Double Electric field Peak Simulation of Irradiated Detectors Using TCAD tools

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Overview

- **Validation**
- **MSSD Simulation**
- **RD50 Simulation task**
    - **To check simulator capabilities**
- **Present Approach**
- **Parameters for simulation**
- **Simulation Results**
- **Summary**

Validation of Simulator

- Comparison with Claudio paper:
  - *"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 were same (although we don't have exact simulation parameters as used by Claudio). Validation with some other papers are also carried out

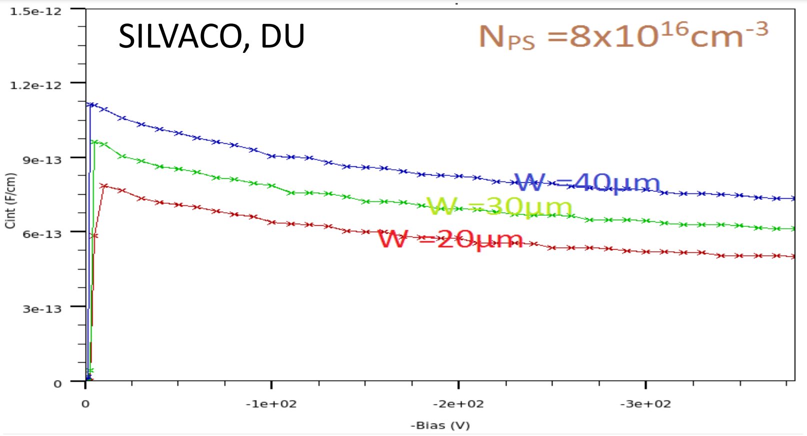


Fig. 9.

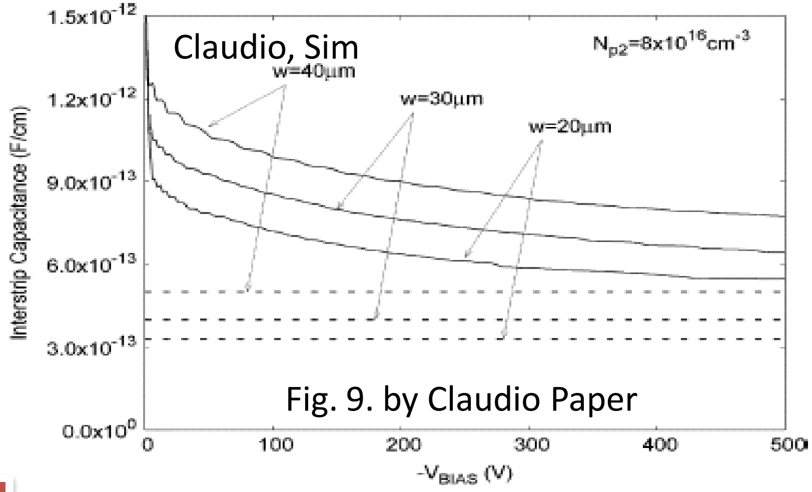
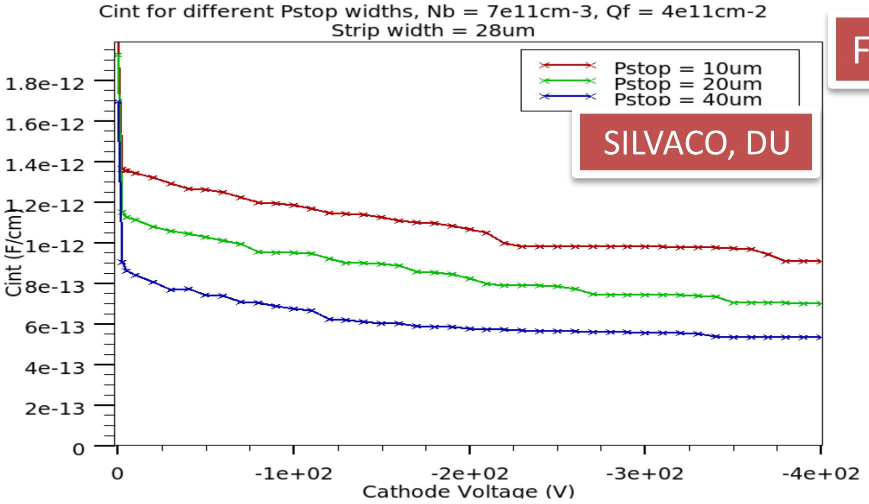
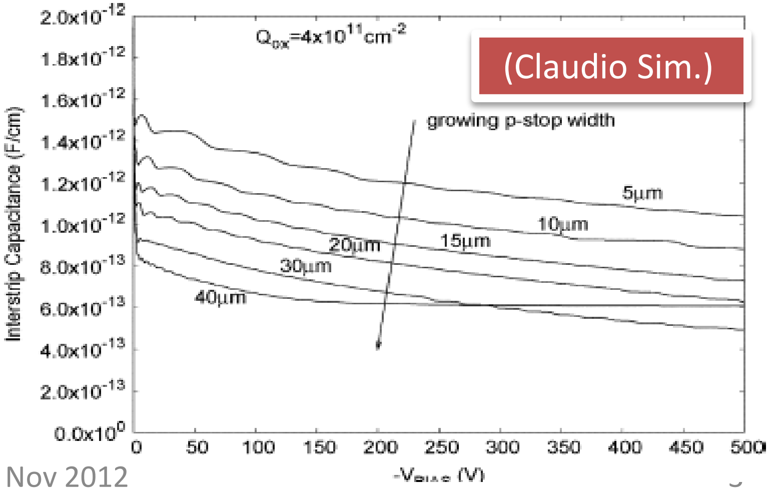


Fig. 9. by Claudio Paper



SILVACO, DU

Fig. 21



(Claudio Sim.)

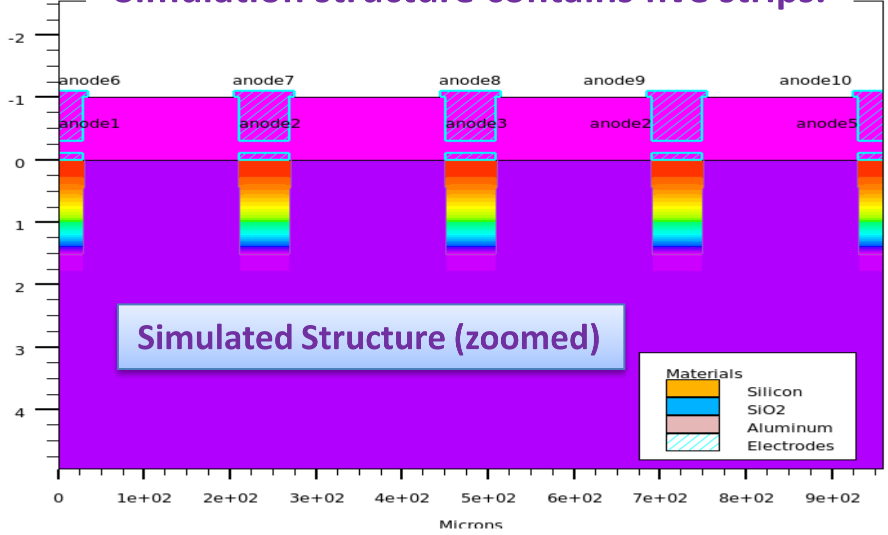
MSSD Simulation: Comparison with Measurements

- ❑ **Simulation vs. Measurement for FZ320N**
  - ✓ All 12 P^{+}-N^{-}-N^{+} configurations
  - ✓ For Non-irradiated
- ❑ **Only FIRENZE Probe station measurements are used for comparison**

Common Parameters for all the configurations

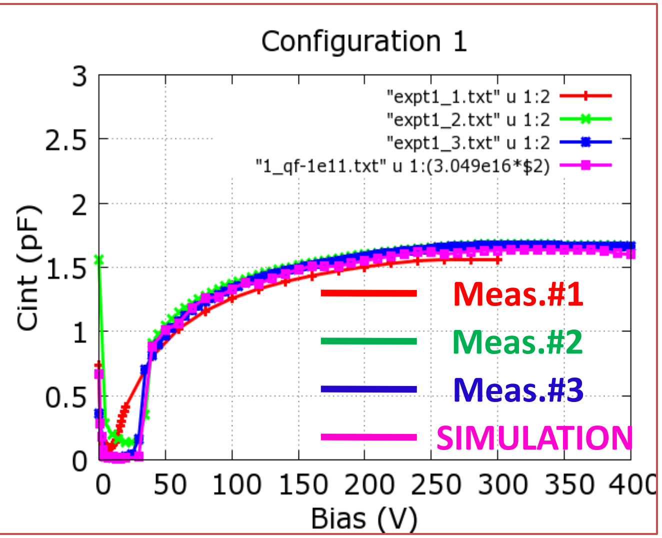
Bulk Doping (cm^{-3})	3x10^{12} cm^{-3}
Strip junction depth (Gaussian)	1.5 µm
Backplane doping depth	30 µm
AC signal frequency used	1x10^{6} Hz

Simulation structure contains five strips.



Simulated Structure (zoomed)

For MSSD- C_{int} vs. Bias Voltage (FZ320N Non-Irradiated)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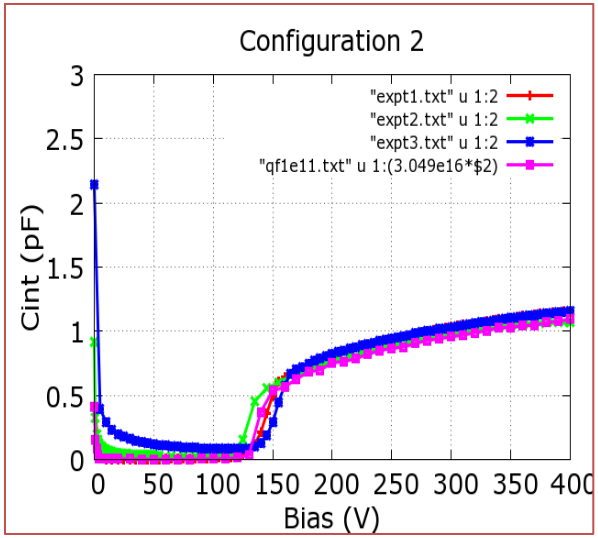
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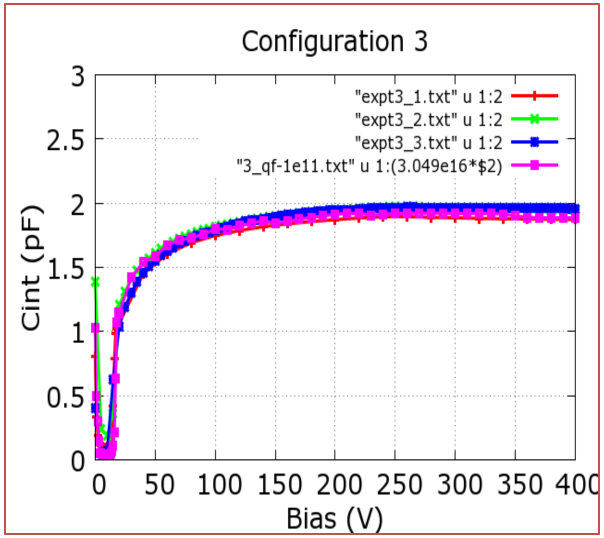
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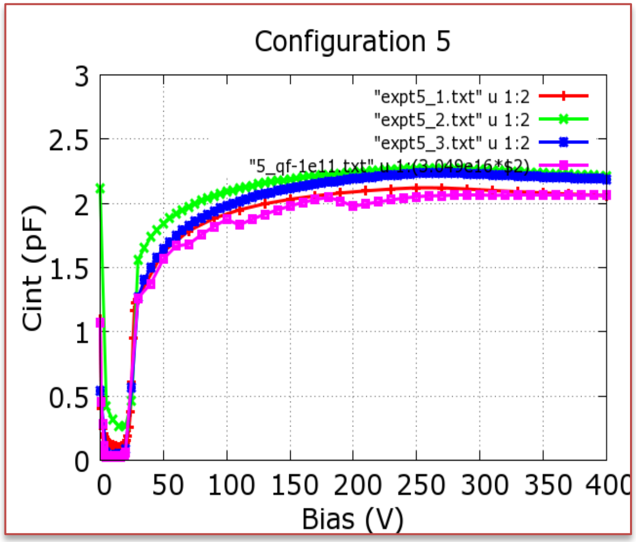
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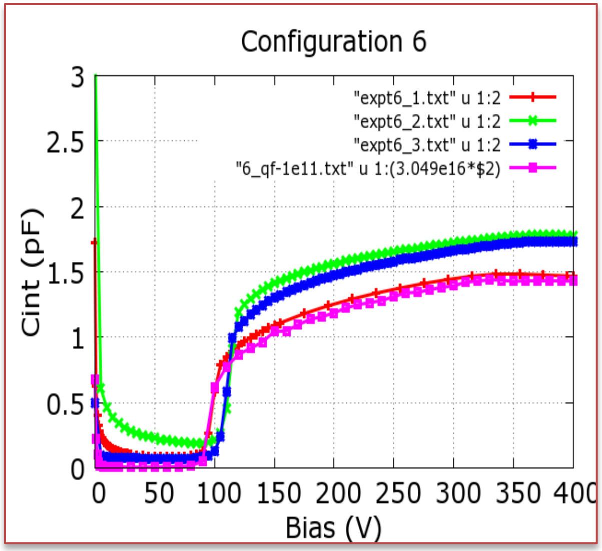
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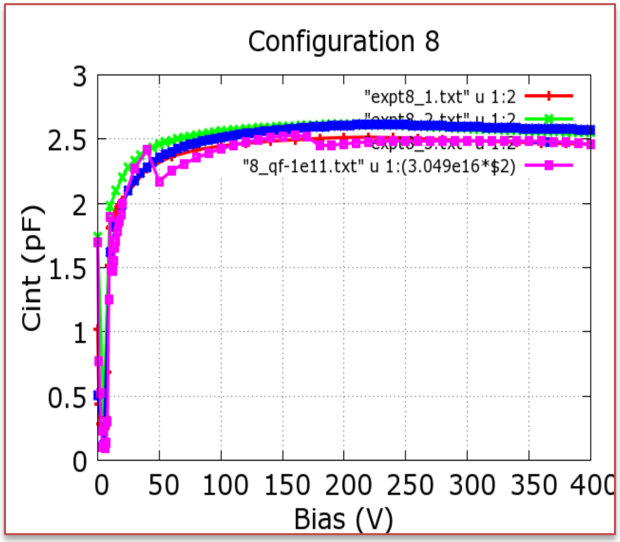

Configuration 8

RD50 Simulation Task

The set of parameters used in simulations:

