Simulation of irradiated silicon p-bulk sensors

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21st RD50 Workshop, CERN

Outline

- Goals of the work: reproduce & predict
- Data to compare the simulations to
- Simulations' models for irradiated sensors
- Results
- Comments & Outlook

Goals

- The goal of simulating irradiated silicon devices is twofold:

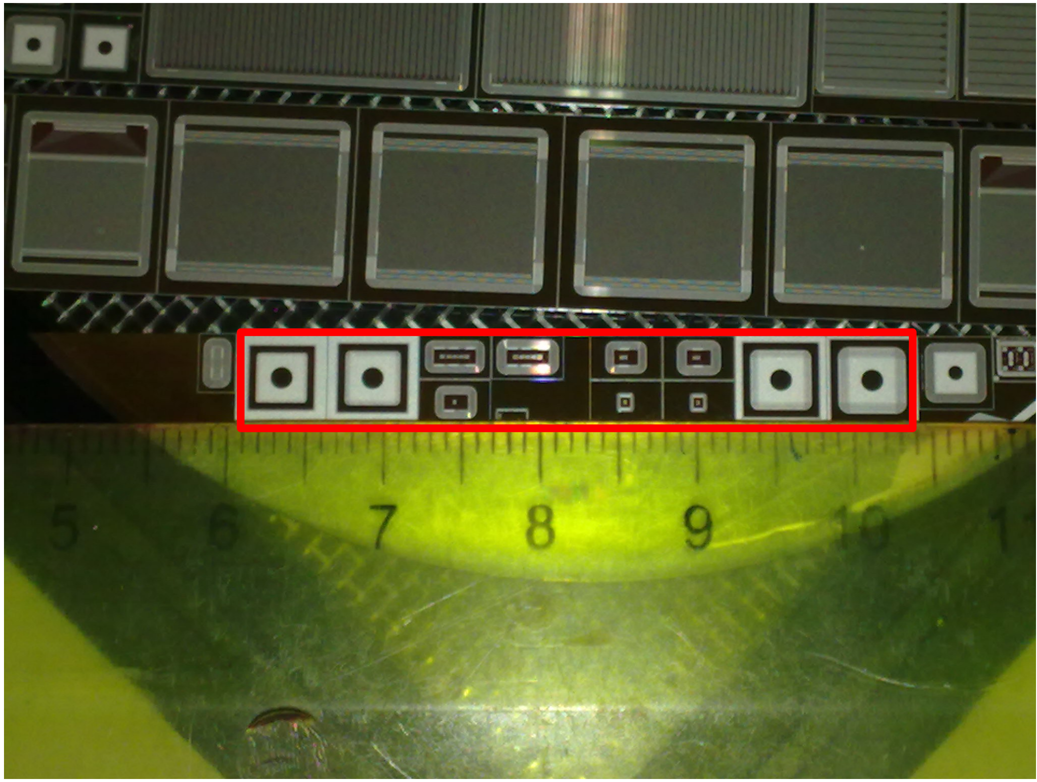
1) Reproduce in an effective way observed behaviors

2) Make predictions for new detectors' performance

  - ➔ E.g. Active edge detectors

Data

- DOFZ N-in-p from CMS/ATLAS/RD50 production
- Batch: 291920
- Wafers: 1, 2, 6, 7, 8, 9, 13 &14
- Thickness: 300 µm
- Diode area: 3 mm x 3 mm
- GRs: 1 to 4
- IV, CV "guarded" measurement after irradiation, at -20° C



Irradiation

- Irradiated with 24 GeV/c protons at CERN

wafer	Fluence (neq/cm^2)
9	1e15
6	1e15
8	5e15
14	5e15
1	1e16
13	1e16

… and annealing

80 minutes at 60 ºC

Radiation damage models

- Non ionizing energy loss (NIEL) creates defects in the **Bulk**

$$N = \eta \times \phi$$

Type	Energy (eV)	$\sigma_e(\mathrm{cm}^2)$	$\sigma_h(\mathrm{cm}^2)$	$\eta(\mathrm{cm}^{-1})$
A	E_C -0.42	9.5×10^{-15}	9.5×10^{-14}	1.613
A	E_C -0.46	5.0×10^{-15}	5.0×10^{-14}	0.9
D	E_V +0.36	3.23×10^{-13}	3.23×10^{-14}	0.9 (1)

Radiation induced bulk damage mode by Pennicard et al.

Radiation damage models

- Ionizing energy loss in the oxide creates defects at the **Surface**:

➔ Increase in interface/oxide charge

➔ Defects at the interface silicon oxide

Type	$E_C - E_{it}$ (eV)	$\sigma_e(\mathrm{cm}^2)$	$\sigma_h(\mathrm{cm}^2)$	$N(10^{11}\mathrm{cm}^{-2})$
A	0.391	1.2×10^{-15}	1.2×10^{-15}	10
A	0.598	6.0×10^{-16}	6.0×10^{-16}	5
A	0.462	2.5×10^{-17}	2.5×10^{-17}	5

(2)

Impact ionization model

- Default model: Selberherr

The general impact ionization process is described by the Equation 3-381.

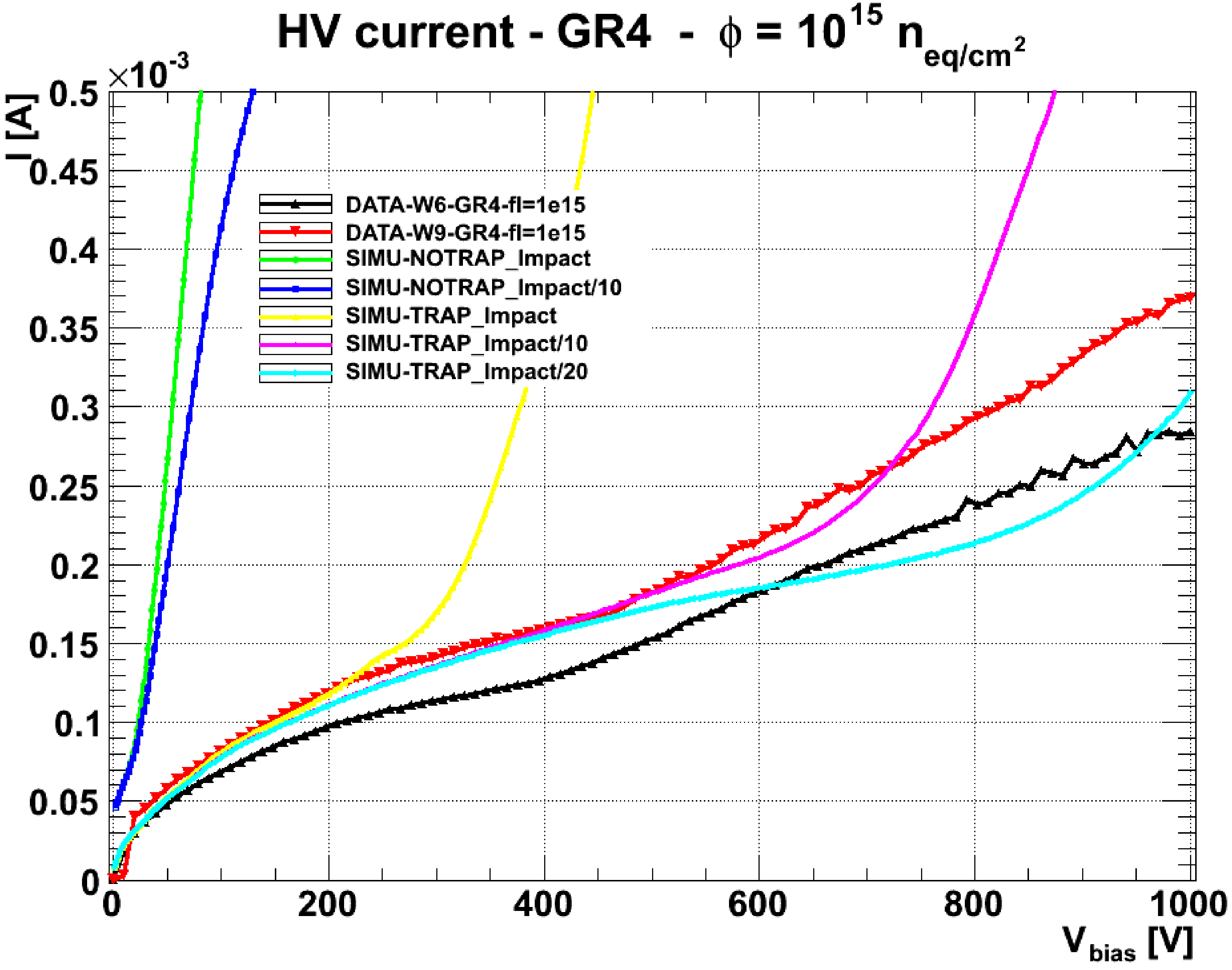
$$G = \alpha_n \left|\vec{J}\right|_n + \alpha_p \left|\vec{J}\right|_p \qquad \text{3-381}$$

Here, G is the local generation rate of electron-hole pairs, $\alpha_{n,p}$ are the ionization coefficient for electrons and holes and $J_{n,p}$ are their current densities.

$$\left.\begin{aligned} \alpha_n &= \mathrm{AN}exp\left[-\left(\frac{\mathrm{BN}}{E}\right)^{\mathrm{BETAN}}\right] \\ \alpha_p &= \mathrm{AP}exp\left[-\left(\frac{\mathrm{BP}}{E}\right)^{\mathrm{BETAP}}\right] \end{aligned}\right\} \longrightarrow \left\{\begin{aligned} \mathrm{AN} &= AN_{1,2}\left(1 + \mathrm{A.NT}\left[\left(\frac{T_L}{300}\right)^{\mathrm{M.ANT}} - 1\right]\right) \\ \mathrm{AP} &= AP_{1,2}\left(1 + \mathrm{A.PT}\left[\left(\frac{T_L}{300}\right)^{\mathrm{M.APT}} - 1\right]\right) \\ \mathrm{BN} &= BN_{1,2}\left(1 + \mathrm{B.NT}\left[\left(\frac{T_L}{300}\right)^{\mathrm{M.BNT}} - 1\right]\right) \\ \mathrm{BP} &= BP_{1,2}\left(1 + \mathrm{B.PT}\left[\left(\frac{T_L}{300}\right)^{\mathrm{M.BPT}} - 1\right]\right) \end{aligned}\right.$$

