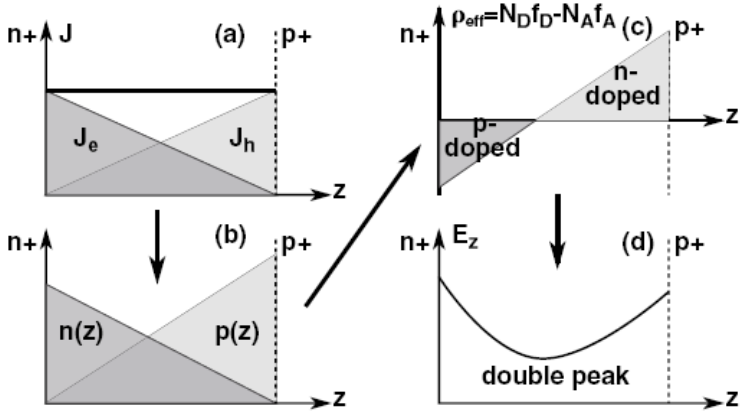


Fig. 6

"EVL model doesn't produce sufficiently large electric field on the p+ side"

Change Introduction rate (trap densitieis/fluence) of carriers to increase the electric field at the p+ side -

Position of the charge density minimum can be obtained by decreasing the ratio of hole to electron cross-sections

$$(\sigma_h^D/\sigma_e^D = 0.25 \text{ and } \sigma_h^A/\sigma_e^A = 0.25)$$

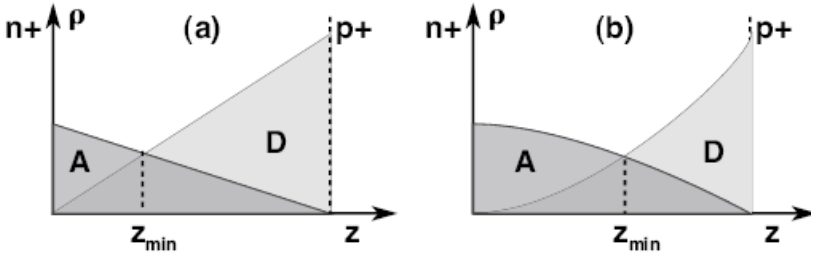


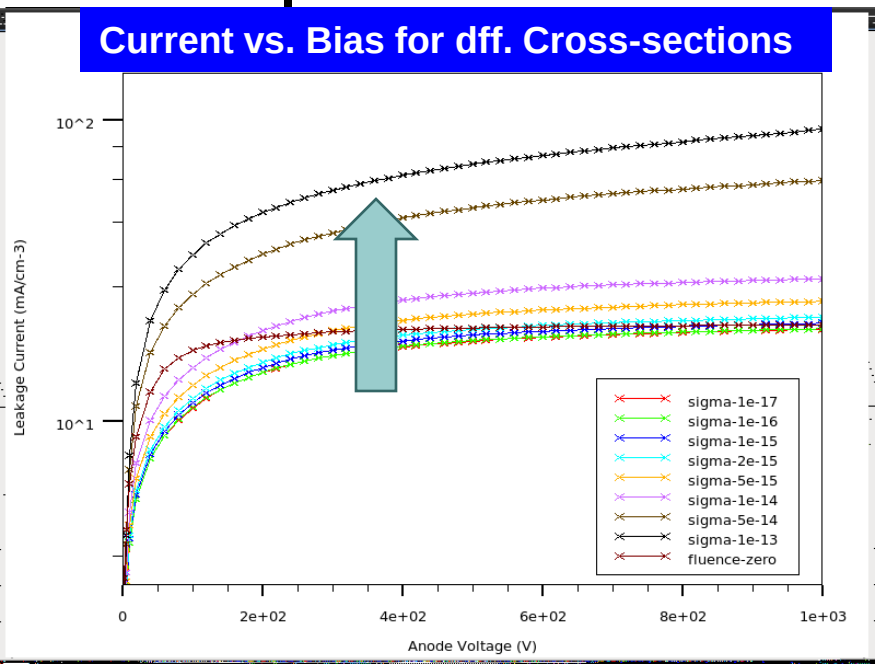
Fig. 8

THE EFFECT OF INCREASING N_D/N_A WHEN (A) THE ELECTRON AND HOLE CROSS SECTIONS ARE EQUAL, AND WHEN (B) $\sigma_h/\sigma_e = 0.25$.