Detector thickness --- *d*=0.03 cm

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

Two level trap model

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

Bulk generated current calculated from

Not available in simulation as separate current level

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

Simulations by different groups are compared for

1. **Effect of temperature variation : T = 290K & 260K**
2. **Effect of irradiation flux variation : 1e13, 1e14, 3e14, 1e15, 3e15 cm^{-2} at V=300V**
3. **Effect of bias voltage : 200V, 300V, 500V, 1000V at F = 5e14cm^{-2} & 1e15cm^{-2}**

Vladimir provided data for E(x), n(x), p(x), Neff (x) for *different fluence* at *different temperature & at different bias voltages.*

Parameters used for Simulations using ATLAS (Silvaco) & Layout / Geometry

ATALS Model	5.15.32.R
Structure (x-y)	300µm - 100 µm
Bulk Doping (cm^{-3})	$6x10^{11}$ cm^{-3} n-type impurity
n+ and p+ junction depth	1 µm
n+ and p+ doping density(cm^{-3})	$5x10^{18}$ cm^{-3}
Cutline position for Electric Field Plot	(50,0) to (50,300)
Models used in simulation	Bipolar (which contain CONMOB,FLDMOB,CONSRH, AUGER & BNG) with P.Canali and N. Canali for mobility along with Selb model for impact ionisation
Band Gap (eV)	1.12
No of Traps levels	Two (One Acceptor and One donor)
Acceptor level	0.525 eV below the Conduction band
Donor Level	0.48eV above the Valence band
Temperature	290K and 260K

Device structure:

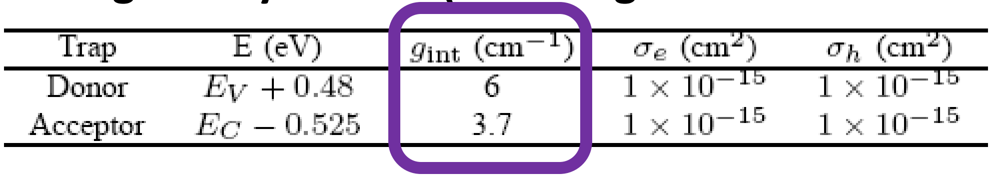
Plane parallel 2-D, p^+-n^--n^+ diode, with 100µm width & 300 µm Depth

1-D electric field is seen at the middle of the diode (i.e. at 50µm) along the device depth.

Our Approach…based on

"Simulation of Heavily Irradiated Silicon Pixel Sensors and Comparison with Test Beam Measurements" **by V. Chiochia et al., IEEE NSS 2005**

EVL – 1: Trap levels given by Eremin (no bulk generation current level)



Trap	E (eV)	g_{int} (cm^{-1})	σ_e (cm^2)	σ_h (cm^2)
Donor	$E_V + 0.48$	6	1×10^{-15}	1×10^{-15}
Acceptor	$E_C - 0.525$	3.7	1×10^{-15}	1×10^{-15}

EVL – 2: Trap levels given by Eremin and Bulk current generated by varying cross-section

$$\sigma_{e/h} = 1.48 \times 10^{-14} \text{ cm}^2$$

EVL – 3: Trap levels given by Eremin and Bulk current generated by varying cross-section and electric field position adjusted by varying the hole to electron cross-section ratio.

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

EVL – 4: Trap levels given by Eremin and Bulk current generated by varying cross-section and electric field position adjusted by varying the hole to electron cross-section ratio & ratio of the introduction rates changed to fix the peak electric field

$$N_A/N_D \text{ from the EVL value of } 0.62 \text{ to } 0.40$$

Nomenclature

EVL Simulations

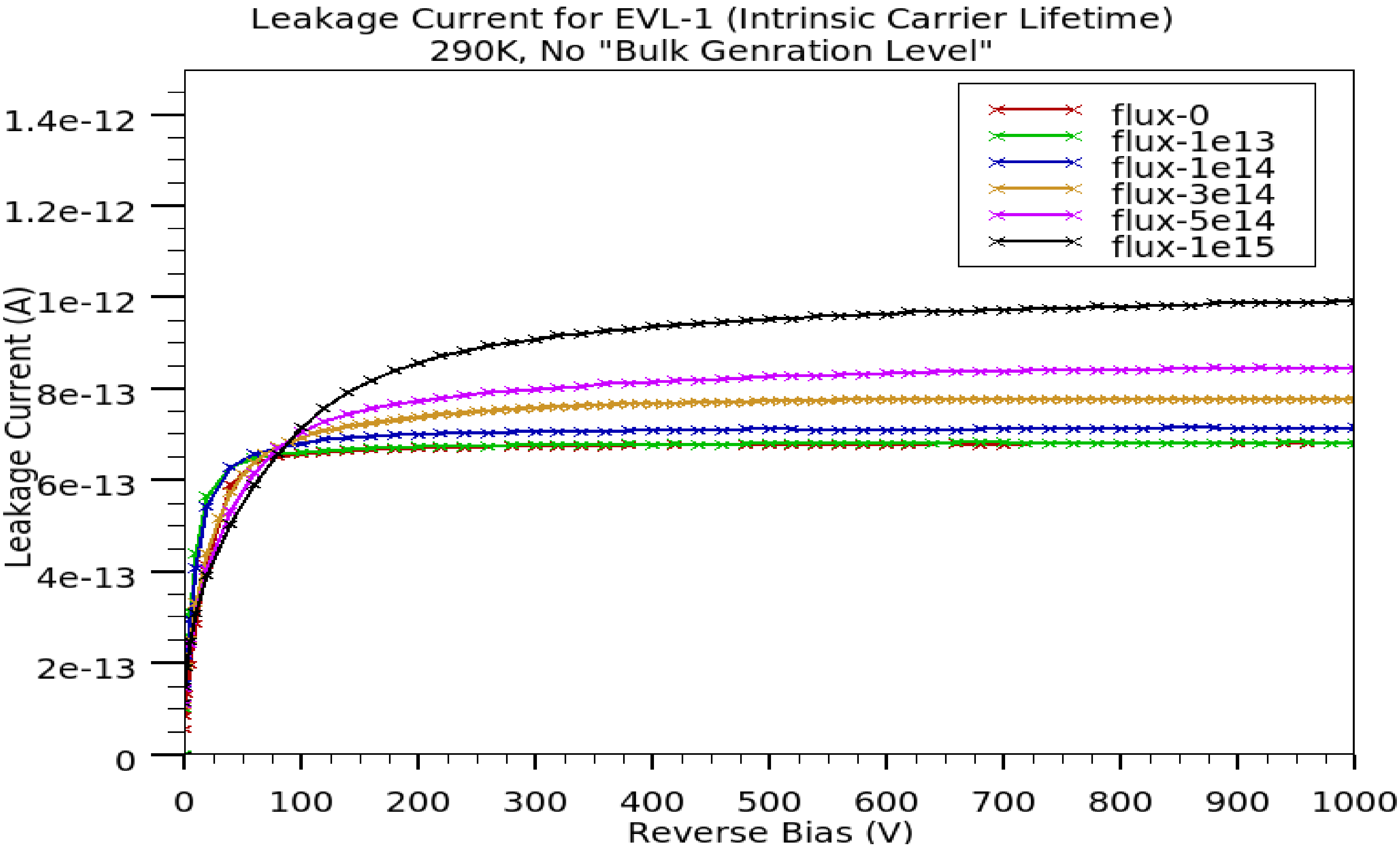
- Modeled data provided by Vladimir Eremin is labeled as EVL

EVL – 1 Simulations

- Simulation data obtained using Atlas (Silvaco) : keeping exact trap energy levels/parameters as given in simulation task layout
- No additional bulk generation current level

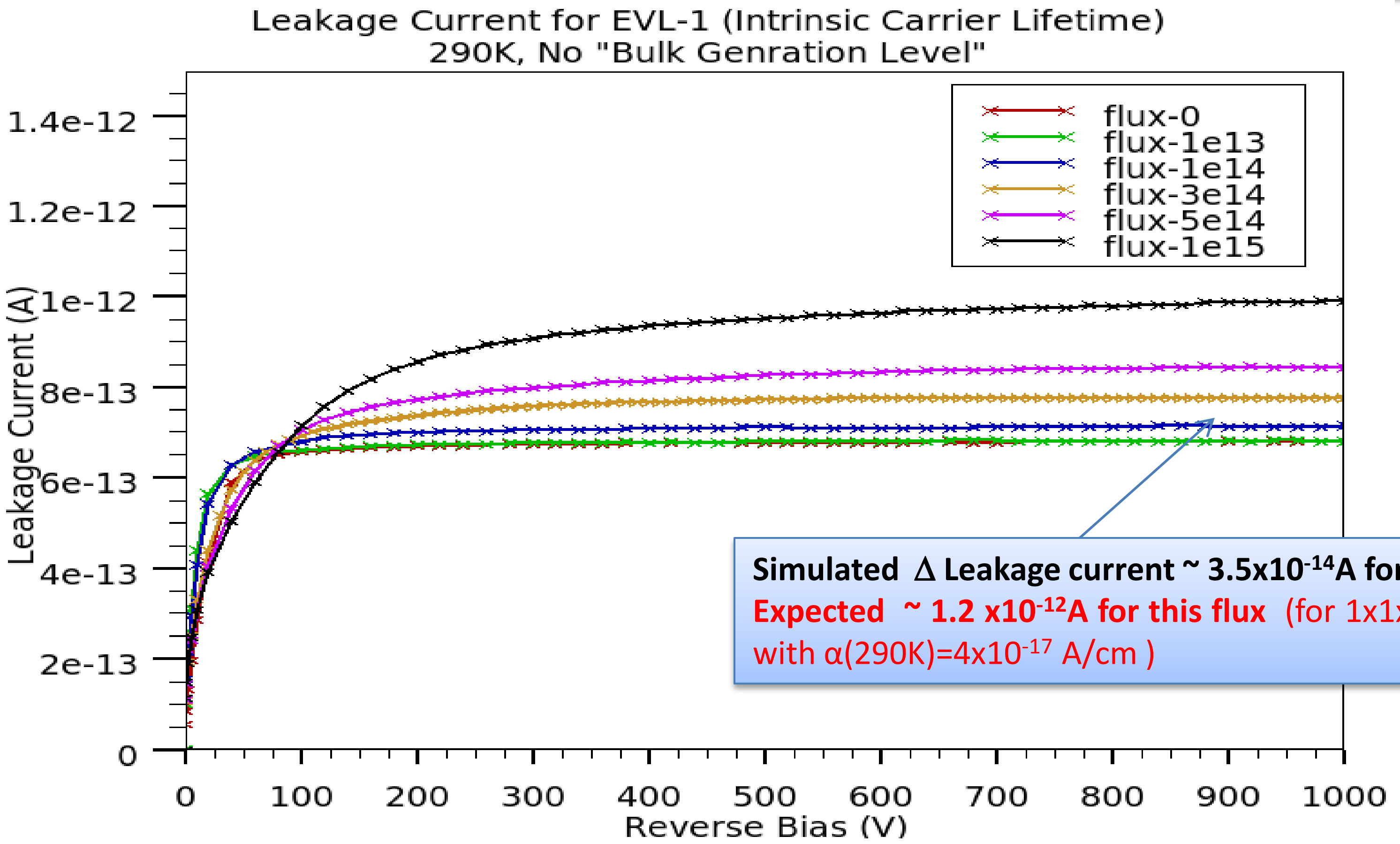
EVL Vs. EVL – 1 : Comparison between Eremin Simulations and Atlas simulation

EVL model with Cross section=1e-15cm^2, Introduction rate =1 (EVL-1)



EVL Vs. EVL – 1 : Comparison between Eremin Simulations and Atlas simulation

EVL model with Cross section=1e-15cm^2, Introduction rate =1 (EVL-1)



Simulated Δ Leakage current ~ 3.5x10^{-14}A for flux 1x10^{14} cm^{-2}

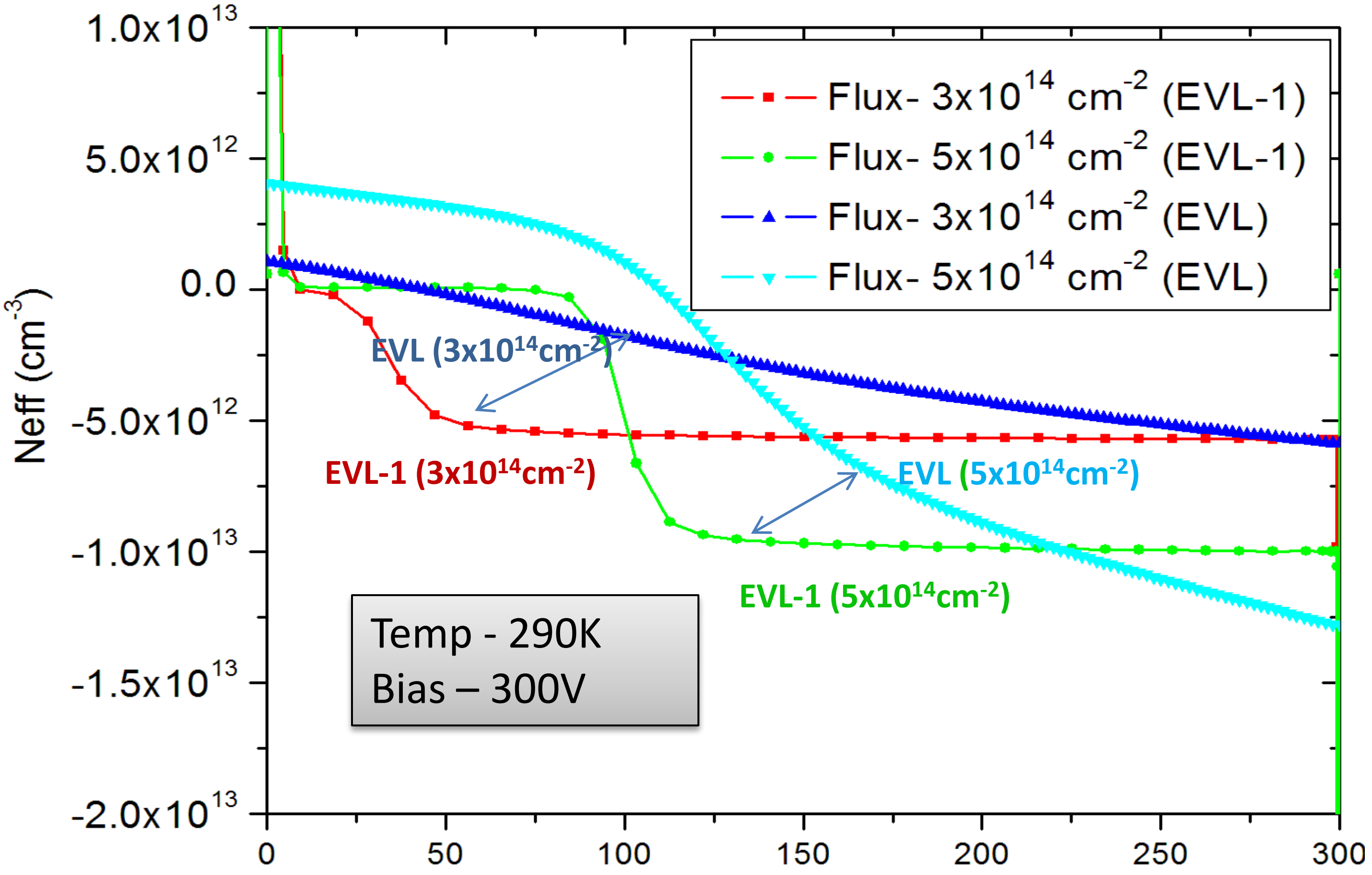
Expected ~ 1.2 x10^{-12}A for this flux (for 1x1x300um^3 structure with α(290K)=4x10^{-17} A/cm)