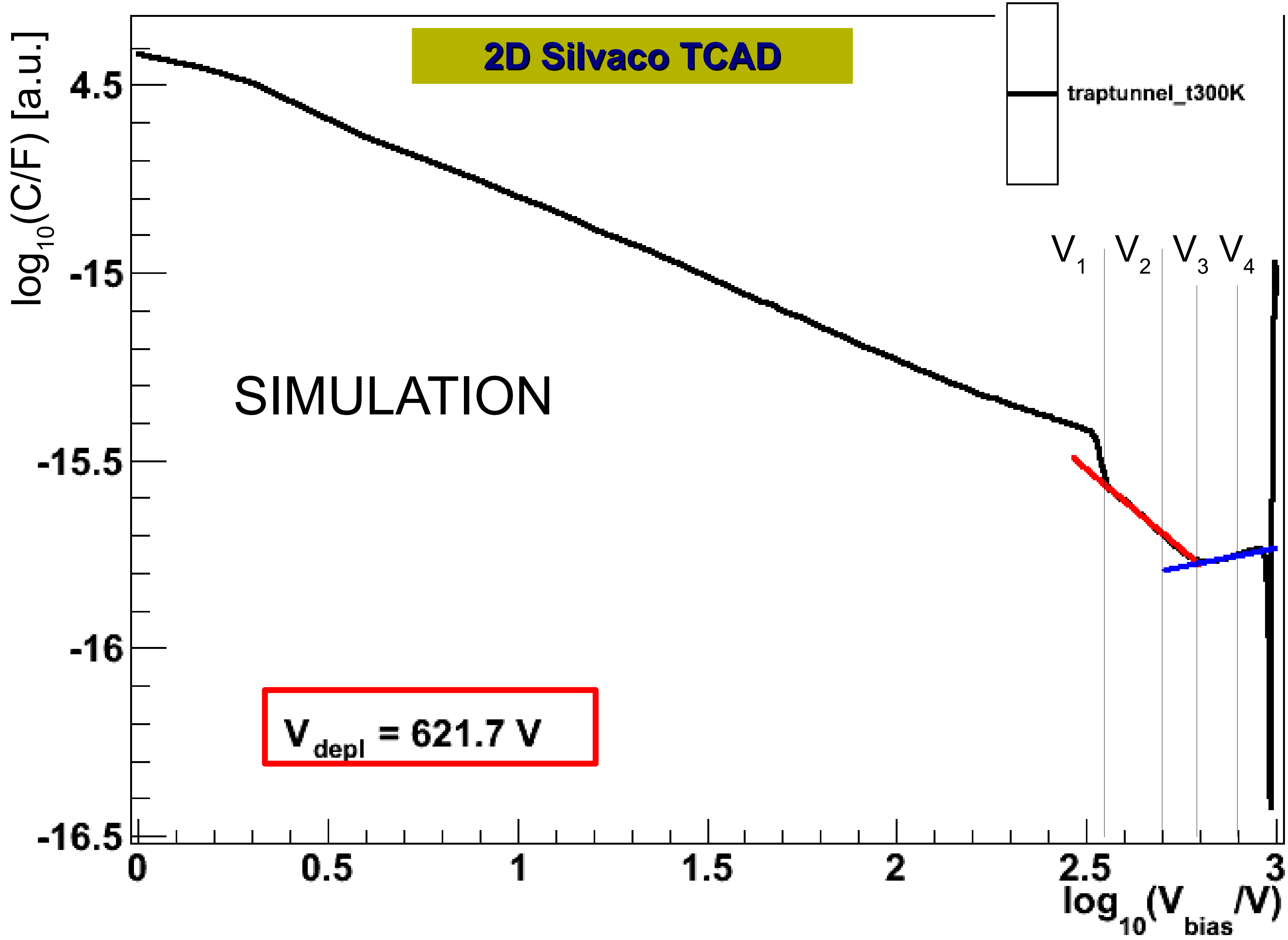
In the case of **AN**, **AP**, **BN**, and **BP** you can define a value of electric field, **EGRAN** V/cm, where for electric fields, >**EGRAN** V/cm, the parameters are: **AN1**, **AP1**, **BN1**, **BP1**, while for electric fields, <**EGRAN** V/cm, the parameters become **AN2**, **AP2**, **BN2**, and **BP2**.

Effect of interface traps



Results for depletion voltage

T = 300 K, $\phi = 10^{15}\ n_{eq}/cm^2$

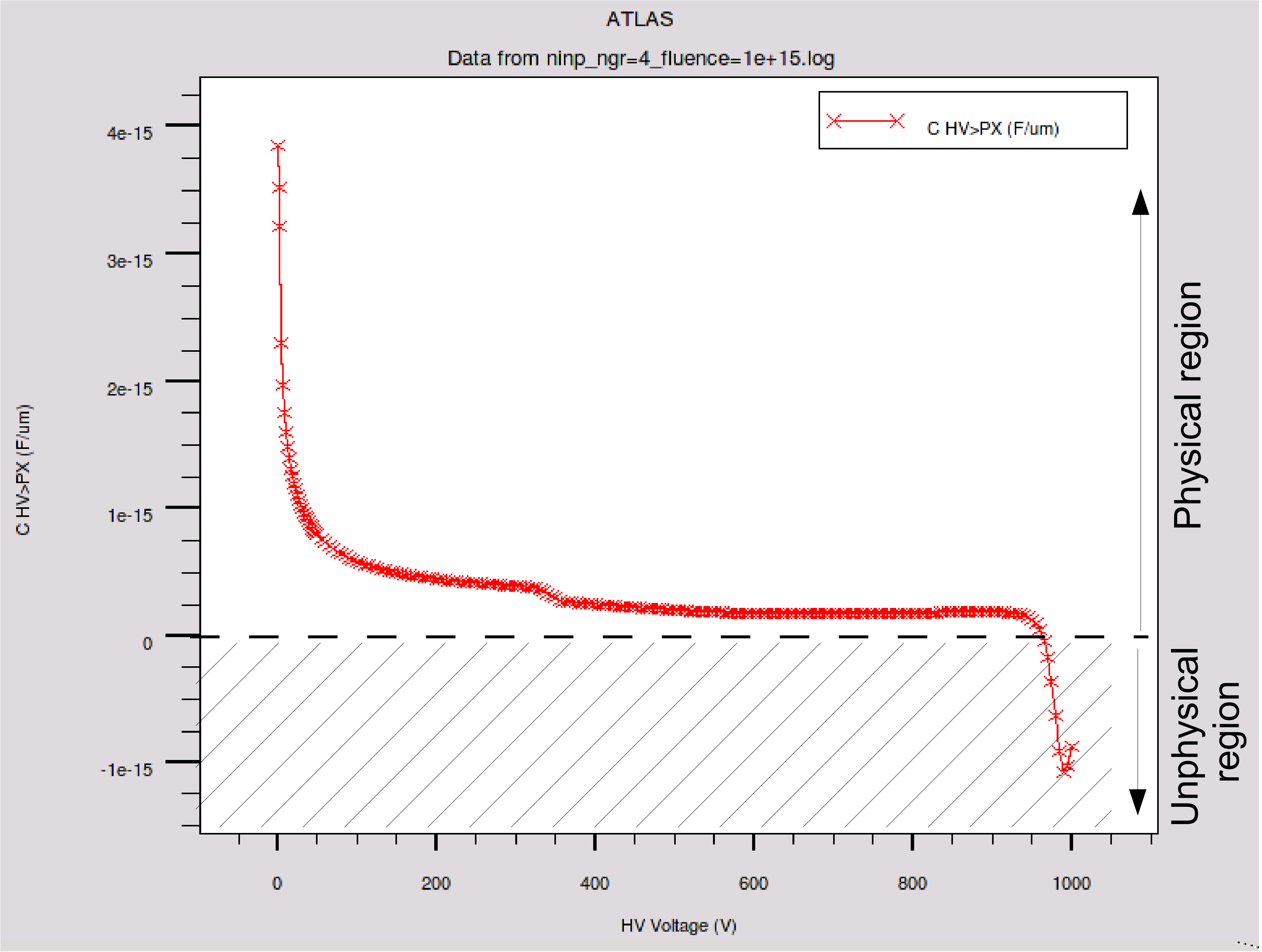


2D Silvaco TCAD

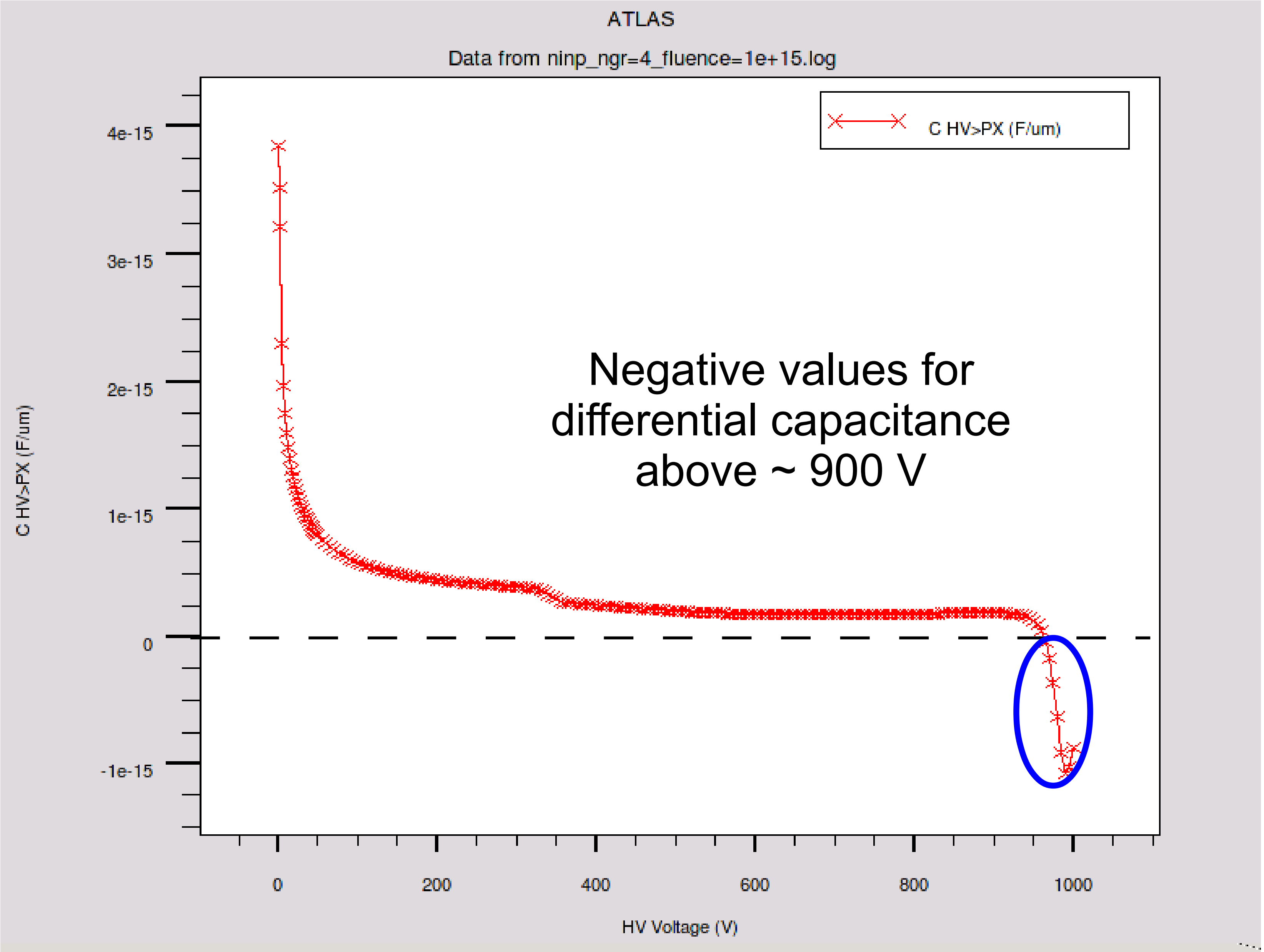
SIMULATION

V_{depl} = 621.7 V

Silvaco bug


ATLAS
Data from ninp_ngr=4_fluence=1e+15.log
C HV>PX (F/um)
4e-15
3e-15
2e-15
1e-15
0
-1e-15
C HV>PX (F/um)
0
200
400
600
800
1000
HV Voltage (V)
Physical region
Unphysical region