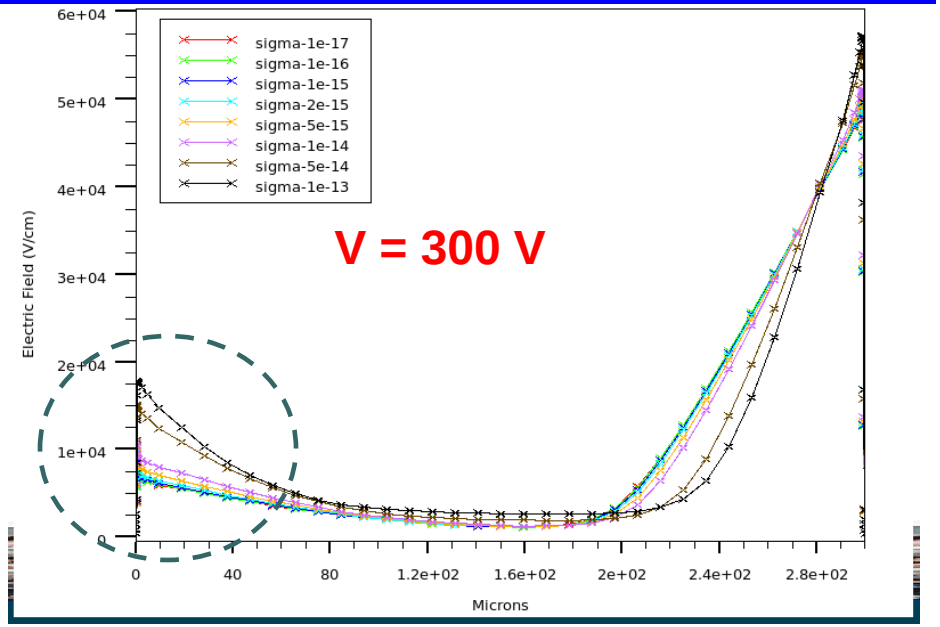
RD50 Simulation Activity – First Task

Varying carrier cross-sections

Current vs. Bias for dff. Cross-sections



Electric field along the depth for dff. Cross-sections



Lifetime = 1×10^{-8}s, fluence = 1×10^{15} cm^{-2} , T=290 K

- **Current increases with increase in cross-section**
- **Electric field profile changes with change in cross-section**
  - **shows signature of double peak for large values of cross-section.**

Summary(2)

- **Simulation of the bulk generation current level may be achieved using:**
  - **carrier lifetime,**
  - **capture cross-section**
    - **introduction rate and ratio of hole to electron cross-sections may need to be varied too.**

(thanks to IUSSTF for financial assistance)

Thanks

Radiation Damage

Bulk damage

- Introduces deep level centers, increasing trapping centers.
  - Higher leakage current, lowering of CCE and change in effective doping conc.
  - Change in the effective doping conc. of the substrate => higher depletion voltage, which requires sensors to be operated at high operational biases to recover CCE => needs higher V_{BD}.

Surface damage

- Creates charged states in SiO_2 and contribute to Q_F, raising it to higher values and saturating around $2\text{-}3 \times 10^{12} cm^{-2}$ => sustainable accumulation electron layer under Si-SiO_2 interface, shorting these n^+-strips and increasing interstrip conductance (G_{int})
- Increase in Interstrip capacitance (C_{int}), typically the largest contributor to the parasitic capacitance => C_{int} has to be small in order to reduce the total electronic noise.

Performance parameters : G_{int}, C_{int} and V_{BD}