✓More than one order of less current compared to expected value

To increase current, three possibilities exist:

- **Change Carrier Life-times**
- **Change Capture Cross-sections of electron and hole**
- **Change Trap Introduction Rate**

EVL Vs. EVL – 1 : Simulation results

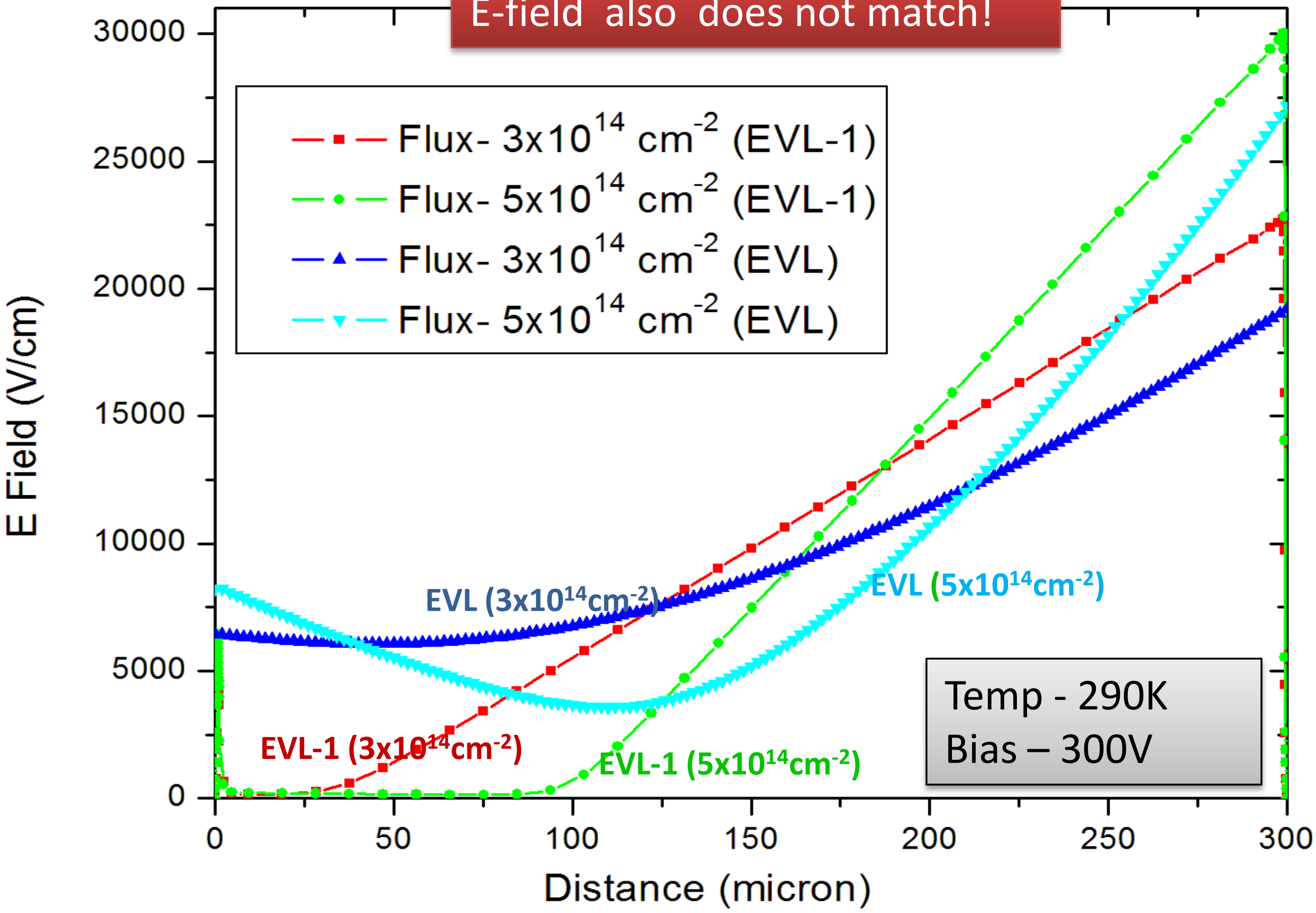


Temp - 290K
Bias – 300V

Neff does not match!

EVL Vs. EVL – 1 : Simulation results

E-field also does not match!



Temp - 290K
Bias – 300V

✓ No Double Electric Field Peaks!

Further Simulations

- **Simulation compared against EVL modeled data**: Since, EVL and EVL-1 simulation results are very different, we have carried out a systematic parameterization study by varying e/h capture cross sections and their ratio, carrier life time, trap introduction rate using leakage current, electric field and N_{eff} data (we have called the various studies as EVL-2, EVL-3, EVL-4 etc)

EVL – 2

- Trap levels are same as in proposed simulation task.

- Additional bulk current is generated by increasing cross-sections of the trap levels from **$1x10^{-15}cm^2$ (in EVL1) to $4x10^{-14}cm^2$ (in EVL2)** such that simulated leakage current match with experimental observed current
(Sigma_e = Sigma_h = $4x10^{-14}$ cm^2)
(for $1x1x300um^3$ structure with $\alpha(290K)=4x10^{-17}$ A/cm at $\phi= 1x10^{14}$ n_{eq}/cm^2
Expected $\Delta I \sim 1.2x10^{-12}$ A)

- Lifetime of charge carrier is = 10^{-7}sec (Intrinsic in ATLAS simulator)
Simulated Leakage current without irradiation ~ $0.8x10^{-12}$A (for $1x1x300um^3$ structure)
ΔI (for fluence $\phi= 1x10^{14}$ n_{eq}/cm^2 with $\alpha(290K)=4x10^{-17}$ A/cm) ~ $1.2x10^{-12}$ A
So, total leakage current expected in simulation (for $1x1x300um^3$ structure at $\phi= 1x10^{14}$ n_{eq}/cm^{2}) = 2.0×10^{-12}A

- Acceptor Introduction rate = Donor Introduction rate = 1 cm^{-1}

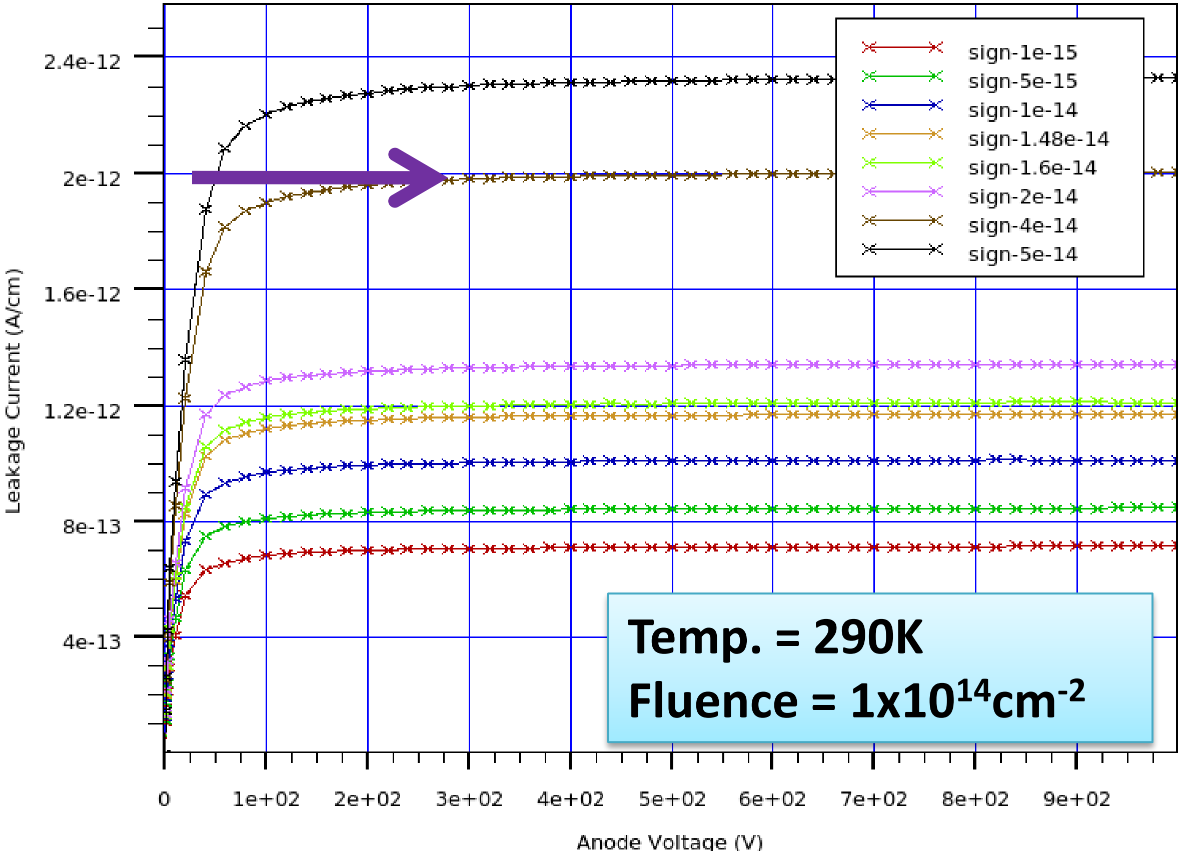
EVL -2: Cross – section ramp to match the Leakage Current

Simulated Leakage current is same as Expected Leakage Current = 2.0×10^{-12} A

(for $1 \times 1 \times 300 \mathrm{um}^3$ structure with $\alpha(290\mathrm{K}) = 4 \times 10^{-17}$ A/cm at $\phi = 1 \times 10^{14}\ n_{eq}/\mathrm{cm}^2$)

sigma_e = sigma_h = $4 \times 10^{-14} \mathrm{cm}^2$

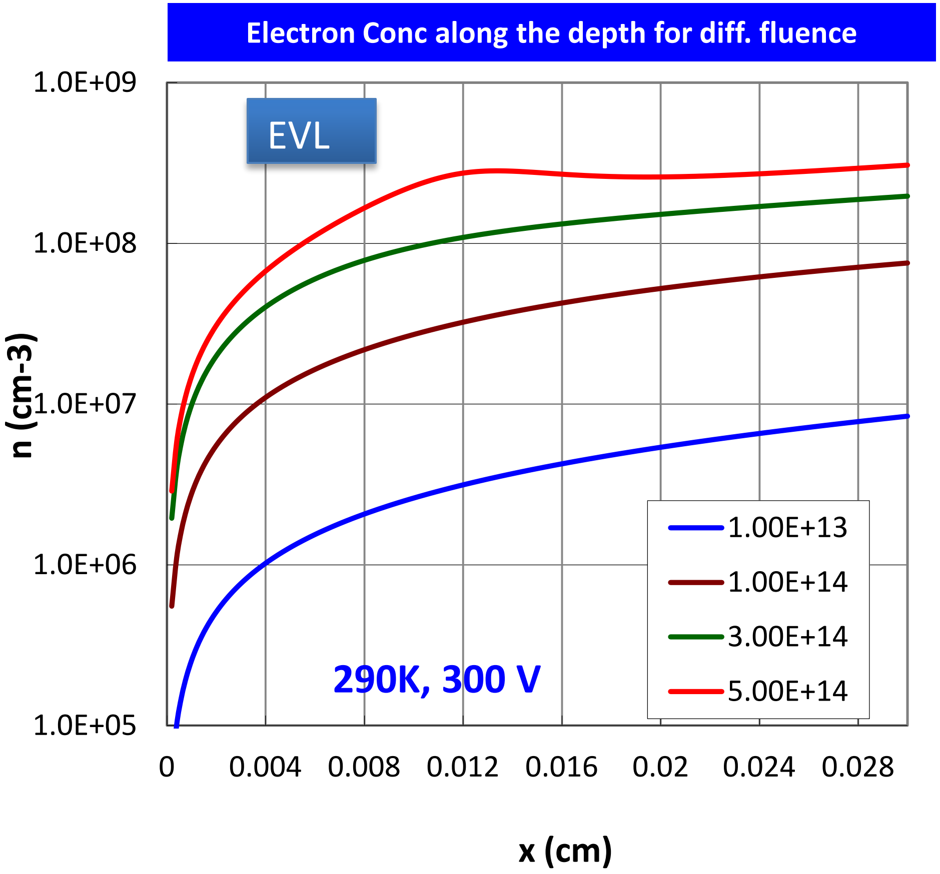
Leakage Current for different cross sections for fluence=1e14neq/cm2, Temp=290K
Nb=6e11cm-3, Str is 1umx1umx300um