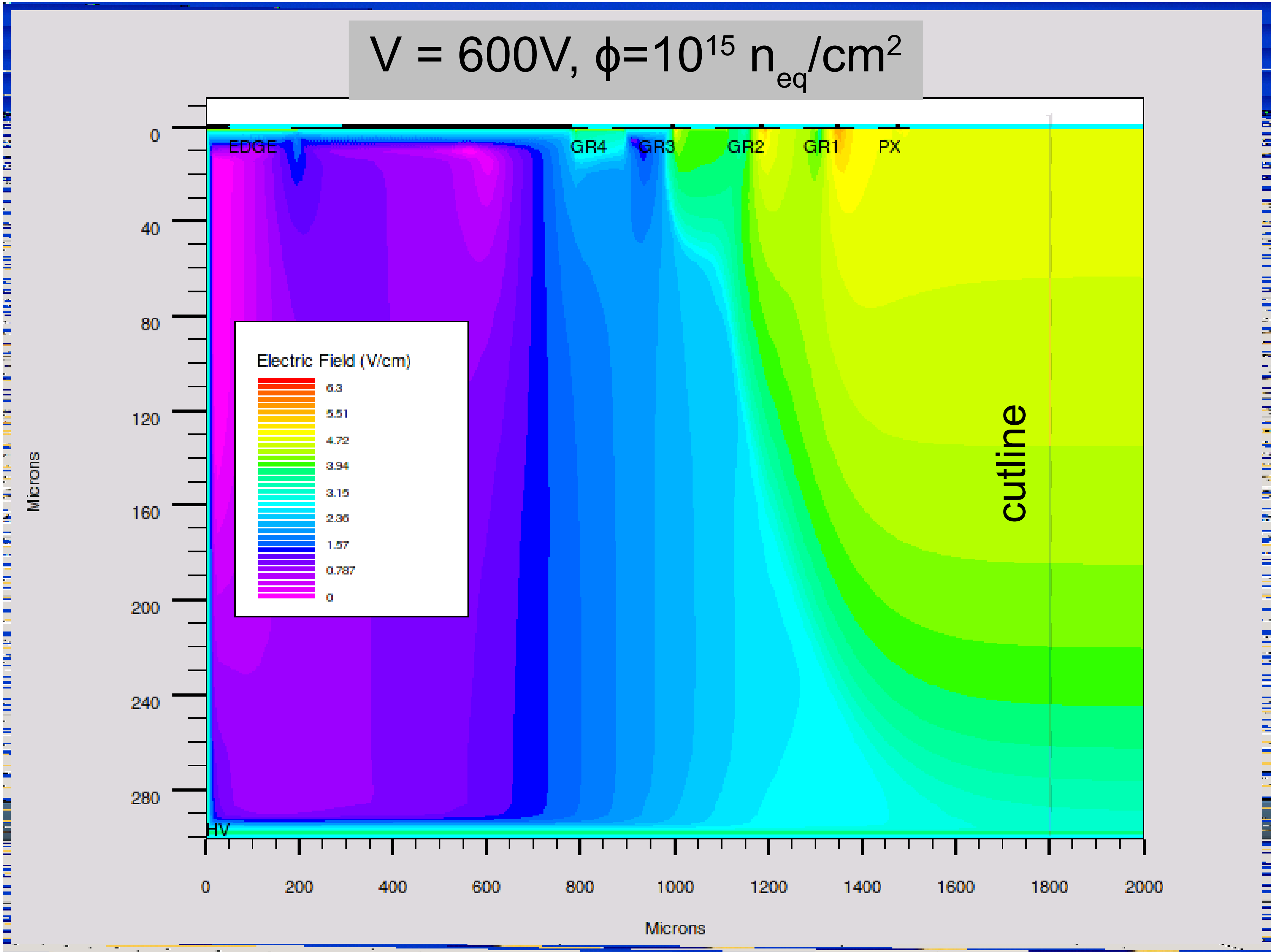
Silvaco bug



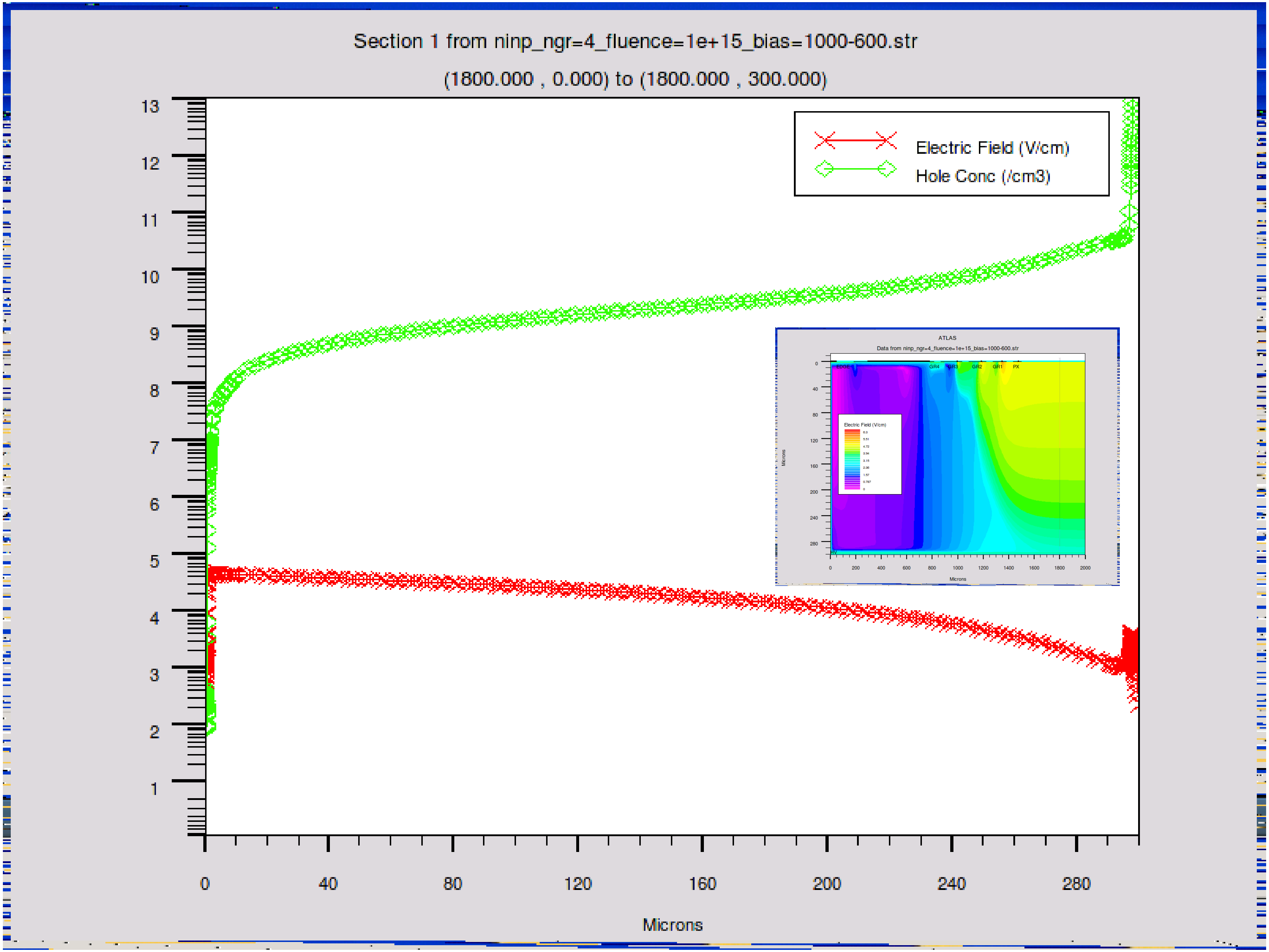
Negative values for differential capacitance above ~ 900 V