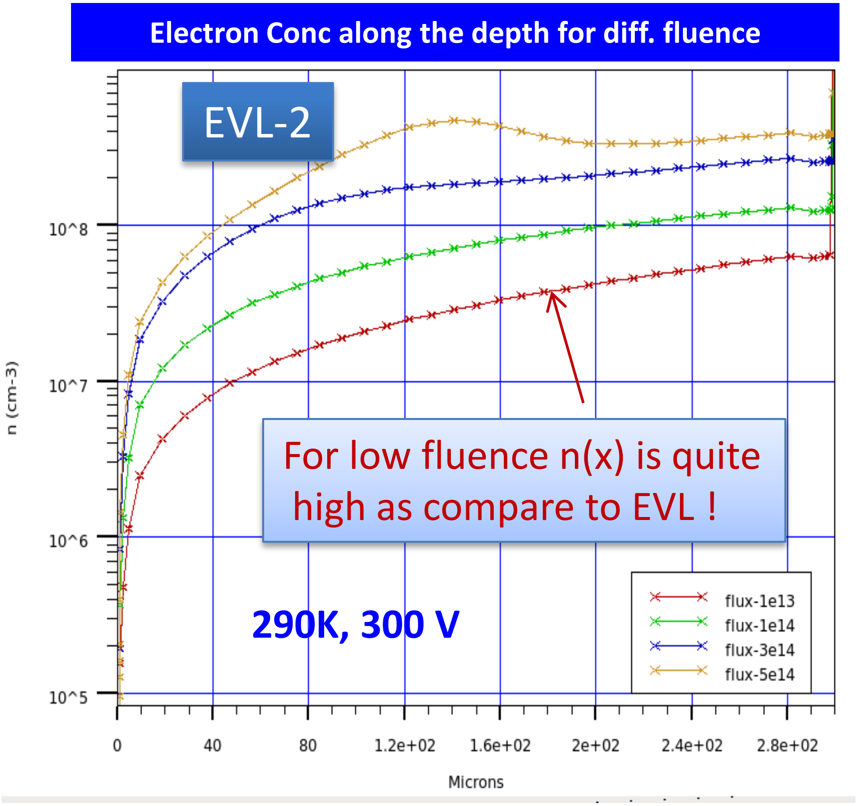


Temp. = 290K

Fluence = $1 \times 10^{14} \mathrm{cm}^{-2}$

EVL Vs. EVL – 2 : Simulation results n(x) comparison


Electron Conc along the depth for diff. fluence


Electron Conc along the depth for diff. fluence

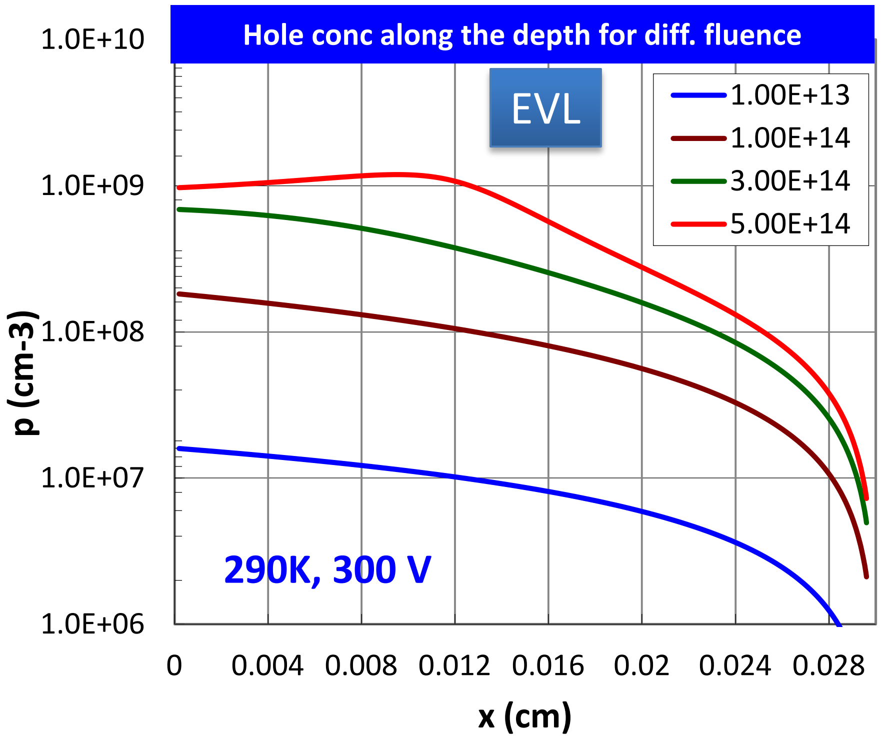
For low fluence n(x) is quite high as compare to EVL !

❖The behaviour of EVL2 simulated results for n(x) looks similar to EVL

❖ The simulated value of n(x) is very high for low irradiation flux

❖ -***May Need to reduce the carrier lifetime***

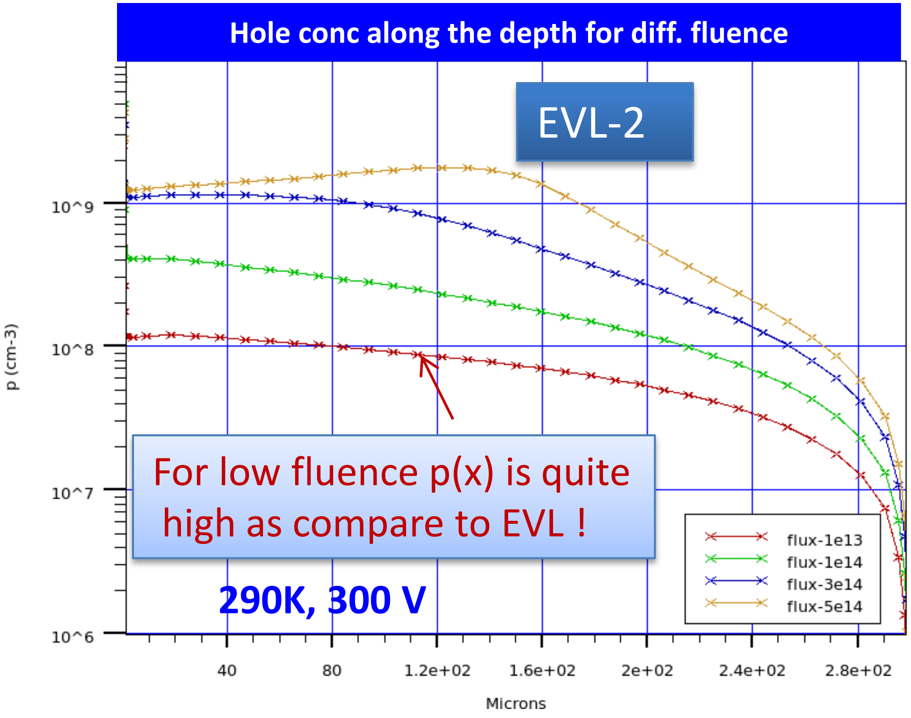
EVL Vs. EVL – 2 : Simulation results
p(x) comparison



Hole conc along the depth for diff. fluence

EVL

290K, 300 V



Hole conc along the depth for diff. fluence

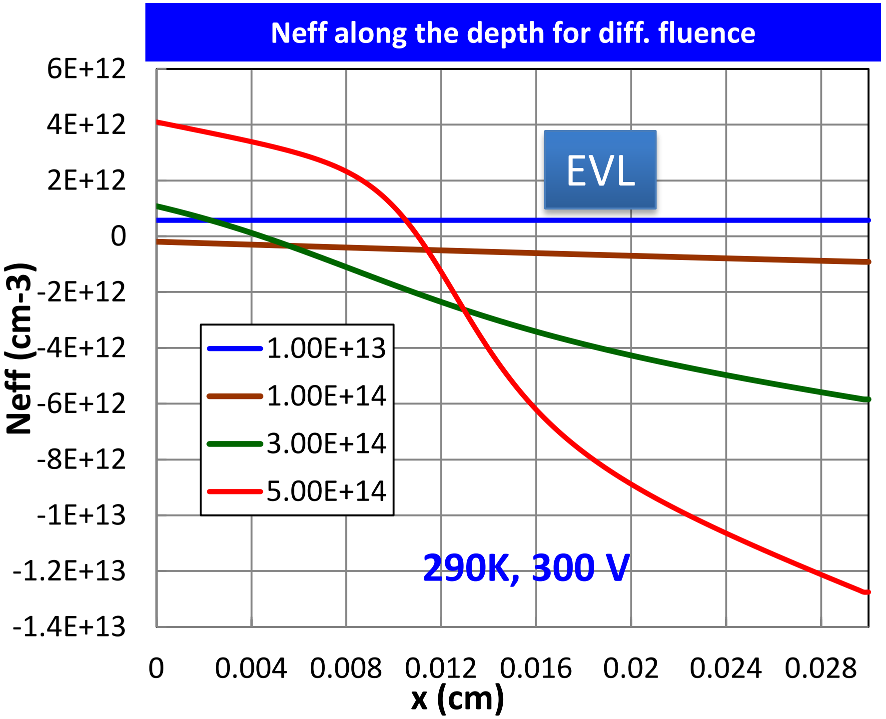
EVL-2

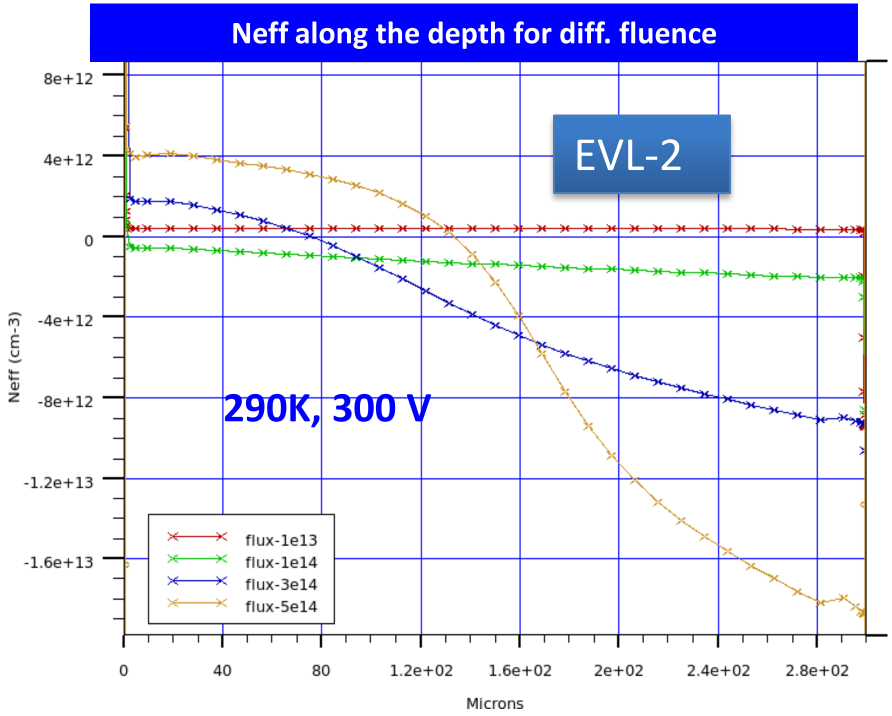
For low fluence p(x) is quite high as compare to EVL !

290K, 300 V

- ❖The behavior of EVL2 simulated results for p(x) looks similar to EVL
- ❖ The simulated value of p(x) is very high for low irradiation flux

EVL Vs. EVL – 2 : Simulation results
$N_{eff}(x)$ comparison



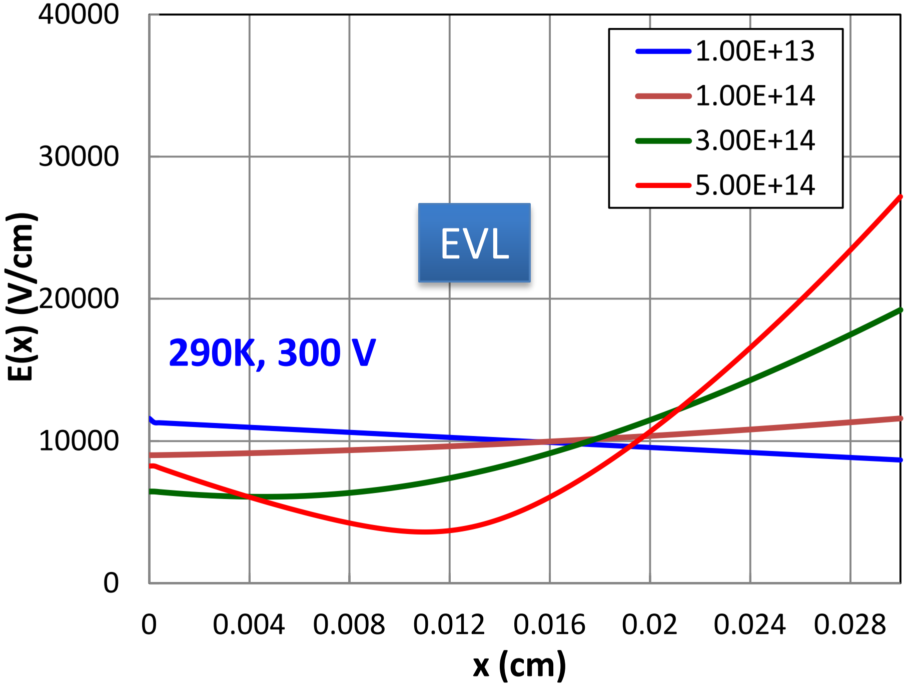


❖$N_{eff}(x)$ simulated by ATLAS have similar appearance to $N_{eff}(x)$ modeled by EVL

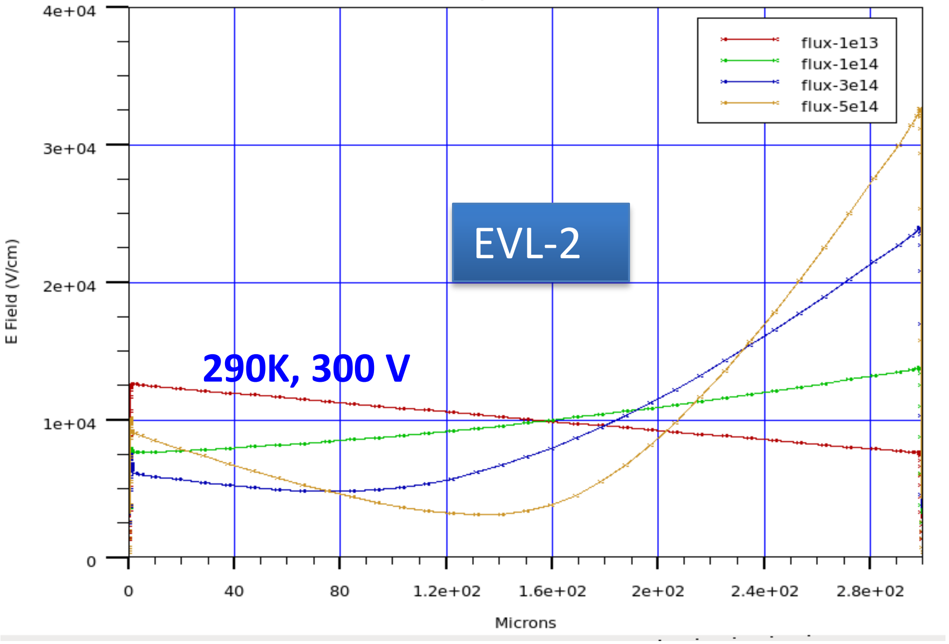
❖Double Peak feature is expected!

EVL Vs. EVL – 2 : Simulation results
E(x) comparison

Electric Field along the depth for diff. fluence



Electric Field along the depth for diff. fluence



- ❖E(x) simulated by ATLAS have similar appearance to E(x) modeled by EVL
- ❖Double Peak feature is produced!

Further Tweaking of Simulation Parameters is needed

Parameters used for simulations in **EVL – 4**

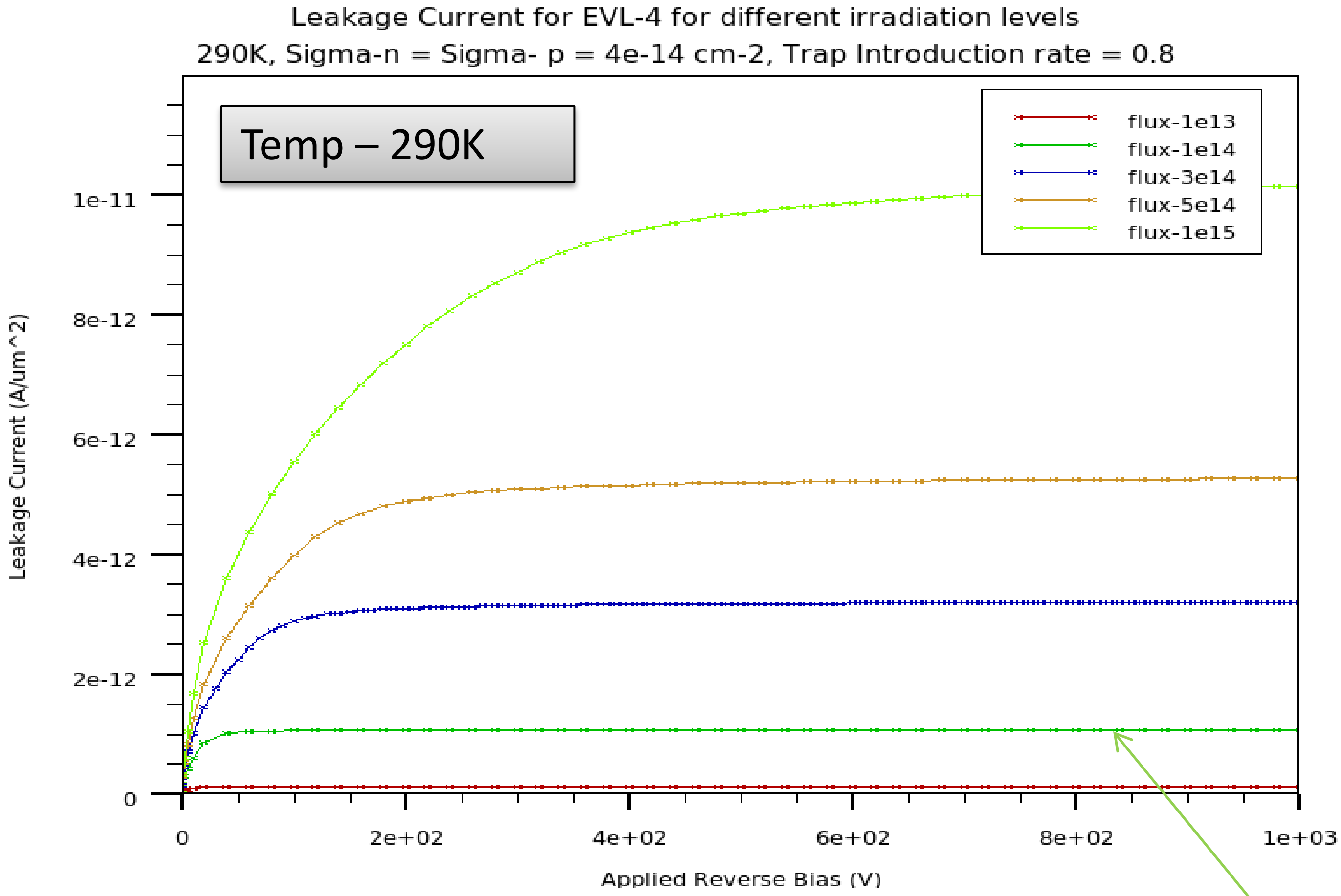
- Trap levels are same as in proposed simulation task.
- Sigma_e = Sigma_h = **$4x10^{-14}$ cm^2** (same as used in EVL-2)
- To reduce the n(x) and p(x) for low irradiation flux, lifetime of charge carrier is increased to = 10^{-4}sec.
- This leads to simulated Leakage current without irradiation < 0.1 x 10^{-12}A (for $1x1x300um^3$ structure)

So, total expected leakage current for $1x1x300um^3$ structure for ϕ= $1x10^{14}$ n_{eq}/cm^2 = 1.2 x 10^{-12}A (reduced from EVL2)

- Electric Field profile is further tailored by decreasing trap introduction rate to 0.8 (reduction of 20%)

Acceptor Introduction rate = Donor Introduction rate = **0.8**

EVL Vs. EVL -4 : Leakage Current for different flux



Simulated Δ I ~ 1.0×10^{-12}A for flux 1×10^{14} cm^{-2}
Expected Δ I ~ 1.2 $\times10^{-12}$A for this flux

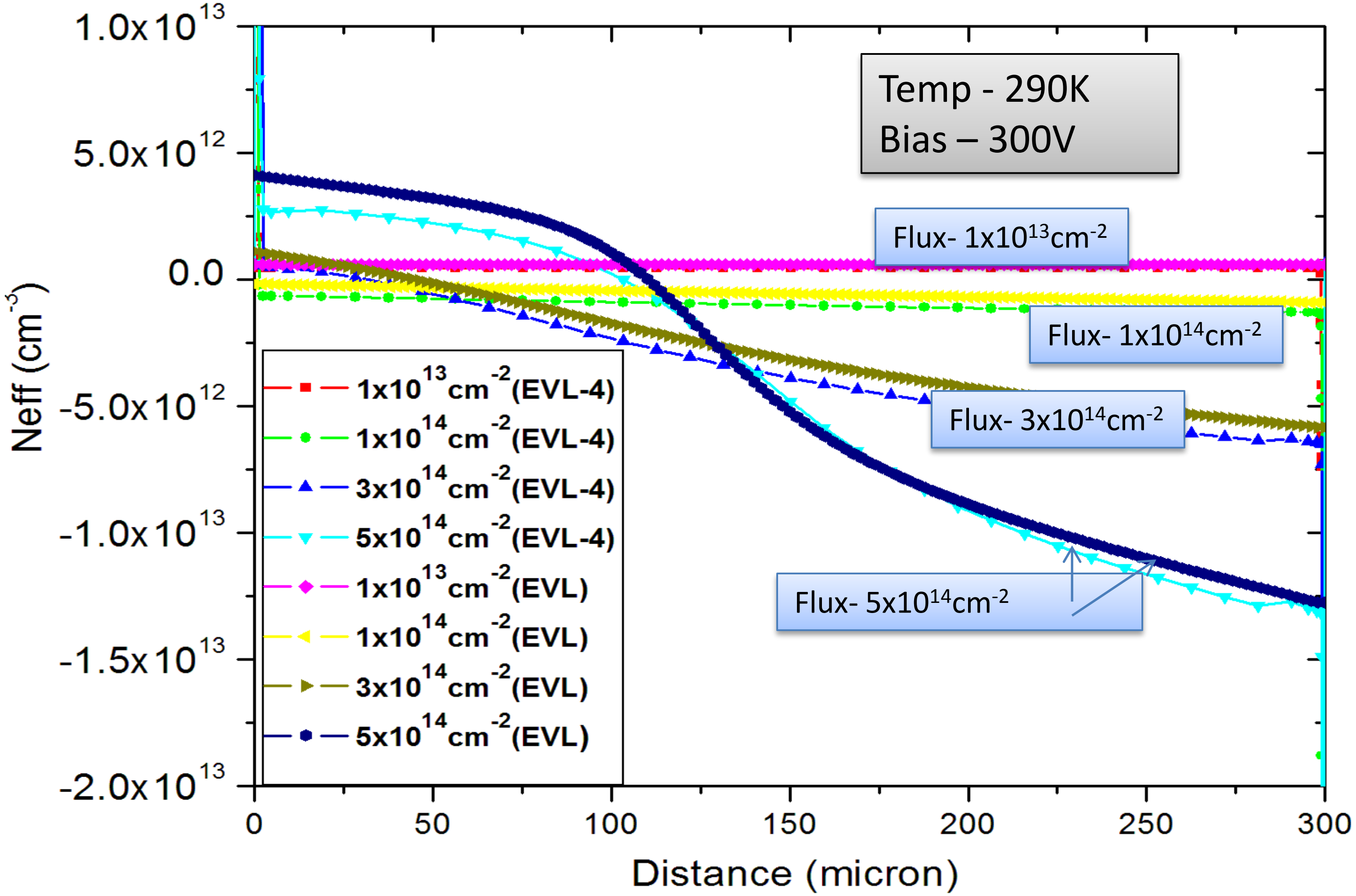
RESULTS FOR EVL-4

Flux – Vary ($1 \times 10^{13} cm^{-2}$, $1 \times 10^{14} cm^{-2}$, $5 \times 10^{14} cm^{-2}$)

Reverse Bias – 300V

Temp – 290K

EVL Vs. EVL -4 : Neff for different flux (Temp. and Bias are constant)



Temp - 290K
Bias – 300V

Flux- $1x10^{13}cm^{-2}$

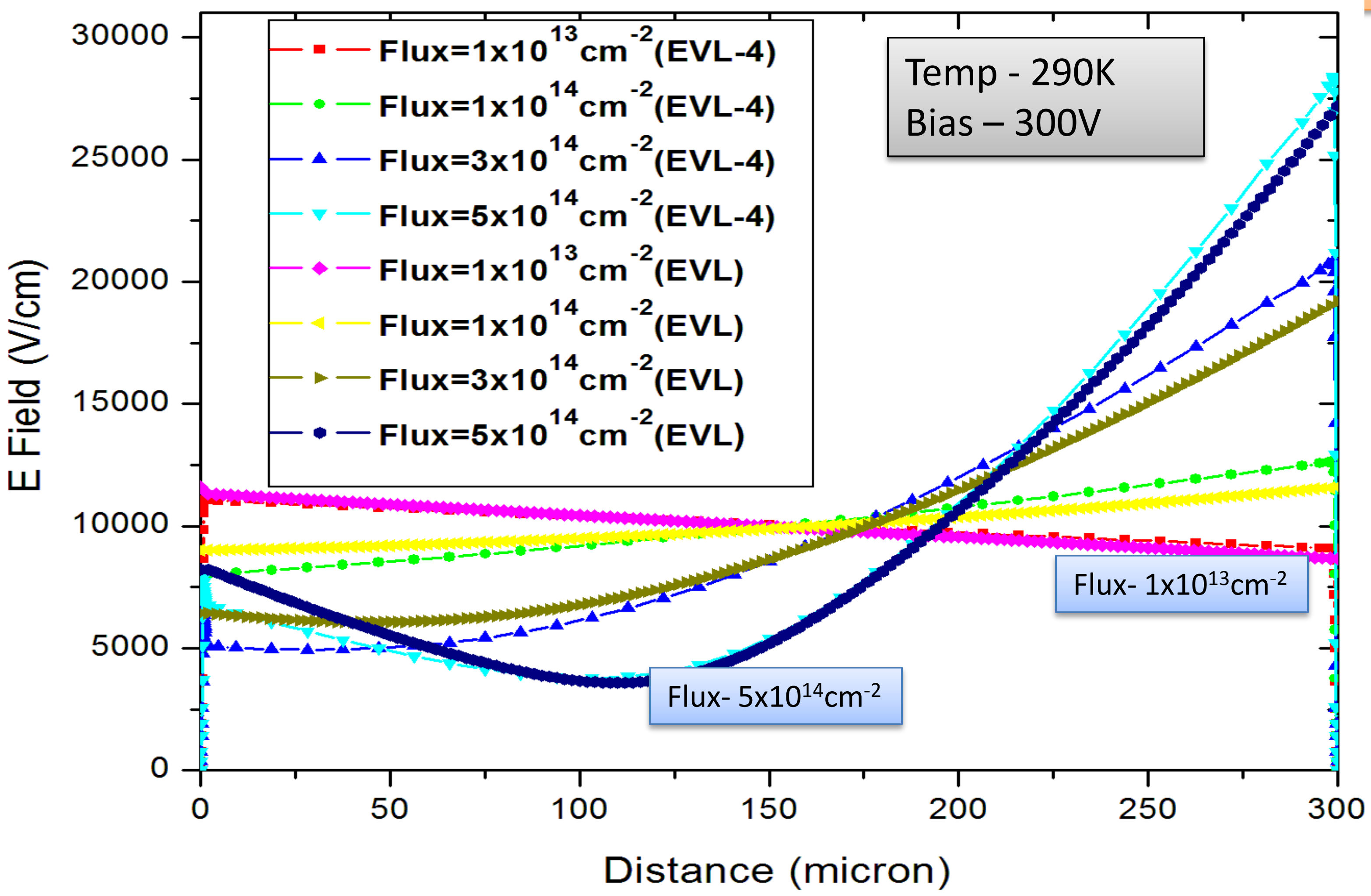
Flux- $1x10^{14}cm^{-2}$

Flux- $3x10^{14}cm^{-2}$

Flux- $5x10^{14}cm^{-2}$

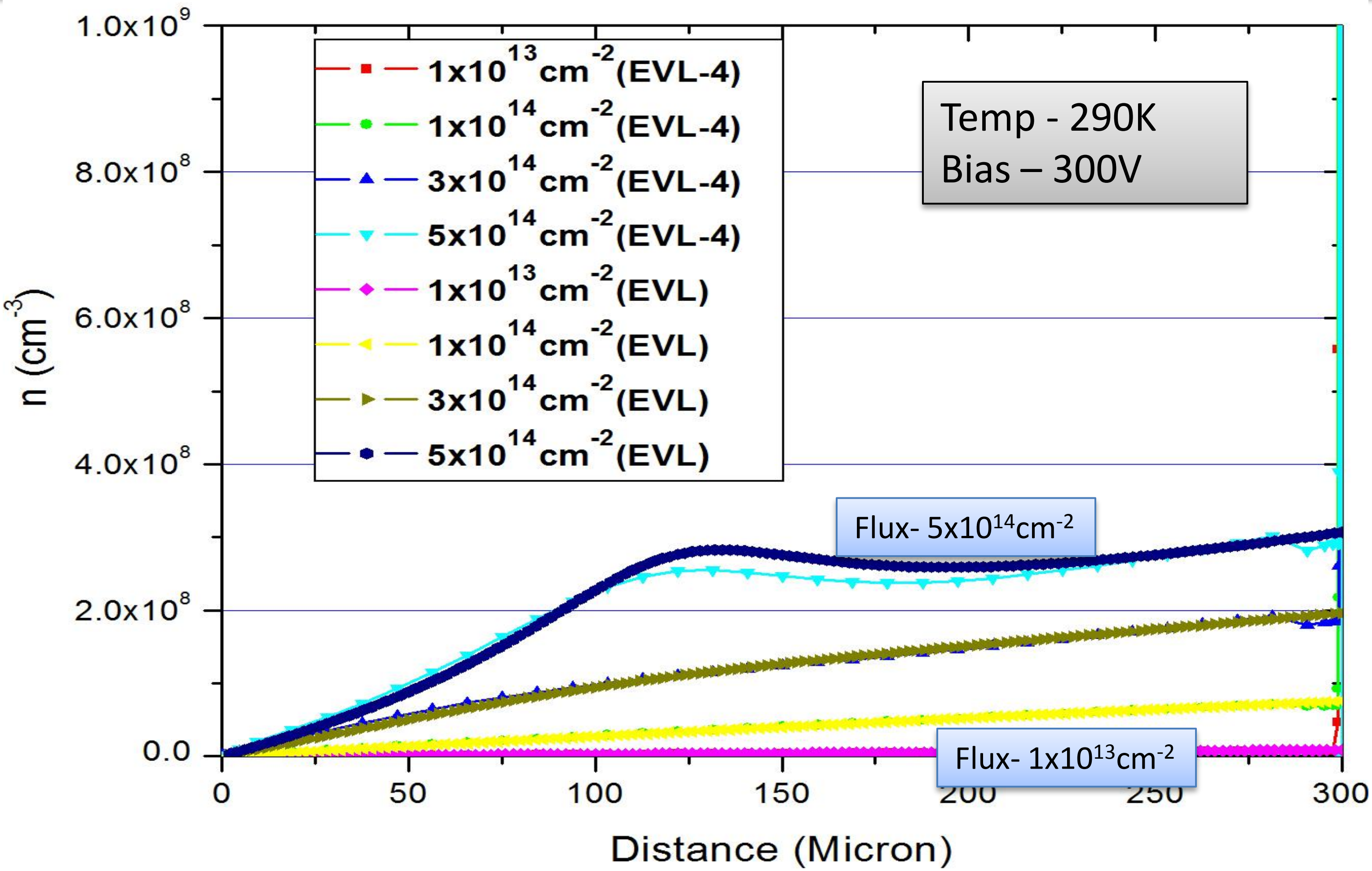
✓ Similar behavior of N_{eff} for EVL and EVL-4