Simulated depleted sensor

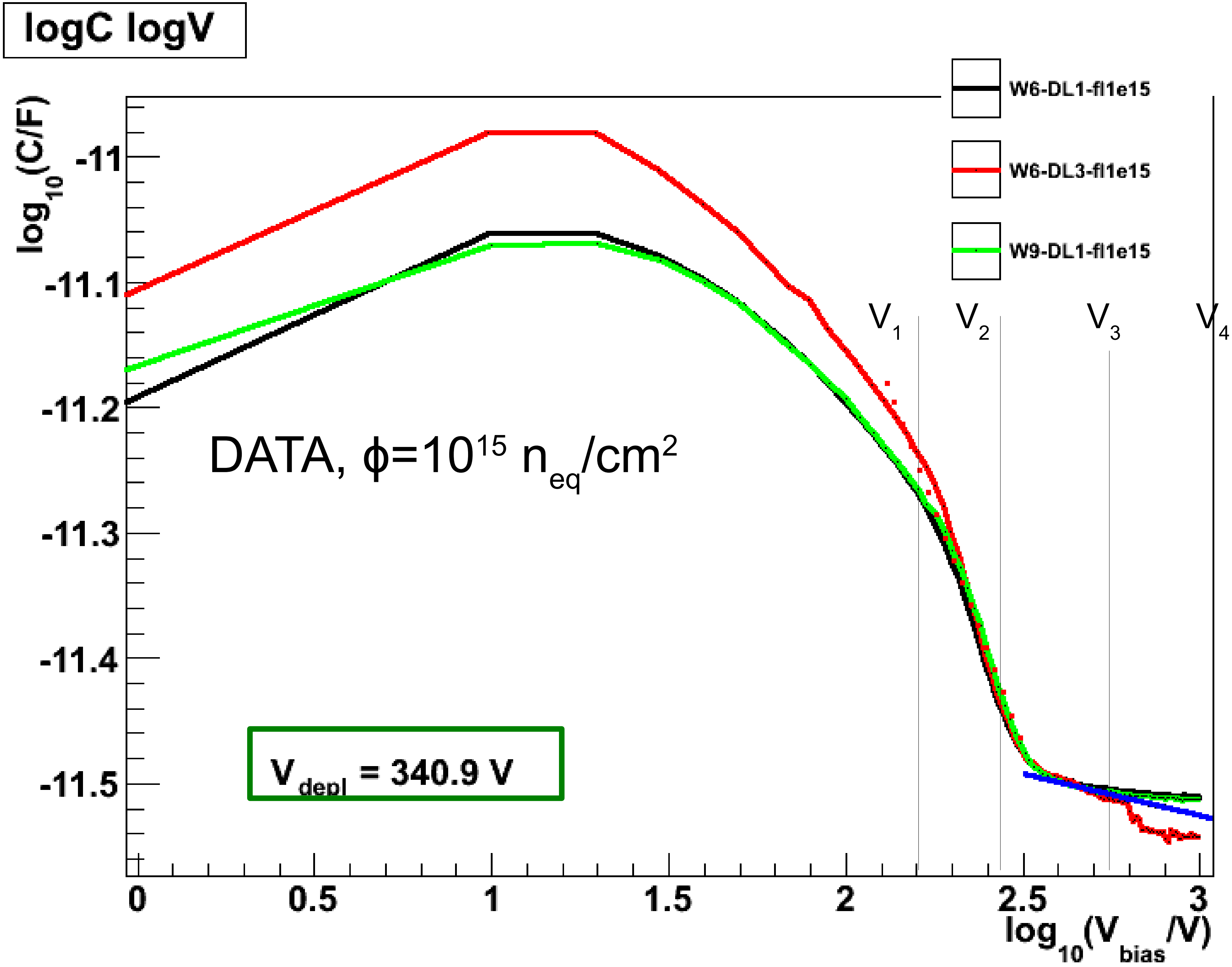
V = 600V, $\phi=10^{15}\ n_{eq}/cm^2$



Simulated depleted sensor

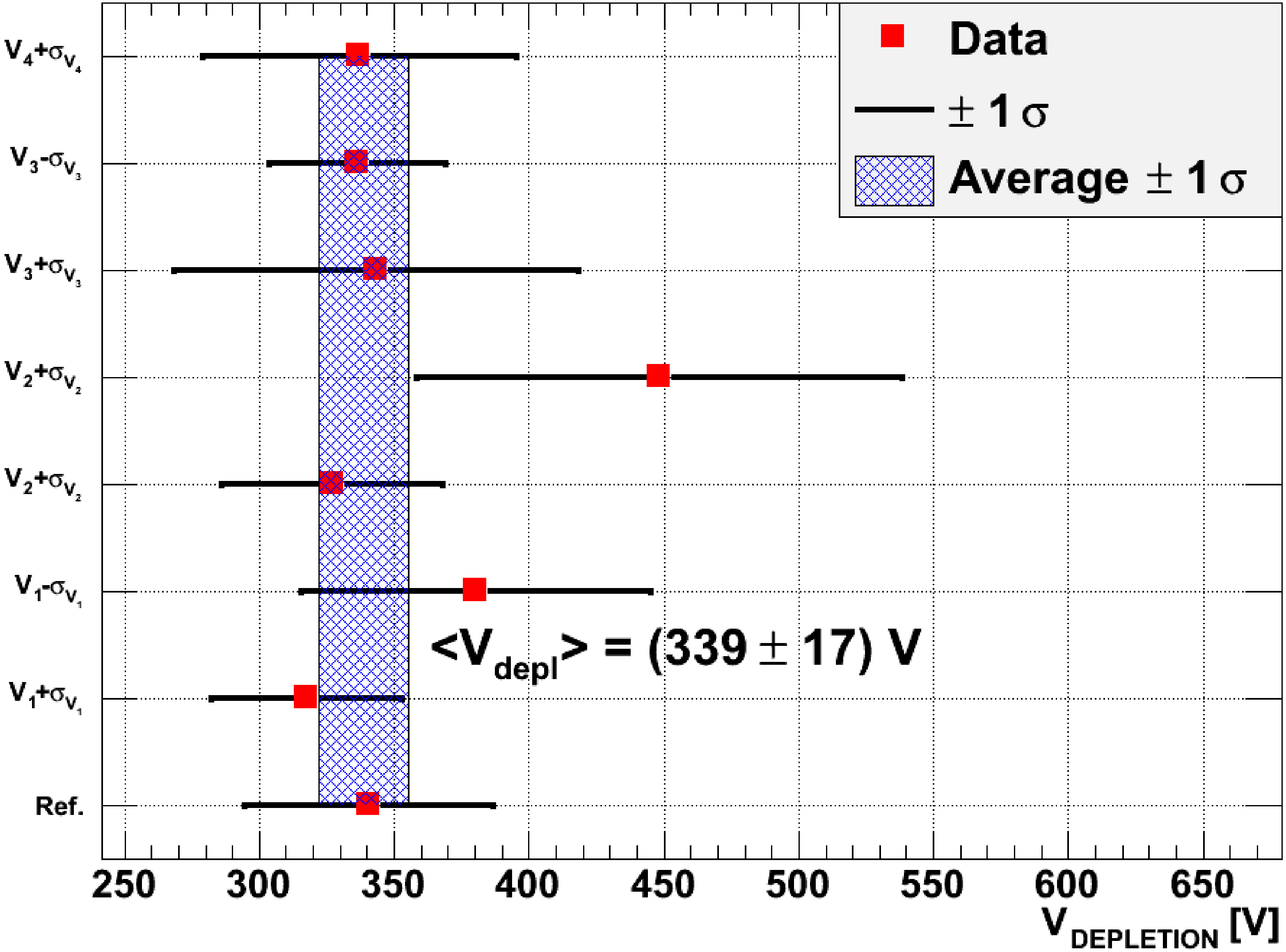


Results for depletion voltage



Depletion voltage: data

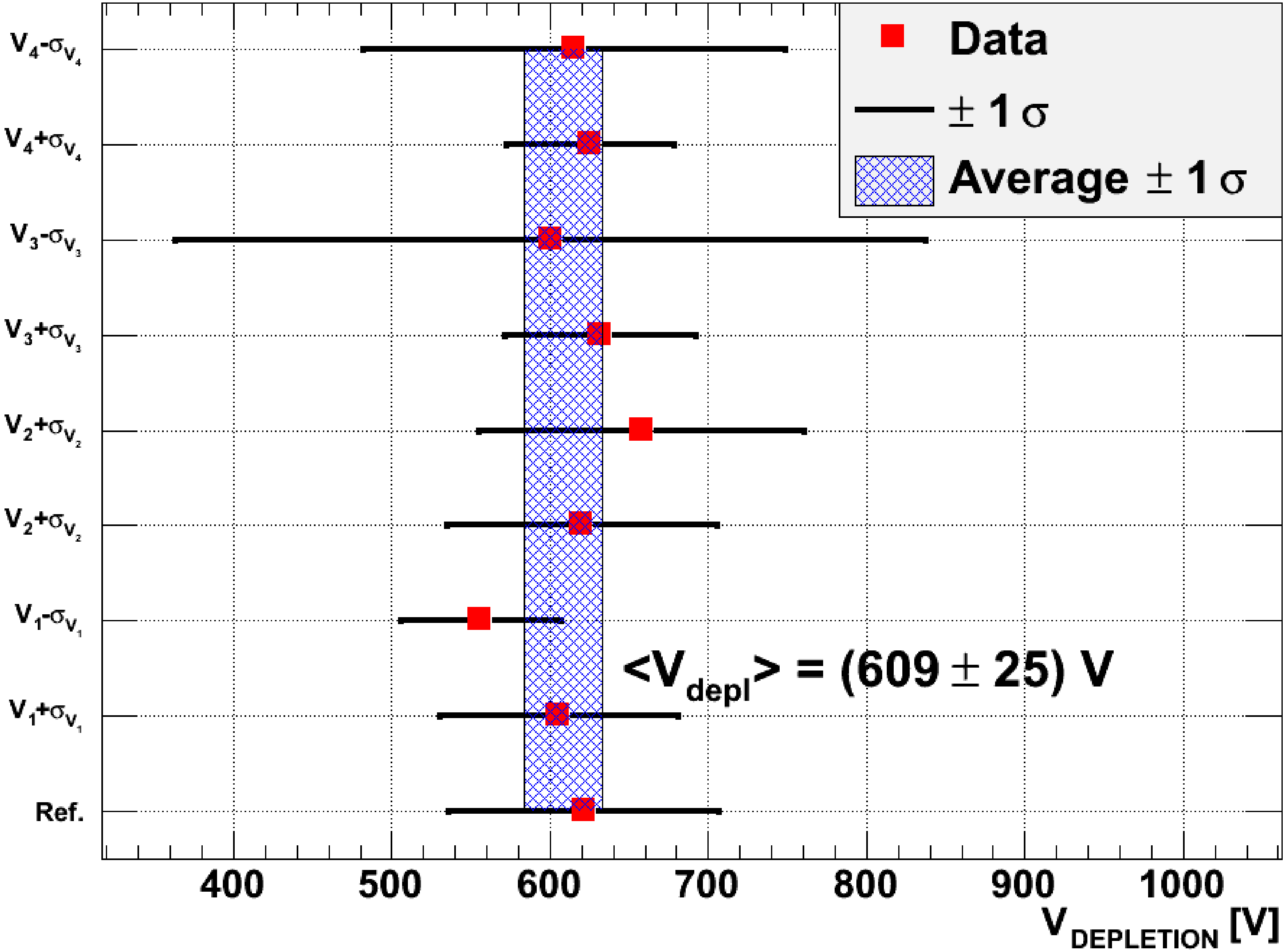
DATA, $\phi=10^{15}\ n_{eq}/cm^2$



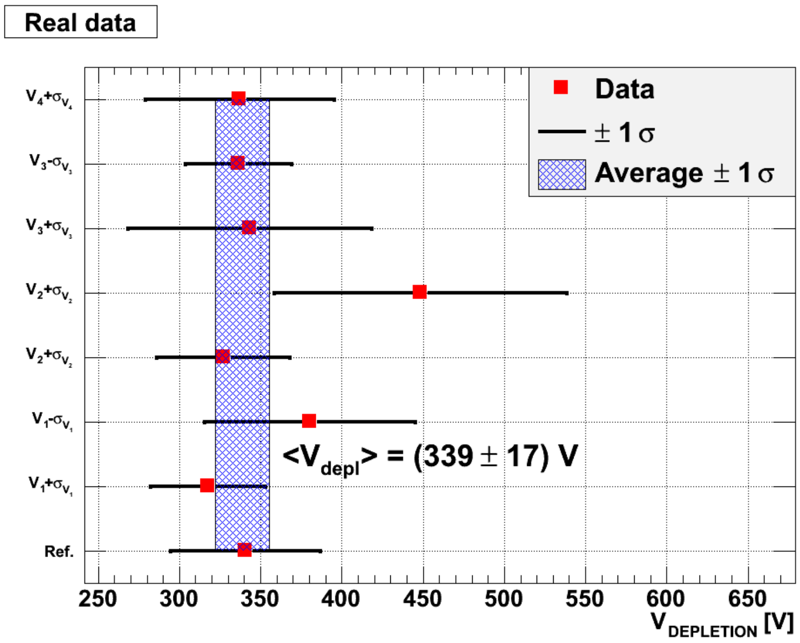
$\langle V_{depl}\rangle = (339 \pm 17)$ V