EVL Vs. EVL -4 : E-field for different flux



- ✓ Similar behavior of E field for EVL and EVL-4
- ✓ Double Peaked Electric field is visible

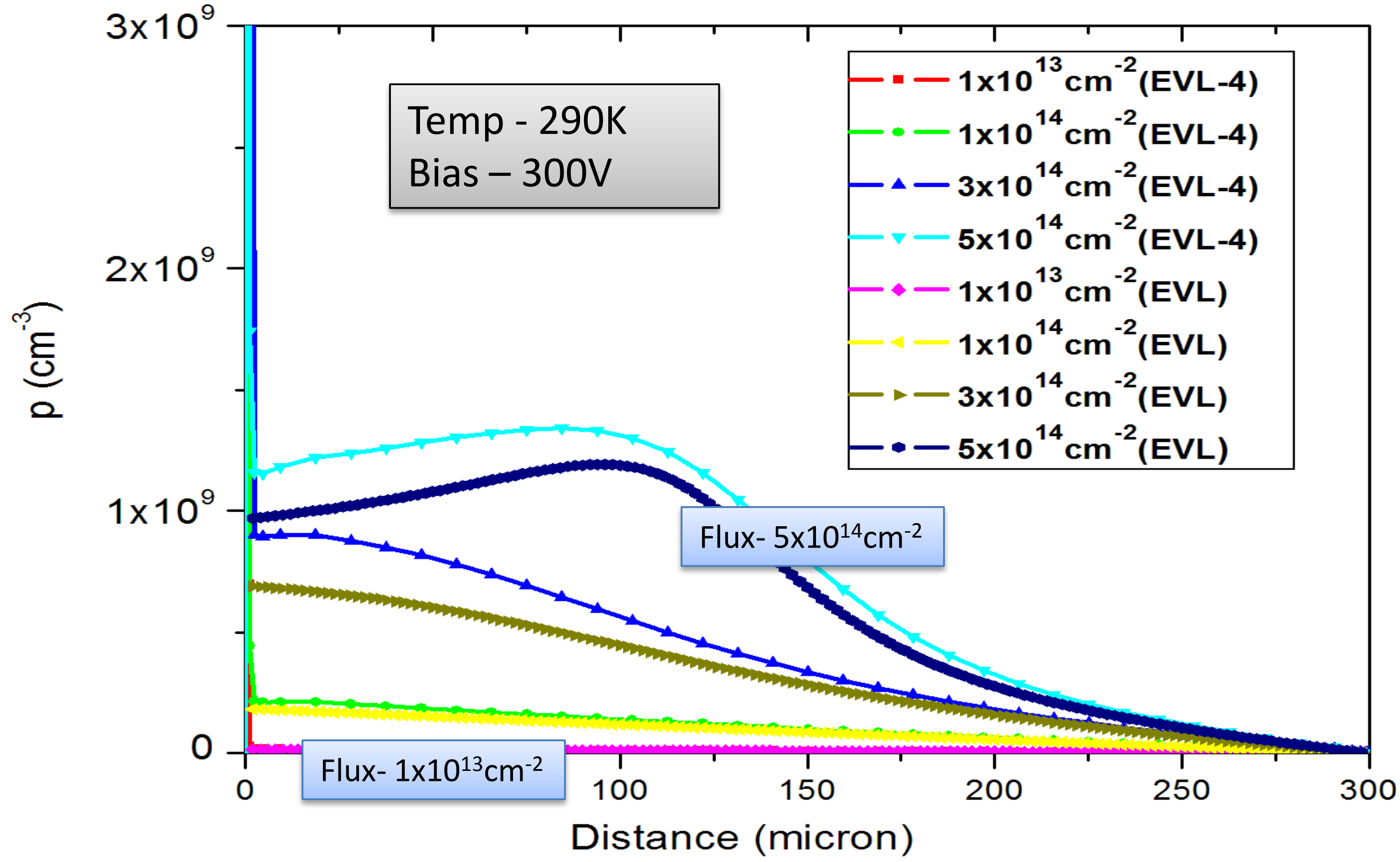
EVL Vs. EVL -4 : n conc. for different flux



Temp - 290K
Bias – 300V

- ✓ Good agreement of n(x) for EVL and EVL-4
- ✓ n & p conc. strongly depend on carrier life time. Used **$1x10^{-4}$sec** for e & h lifetime

EVL Vs. EVL -4 : p conc. for different flux



- ✓ p (x) conc. for EVL-4 is ~ 20% more then EVL
- ✓ n & p conc. strongly depend on carrier life time. Used **$1x10^{-4}$sec** for e & h lifetime

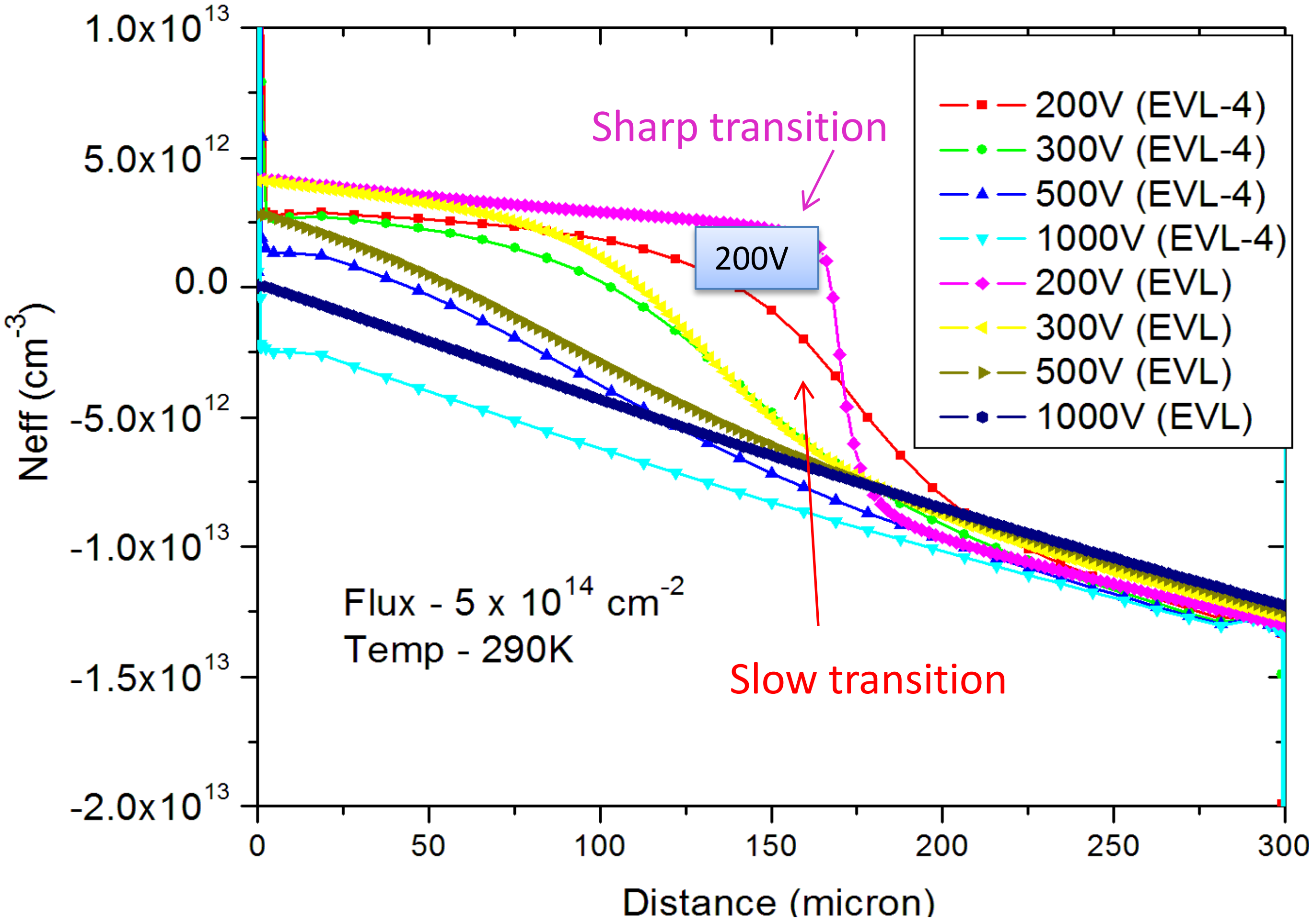
RESULTS FOR EVL-4

Flux – 5×10^{14} cm^{-2}

Reverse Bias – Vary (200V, 300V, 500V, 1000V)

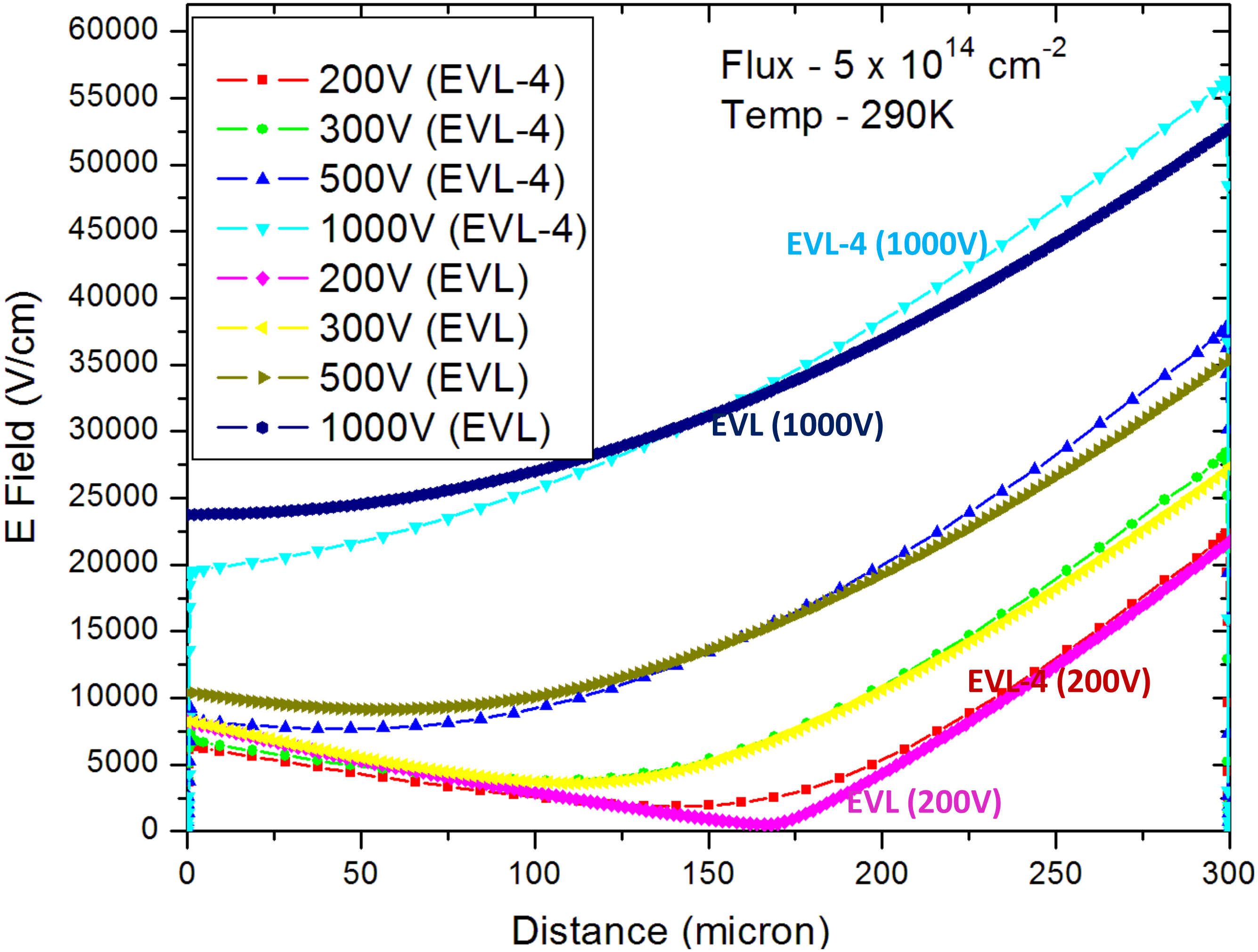
Temp – 290K

EVL Vs. EVL -4 : Neff for flux = 5×10^{14}cm^{-2} (Flux and temp are constant)