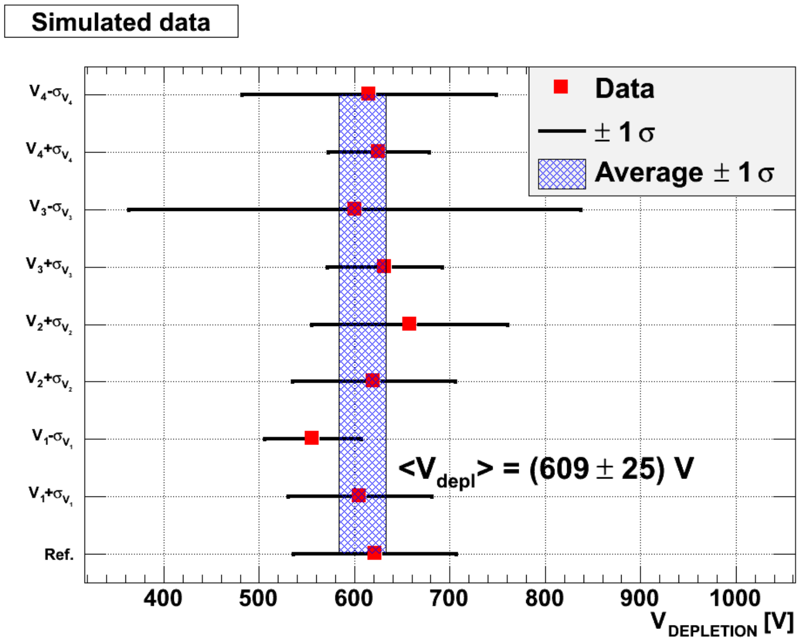
Depletion voltage: simulations

SIMULATION, $\phi=10^{15}\ n_{eq}/cm^2$



Depletion voltage: comparison

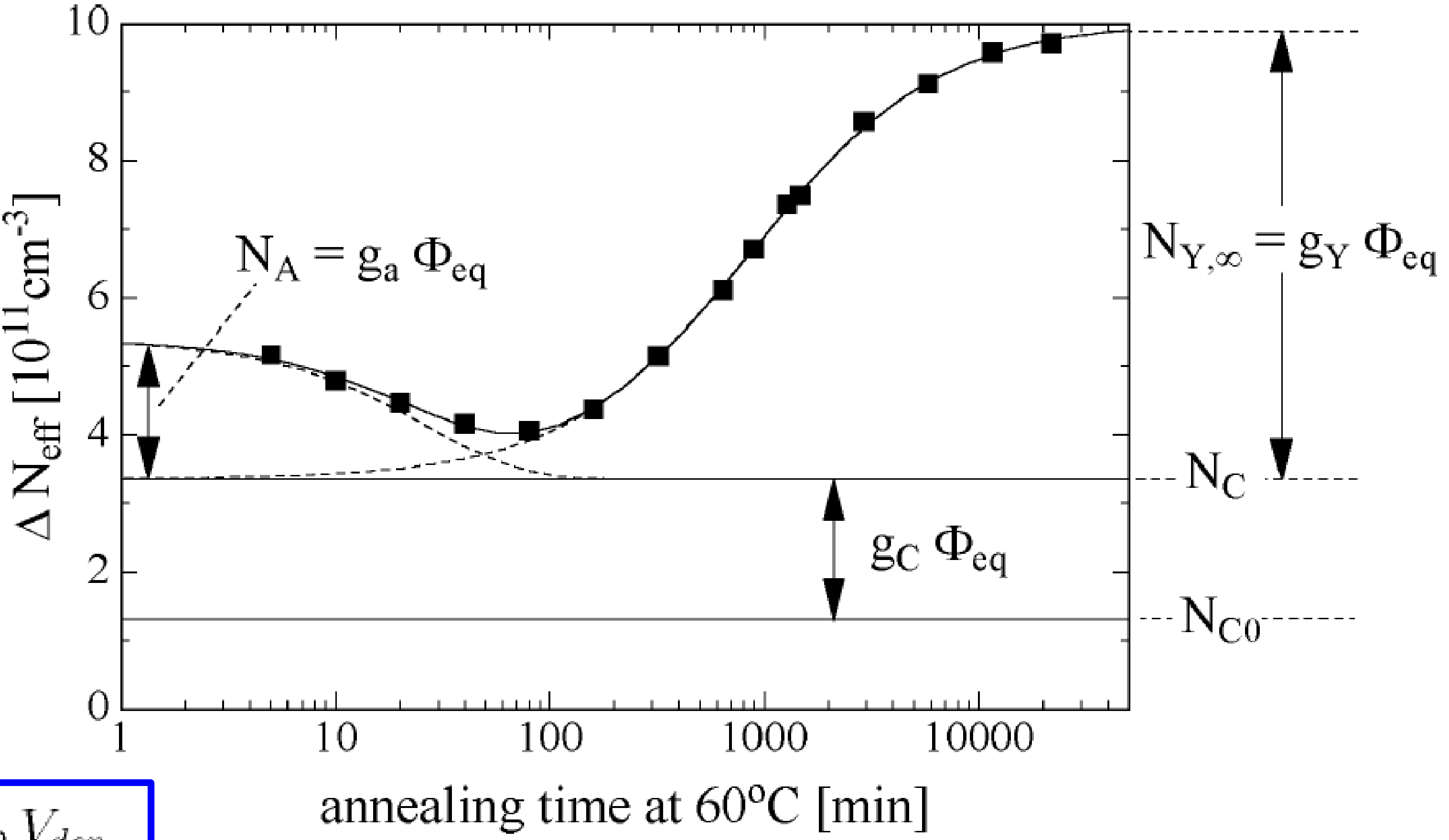




- Why the depletion voltage looks so different?
- Do you remember annealing?
- We have annealed real diodes... but for simulation?
- We have to correct for annealing the simulations!

Annealing

- Annealing in oven is performed to bring the radiation induced change in effective doping concentration to its minimum



(3)

$$|N_{eff}| = \frac{2\epsilon\epsilon_0}{q_0}\frac{V_{dep}}{d^2}$$

Annealing correction

- Two components to be taken into account:

1) Beneficial annealing

2) Reverse annealing → Very important!!!

- Systematic effects taken into account
- Result: $A_{anneal} = (55 \pm 20)\%$
  - Dominant contribution: reverse annealing

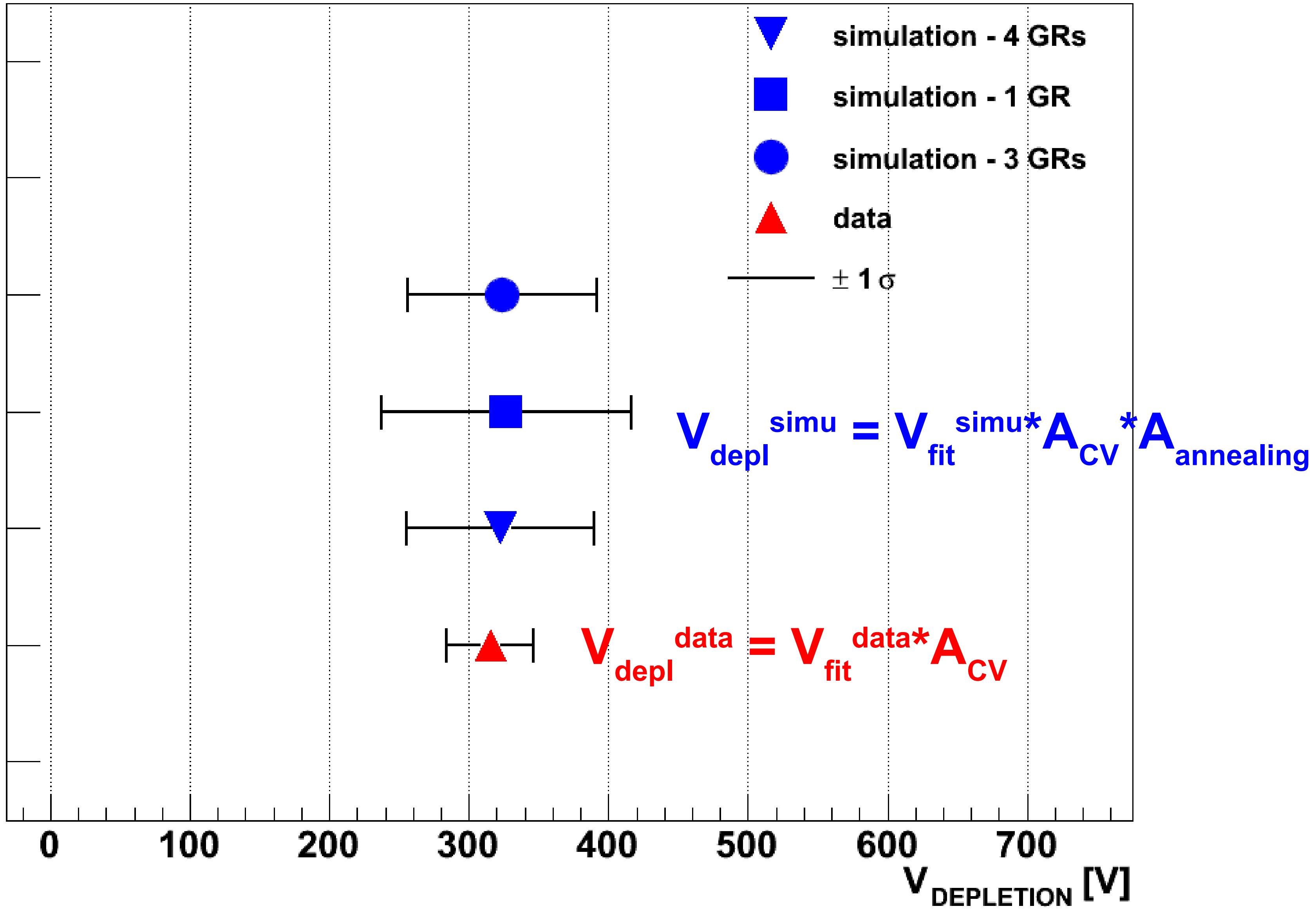
Extra correction

- The measured depletion voltage depends on both the frequency and temperature of CV measurement
- Both to data and simulations scaled to t = 20 °C and v=10 kHz

$$U_d(10\ \mathrm{kHz}, 20^\circ\mathrm{C}) = U_d(f, T) \times \frac{1 + A e^{E_a/0.345\ \mathrm{eV}}}{1 + A e^{(E_a/0.02354\ \mathrm{eV})((T-273{,}15\ \mathrm{K})/T)}} \times \frac{1+\delta}{1+\delta \log_{10}(f/1\ \mathrm{kHz})}. \qquad (4)$$

- $A_{CV}^{data} = (0.93 \pm 0.05)$
- $A_{CV}^{simulation} = (0.96 \pm 0.01)$

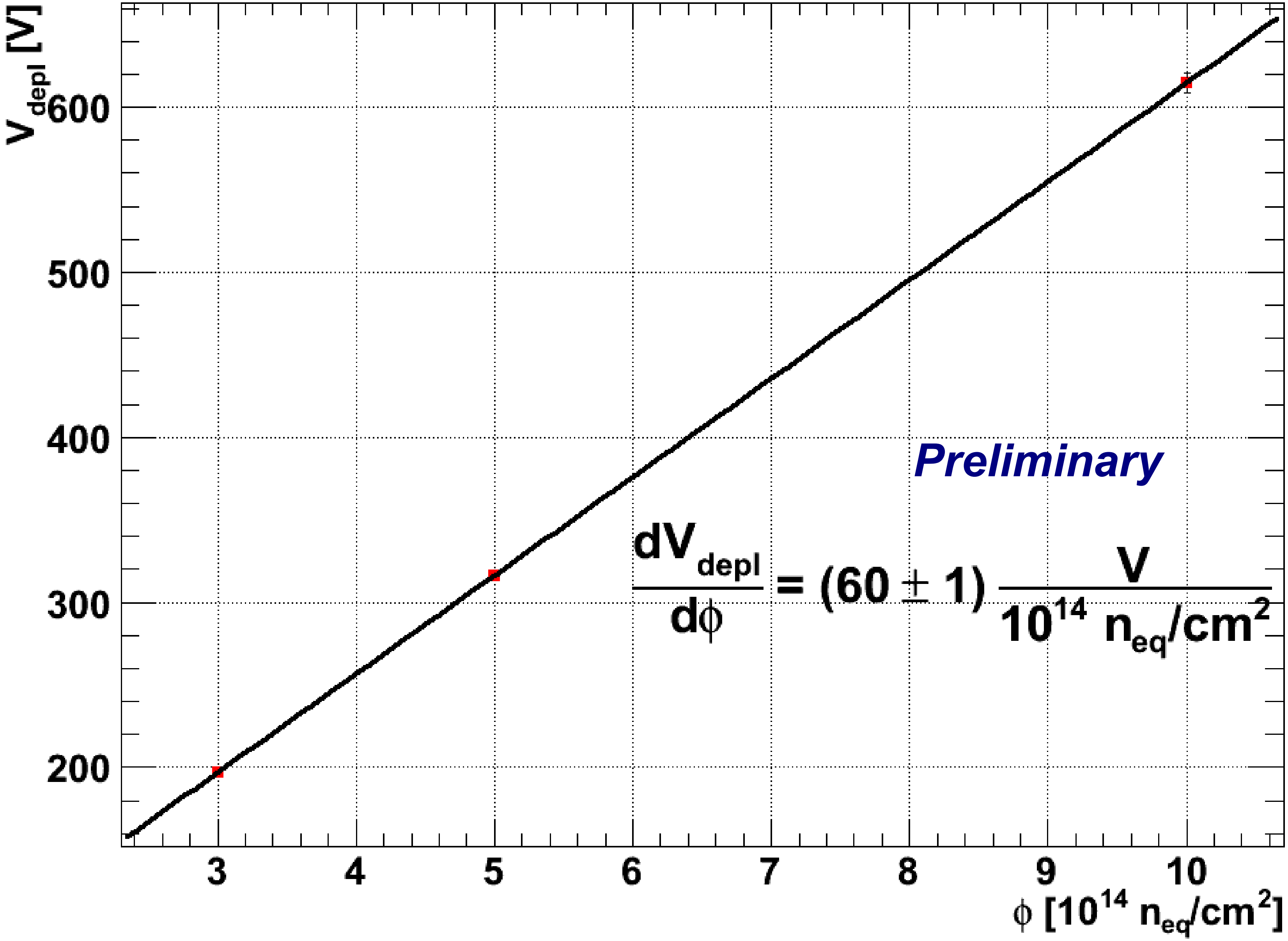
Corrected depletion voltage



$$V_{depl}^{simu} = V_{fit}^{simu} * A_{CV} * A_{annealing}$$

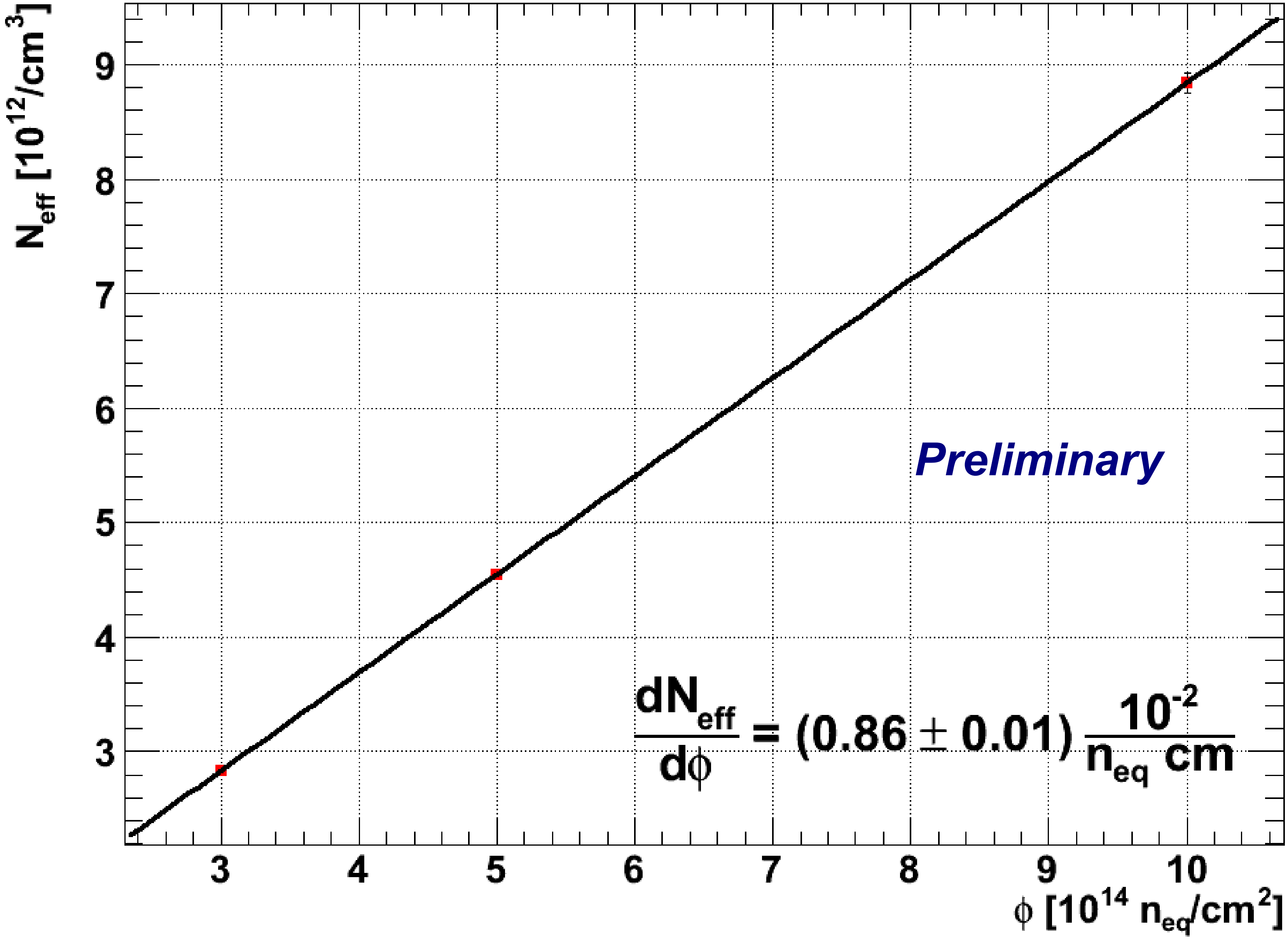
$$V_{depl}^{data} = V_{fit}^{data} * A_{CV}$$

V_{depl} VS Φ



$$\frac{dV_{depl}}{d\phi} = (60 \pm 1)\,\frac{V}{10^{14}\ n_{eq}/cm^2}$$

V_{depl} VS N_{eff}

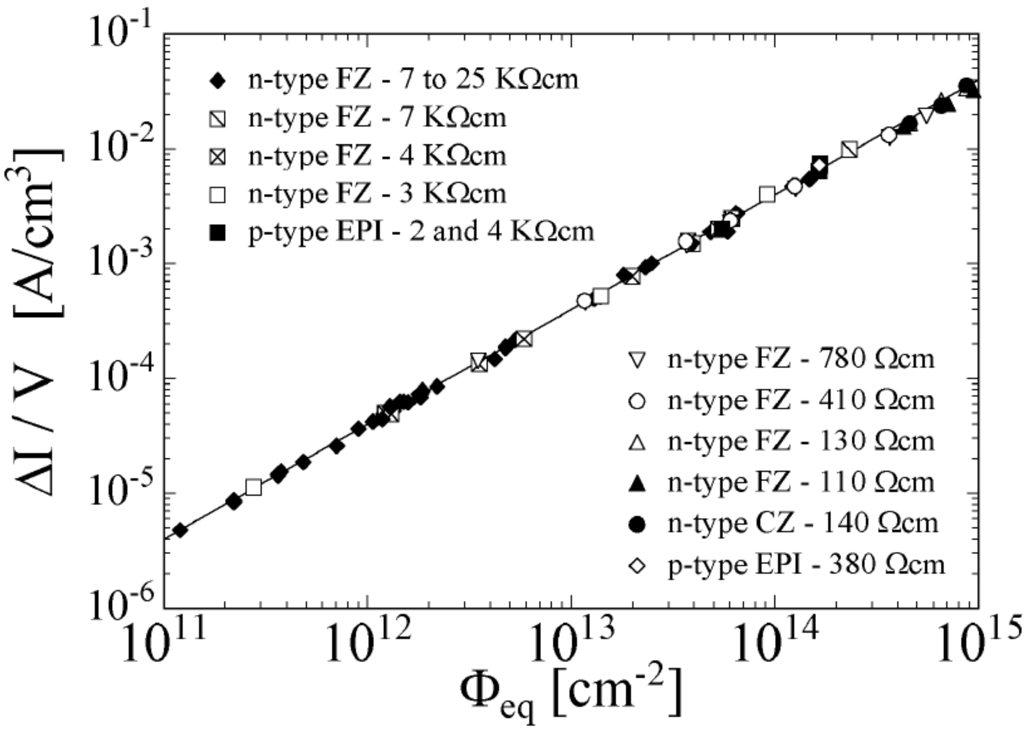


$$\frac{dN_{eff}}{d\phi} = (0.86 \pm 0.01)\,\frac{10^{-2}}{n_{eq}\ \mathrm{cm}}$$

Annealing correction for current

$$\alpha(t,T_a) = \frac{\Delta I(t,T_a)}{\Phi_{eq} V} = \alpha_\infty \sum_i \frac{b_i}{b_\infty} \exp\left(-\frac{t}{\tau_i(T_a)}\right) \qquad (3)$$

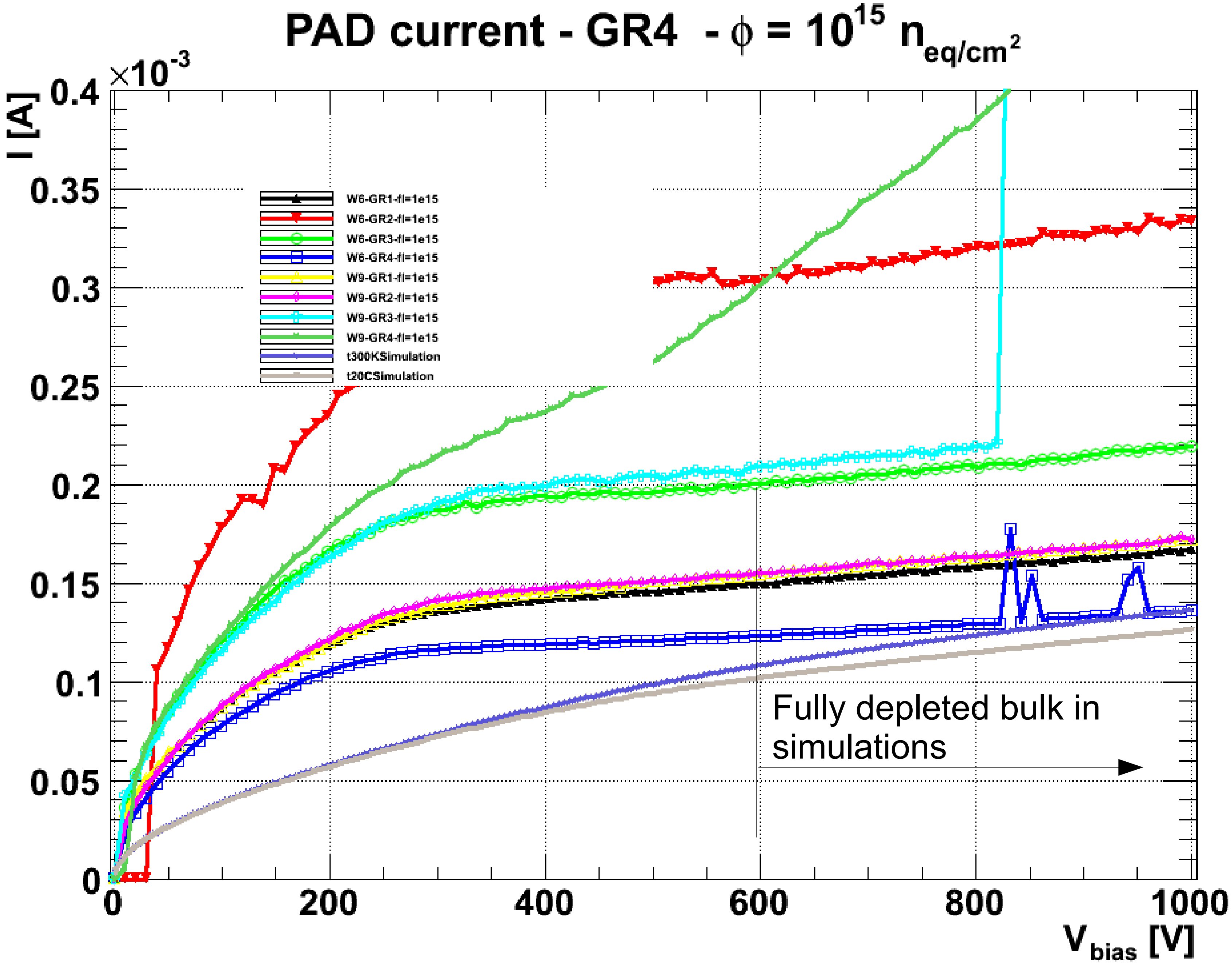
term	$i=1$	$i=2$	$i=3$	$i=4$	$i=5$	$i=\infty$
τ_i [min]	1.78×10^1	1.19×10^2	1.09×10^3	1.48×10^4	8.92×10^4	∞
b_i	0.156	0.116	0.131	0.201	0.093	0.303