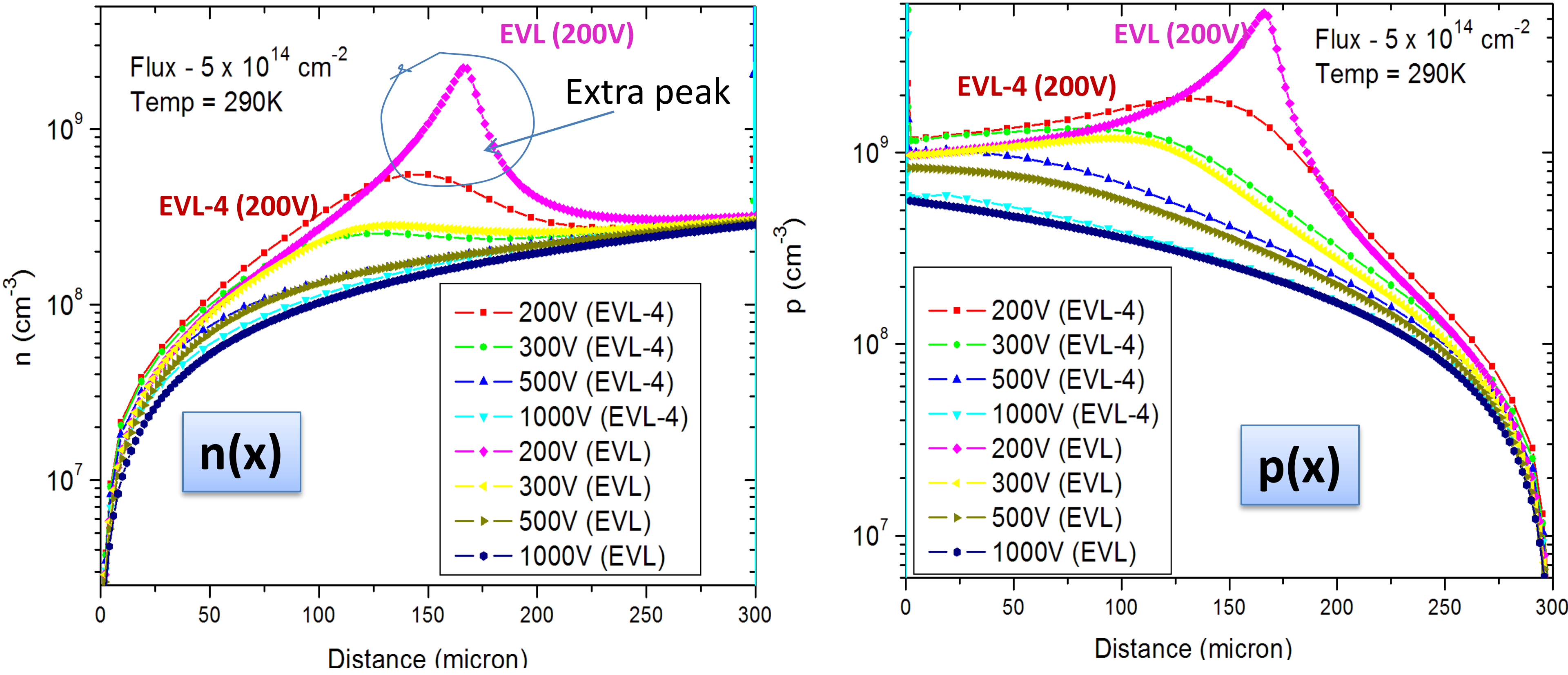
- ❖ A sharp transition in N_{eff} is present in EVL data, whereas EVL-4 have gradual transition (for 200V) from Donor dominated region to Acceptor dominated region (around 160 micron from top)

EVL Vs. EVL -4 : E Field for flux = 5x10^{14}cm^{-2}at different bias point



✓ Similar behavior for E field for EVL and EVL-4

EVL -4 : n and p conc. for flux = 5×10^{14} cm^{-2} at different bias point



Sharp peaks in n and p conc. are present in EVL data, whereas EVL-4 have gradual transition (for 200V) from Donor dominated region to Acceptor dominated region (around 160 micron from top)

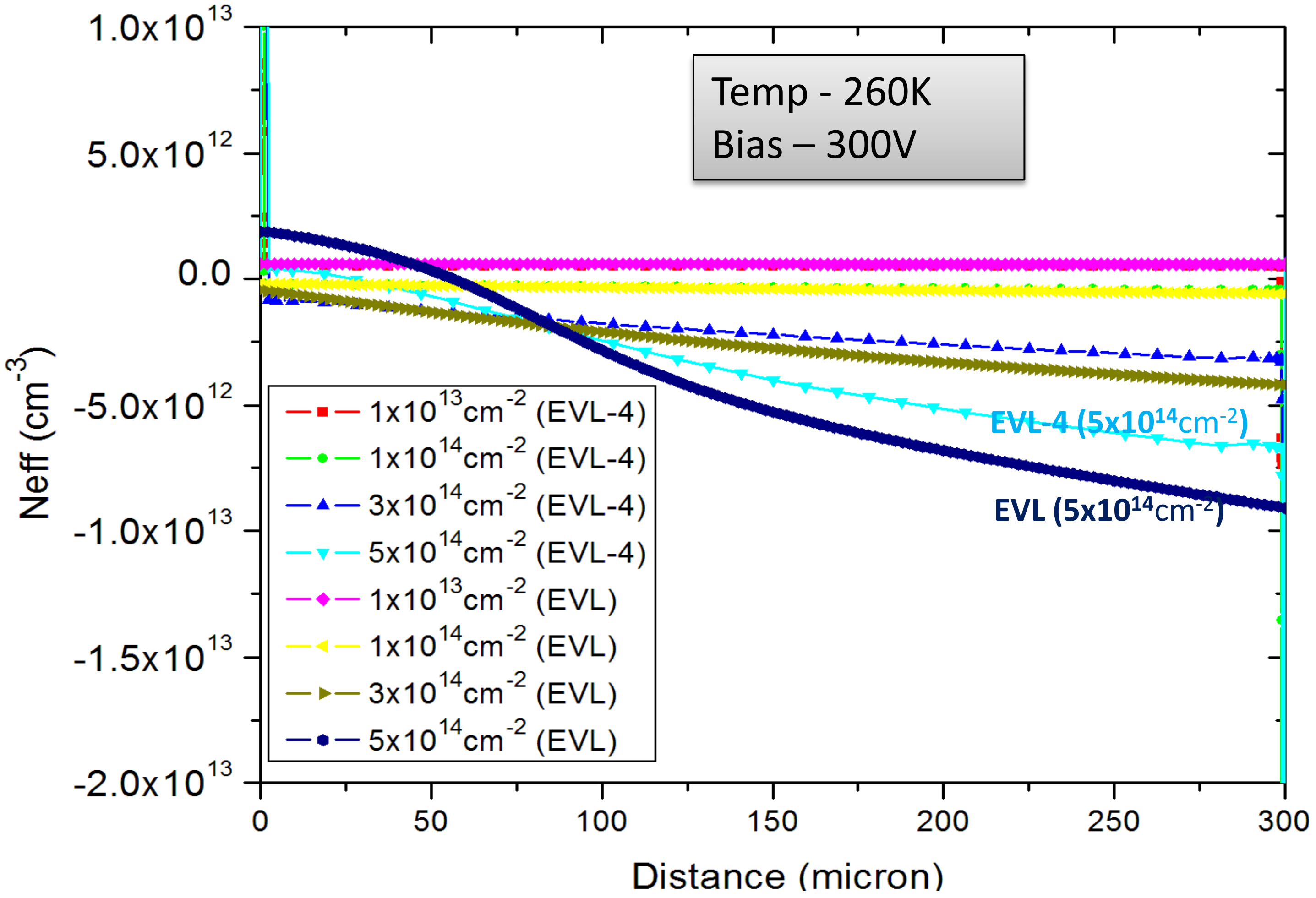
RESULTS FOR EVL-4

Flux – Vary (1x10^{13}cm^{-2},1x10^{14}cm^{-2}, 5x10^{14}cm^{-2})

Reverse Bias – 300V

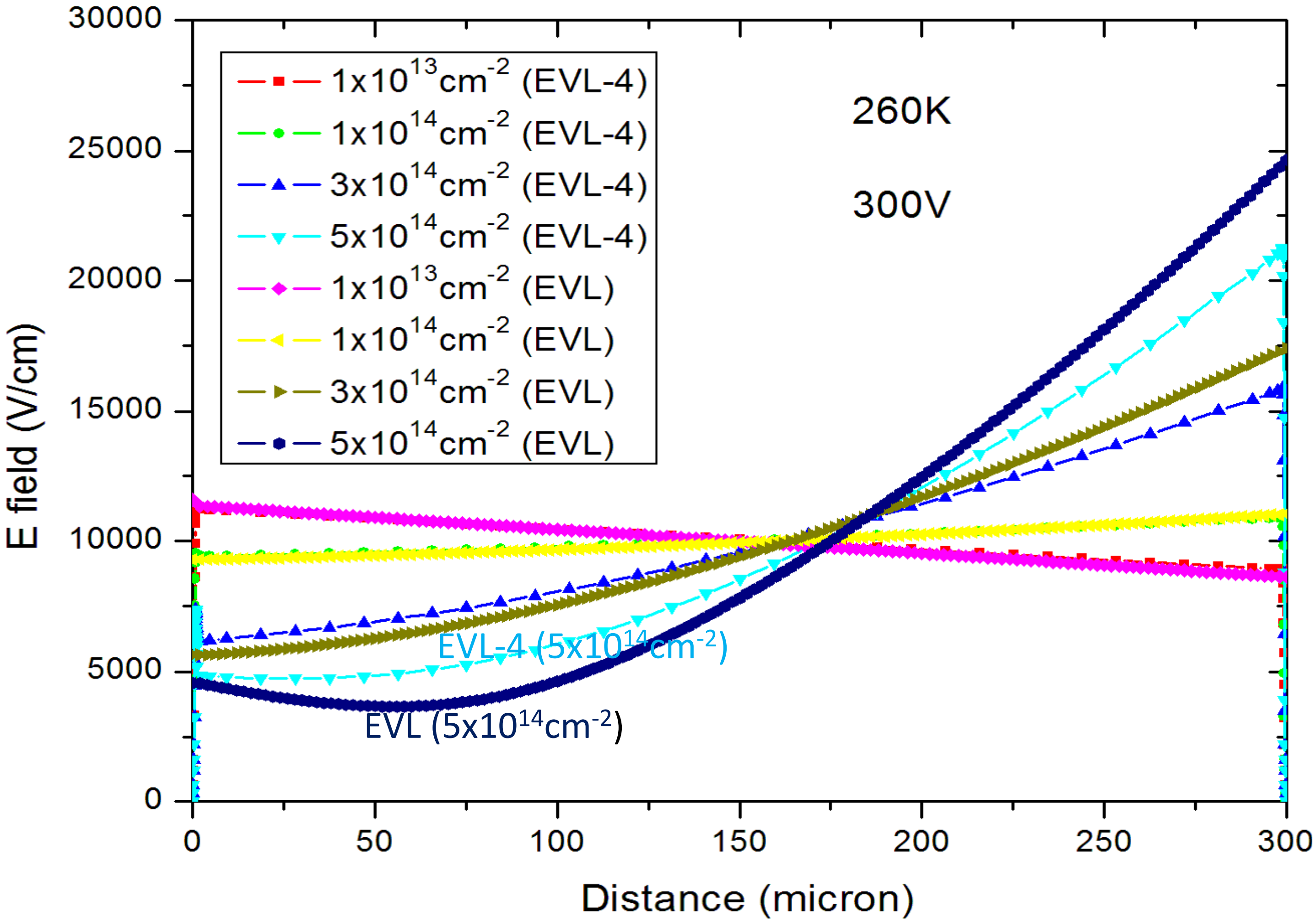
Temp – 260K

EVL Vs. EVL -4 : Neff for different flux at 260K



✓ Lesser no. of traps are activated in ATLAS simulator

EVL Vs. EVL -4 : E Field for different flux at 260K

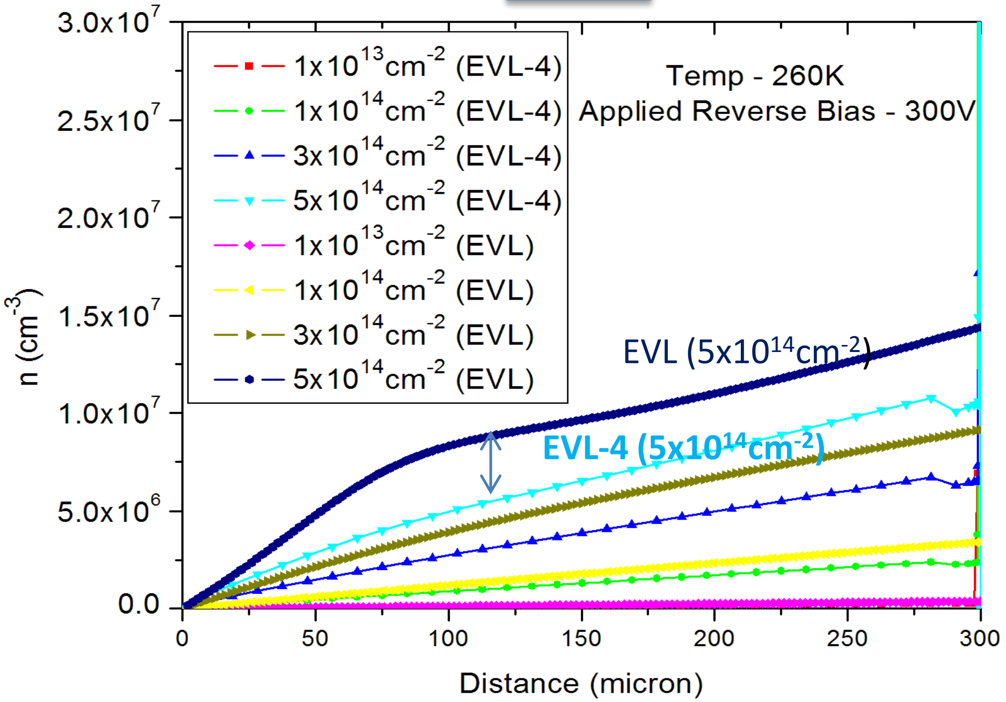


✓ Lesser no. of traps are activated in ATLAS simulator

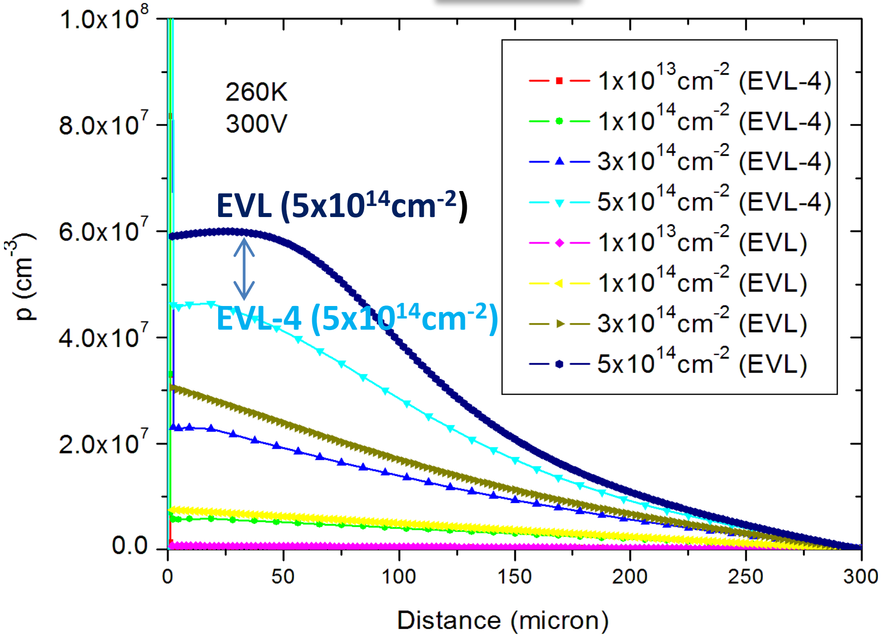
EVL Vs. EVL -4 : n & p conc. for different flux at 260K

Temp - 260K
Bias – 300V

n(x)



p(x)



✓ Lesser no. of traps are activated in ATLAS simulator

Fine tuning can be performed!

- EVL-4 have 20% lower current compare to Expected values with $\alpha(290K)=4x10^{-17}$ A/cm which can be increased by increasing the capture cross section to $5x10^{-14}$ cm^{-2}. This may improve the comparison at 260K where it was observed that less amount of traps are activated in ATLAS.

Summary and future outlook

- Atlas does not have any provision to generate bulk current though a trap which do not contribute to space charge. All the traps which generate current also contribute to the space charge and hence to electric field.
- Leakage current tuning for Temp = 290K, flux = 1×10^{14}cm^2 is carried out by increasing the e/h capture cross-section to 4×10^{-14}cm^2 .
- The trap introduction rate is decreased to 0.8 in EVL-4 by comparing electric field profile in EVL-2.
- A good agreement was obtained for N_{eff}, E field and n conc. for different fluences at temp = 290K and Bias = 300V, while simulated p conc. is ~20% higher than EVL model simulations.
- For flux = 5×10^{14}cm^{-2}, a good agreement is obtained at 300V and 500V but for Bias = 200V, our results are different from EVL data set, particularly around 160 micron below p^+.
- For, data set at Temp = 260K, significantly less no. of traps are activated in Atlas simulation
- **Further understanding of the results can be achieved by changing the e/h capture cross section ratio or/and the ratio of donor/acceptor introduction ratio or/and even by changing the carrier life time – WORK IN PROGRESS!**

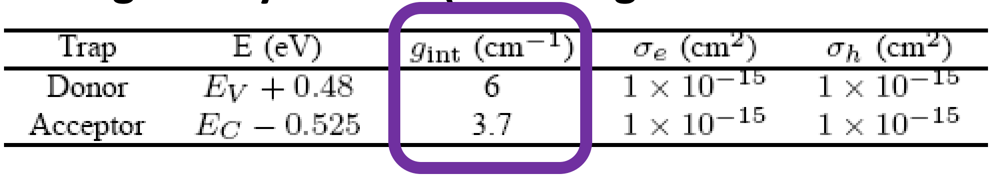
THANKS!

Backup

Our Approach…based on

“Simulation of Heavily Irradiated Silicon Pixel Sensors and Comparison with Test Beam Measurements” **by V. Chiochia et al., IEEE NSS 2005**

EVL – 1: Trap levels given by Eremin (no bulk generation current level)



Trap	E (eV)	g_{int} (cm^{-1})	σ_e (cm^2)	σ_h (cm^2)
Donor	$E_V + 0.48$	6	1×10^{-15}	1×10^{-15}
Acceptor	$E_C - 0.525$	3.7	1×10^{-15}	1×10^{-15}

EVL – 2: Trap levels given by Eremin and Bulk current generated by varying cross-section

$$\sigma_{e/h} = 1.48 \times 10^{-14} \ \mathrm{cm}^2$$

EVL – 3: Trap levels given by Eremin and Bulk current generated by varying cross-section and electric field position adjusted by varying the hole to electron cross-section ratio.

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

EVL – 4: Trap levels given by Eremin and Bulk current generated by varying cross-section and electric field position adjusted by varying the hole to electron cross-section ratio and ratio of the introduction rates changed to fix the peak electric field

N_A/N_D from the EVL value of 0.62 to 0.40

RD50 Simulation Activity – First Task

- **To increase current, three 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 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)

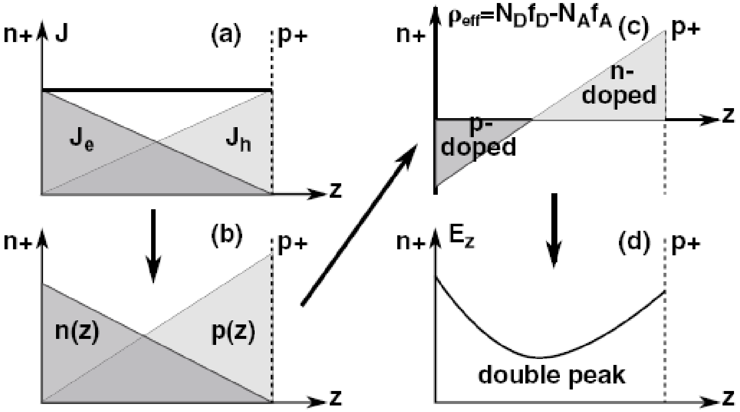


Fig. 6

“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 electro cross-sections

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

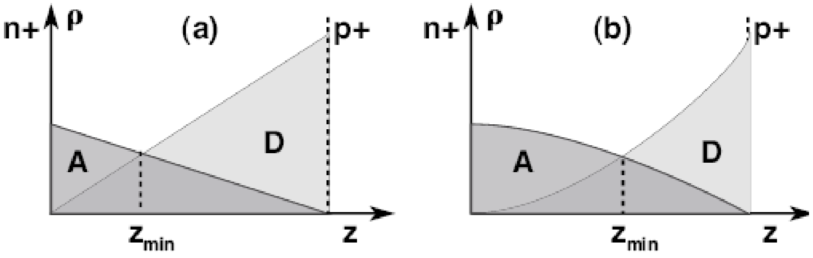


Fig. 8

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

Boundary conditions

Boundary Conditions (BC)

Ohmic BC: Implemented as Dirichlet boundary conditions.

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

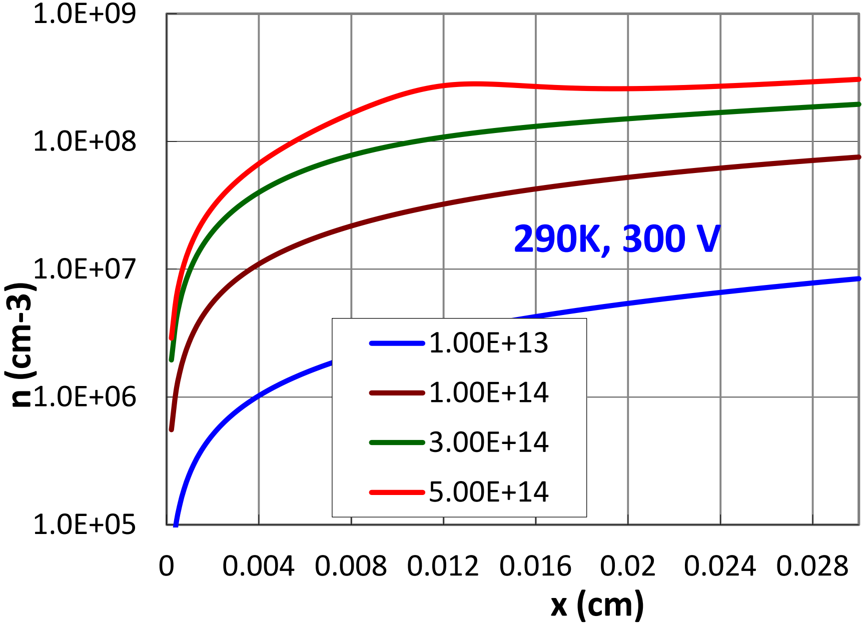
Neumann BC: Along the outer (non contact) edges of devices, homogeneous (reflecting) Neumann

BC are imposed so that current only flows out of the device through the contacts.

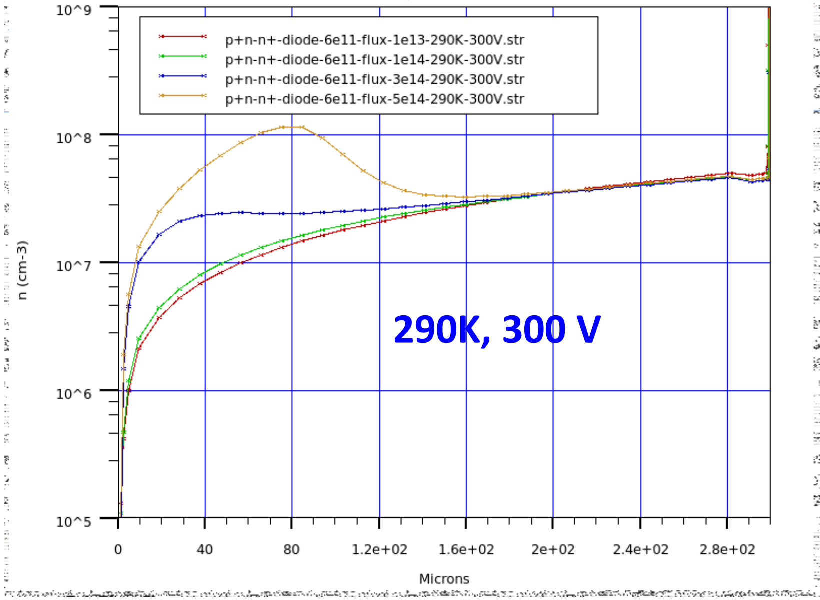
AC small signal analysis: performed as a post-processing operation to a DC solution. The results of AC simulations are the conductance and capacitance between each pair of electrodes @ f=1 MHz.

EVL VS. EVL – n(x) Comparison between Eremin Simulations and Atlas simulation

Electron Conc along the depth for diff. fluence



Electron Conc along the depth for diff. fluence



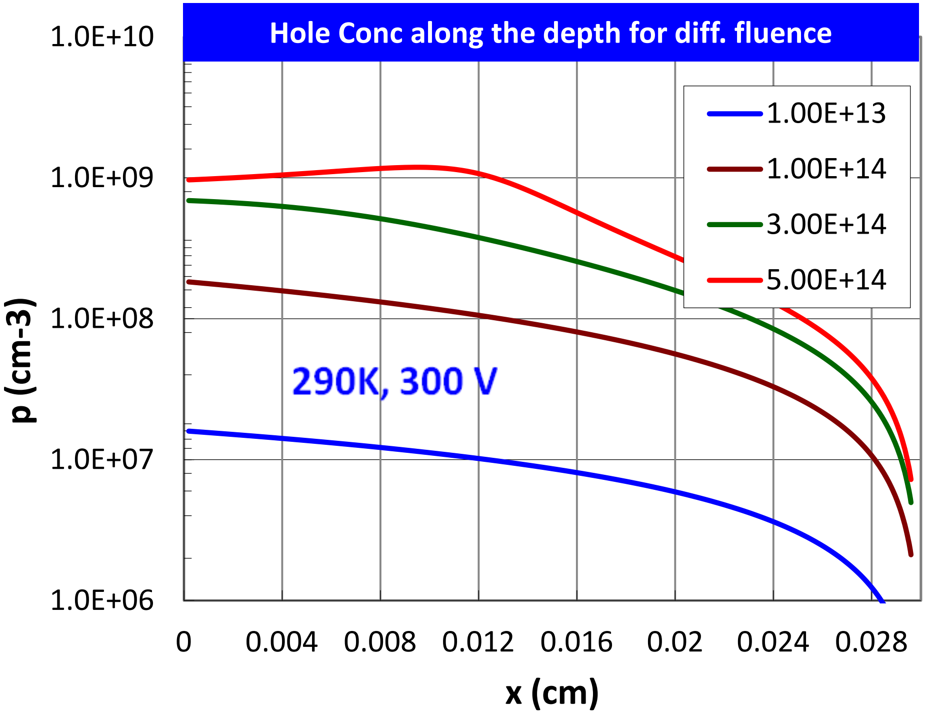
Electron concentration simulated by Eremin

Electron concentration simulated by ATLAS

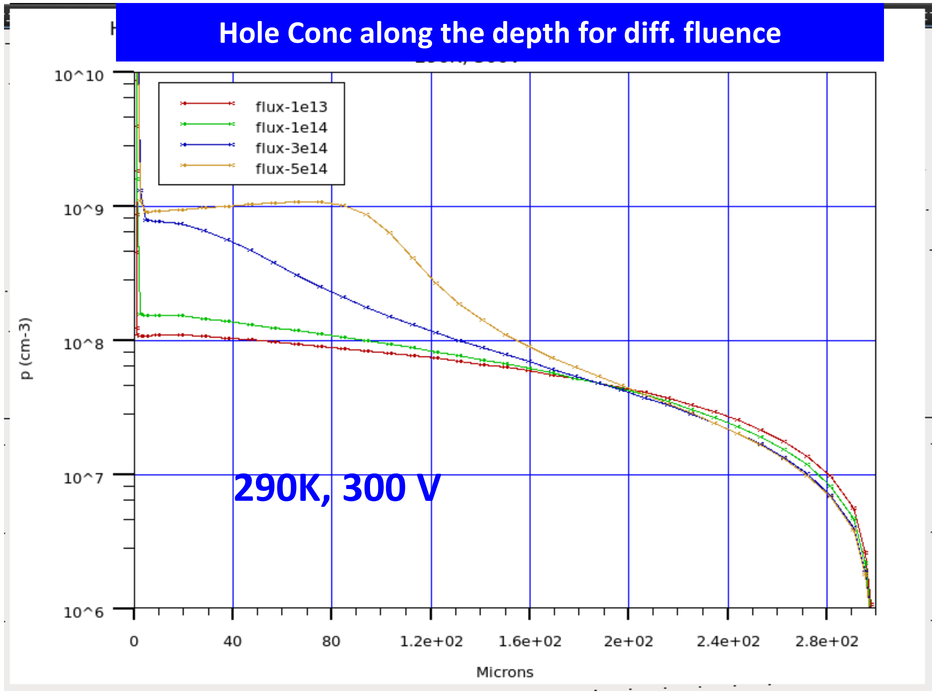
➡ **No current generation level**

n (x) does not match!

EVL VS. EVL – p(x) Comparison between Eremin Simulations and Atlas simulation



Hole concentration simulated by Eremin



Hole concentration simulated by ATLAS

p (x) does not match!