Correction to bulk current:

$A_{bulk}^{IV} = (68 \pm 1)\%$

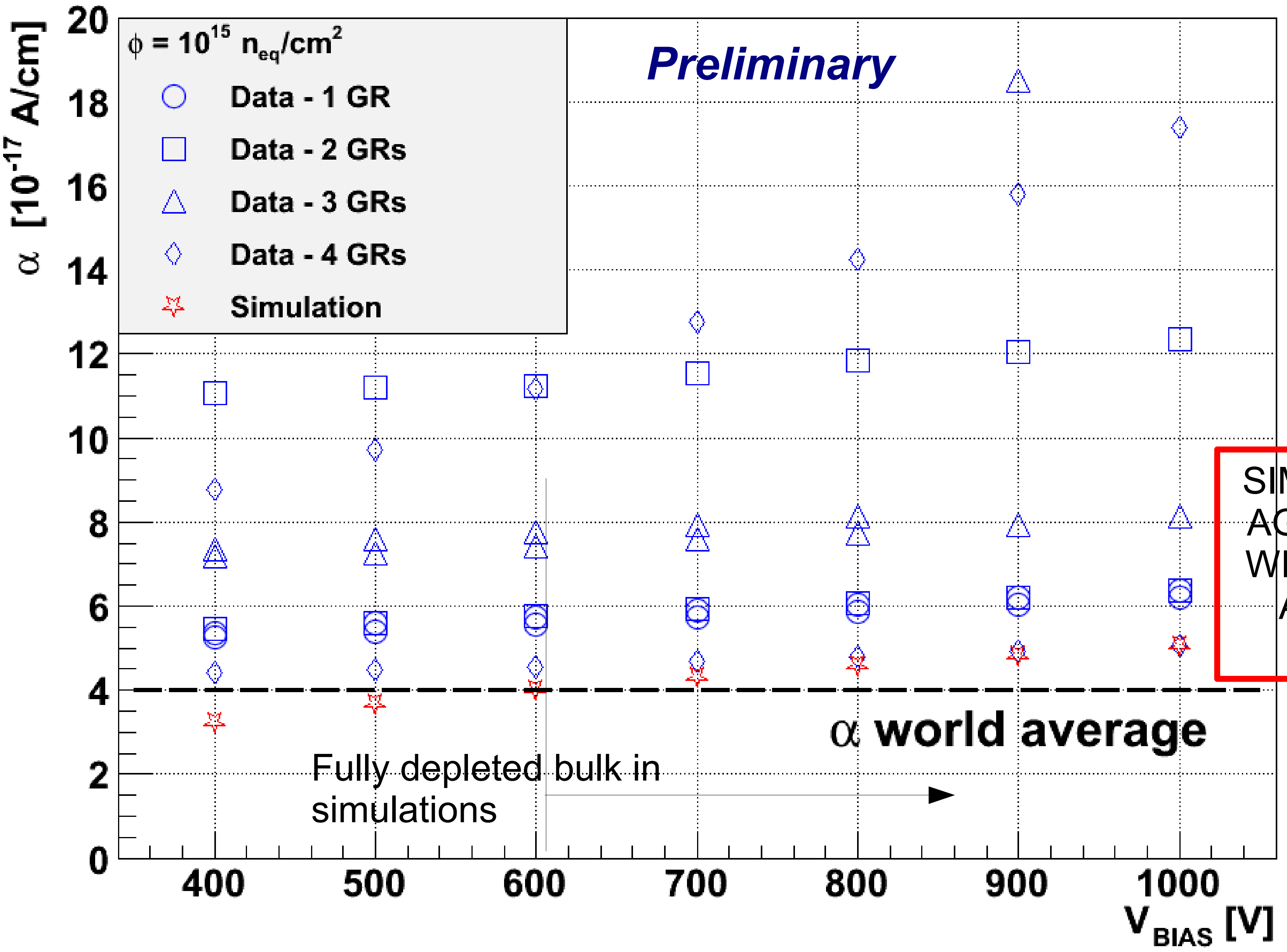
Bulk leakage current



PAD current - GR4 - $\phi = 10^{15}$ n_{eq/cm^2}

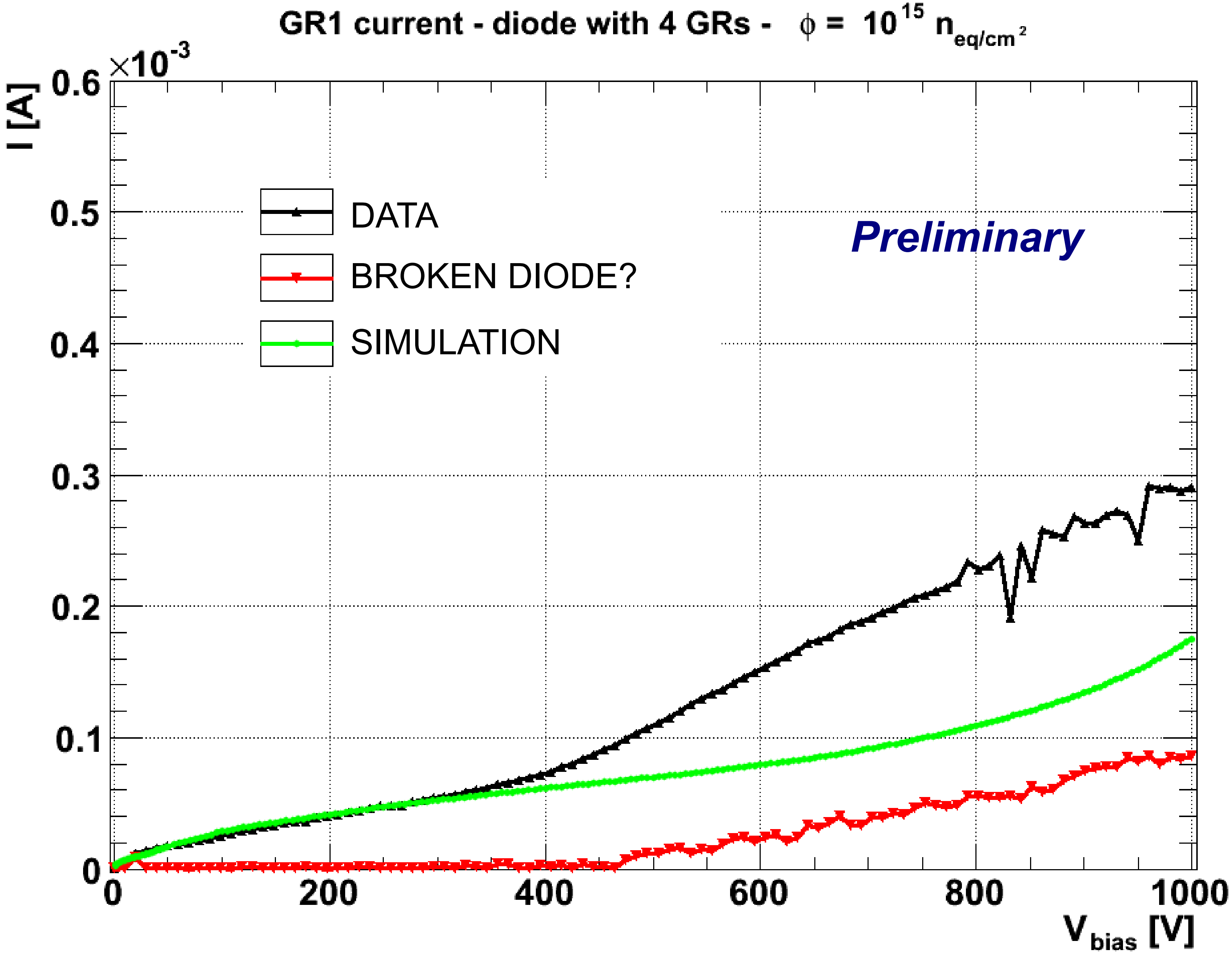
Fully depleted bulk in simulations

Current increase rate: α

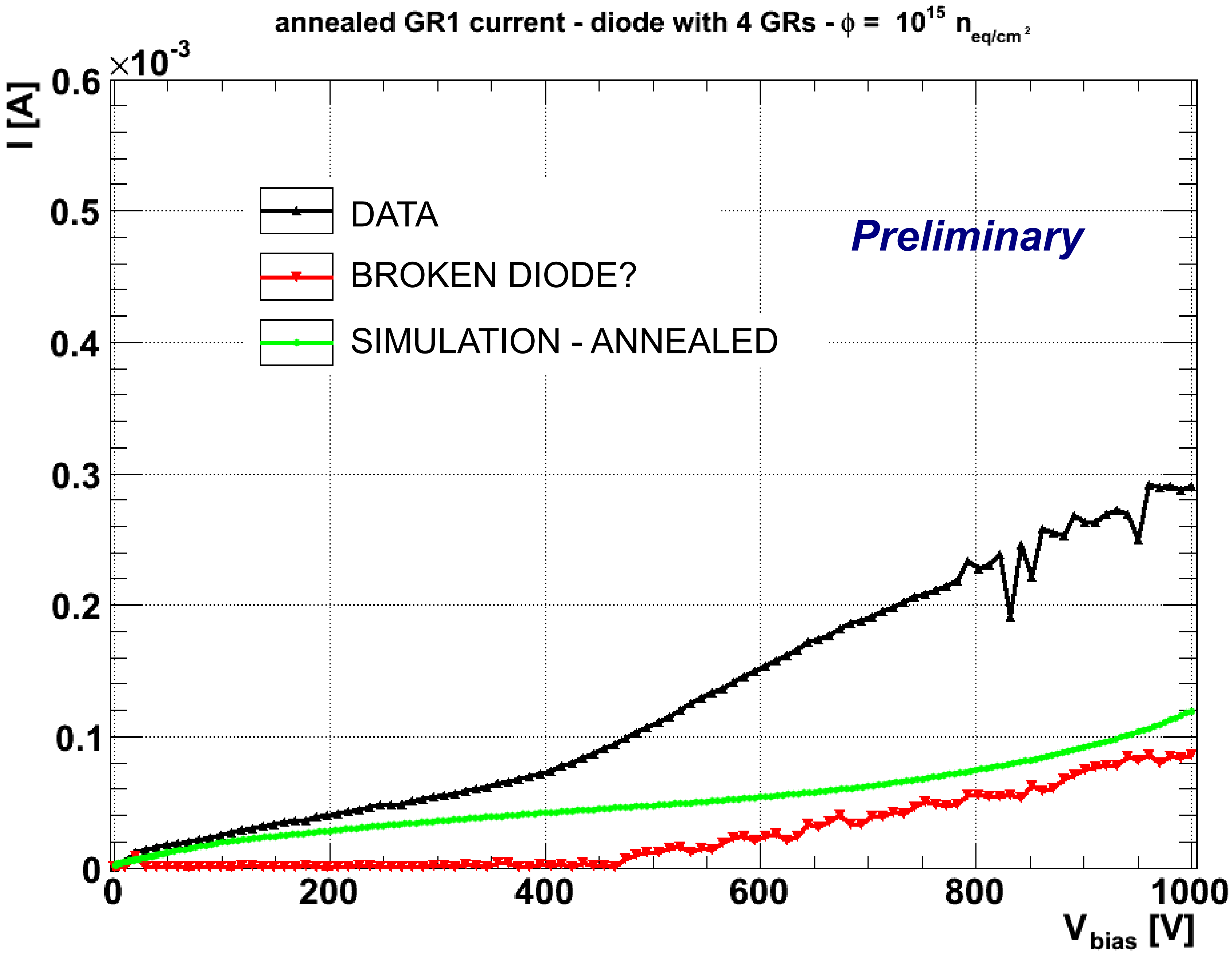


SIMULATIONS AGREE WELL WITH WORLD AVERAGE VALUE

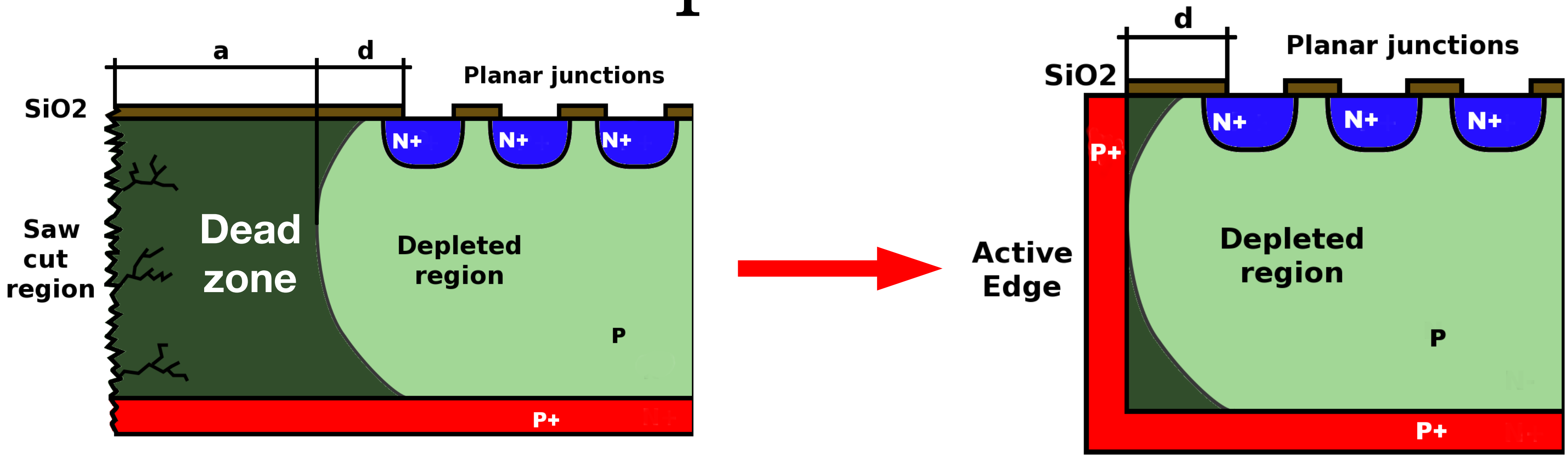
GR1 current


GR1 current - diode with 4 GRs - ϕ = 10^{15} n_{eq/cm^2}
I [A]
$\times 10^{-3}$
0.6
0.5
0.4
0.3
0.2
0.1
0
0
200
400
600
800
1000
V_{bias} [V]
DATA
BROKEN DIODE?
SIMULATION
Preliminary

GR1 current


annealed GR1 current - diode with 4 GRs - ϕ = 10^{15} n_{eq/cm^2}
$\times10^{-3}$
I [A]
0.6
0.5
0.4
0.3
0.2
0.1
0
0
200
400
600
800
1000
V_{bias} [V]
DATA
BROKEN DIODE?
SIMULATION - ANNEALED
Preliminary

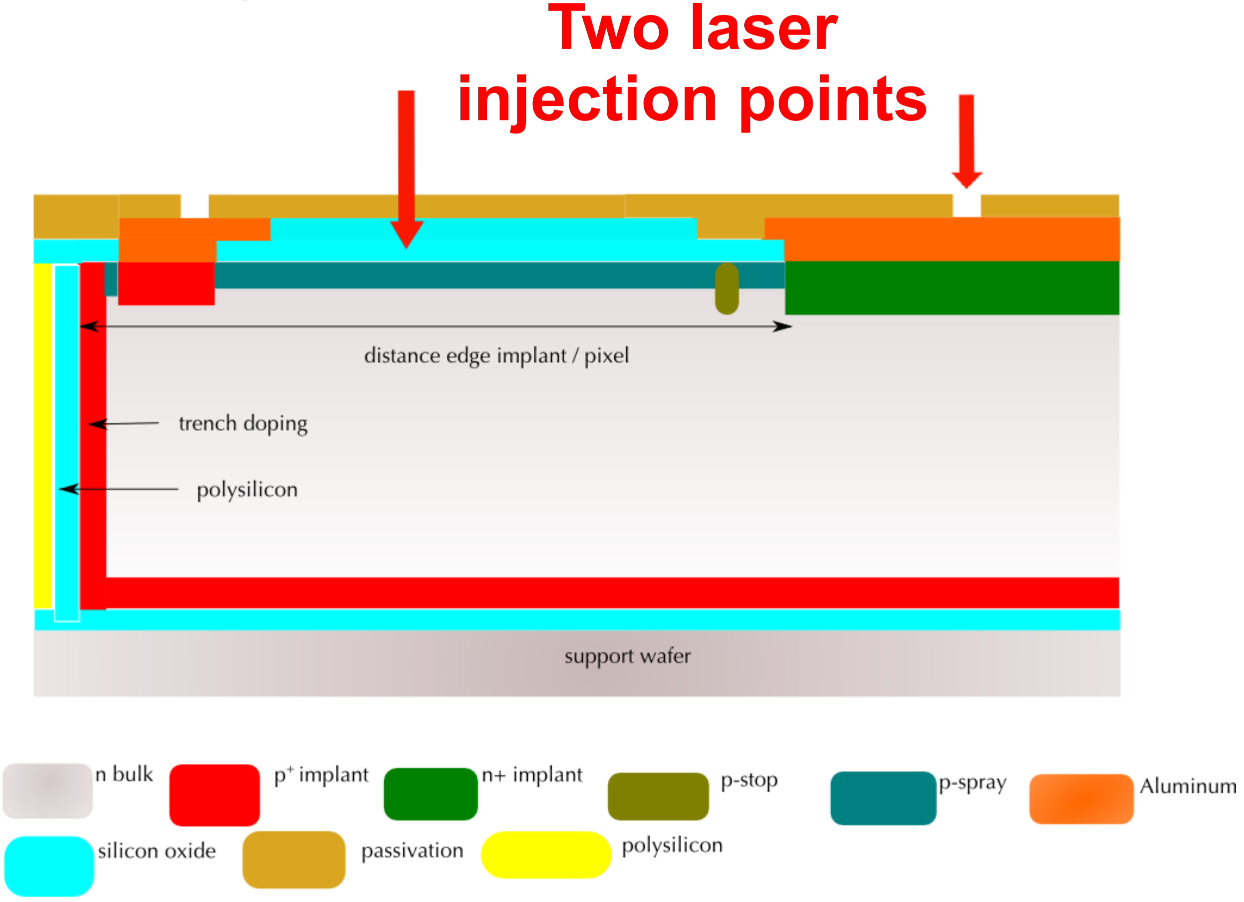
Predictions: Active edge production



- Joint project FBK-LPNHE
- Goal: make the border a damage free ohmic contact
- How: DRIE as for 3D process
- Trench doped by diffusion

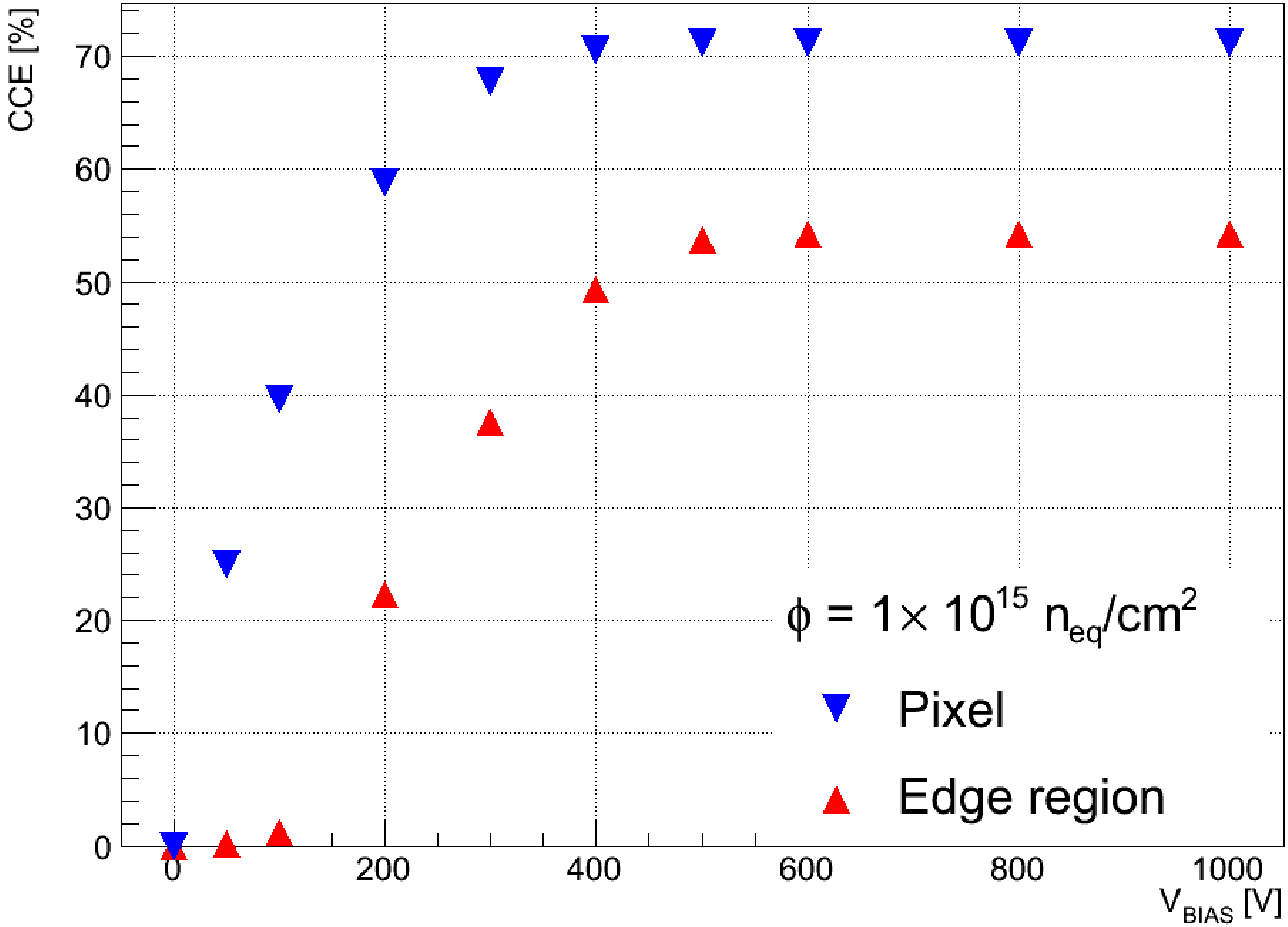
CCE predictions

- We can now use this sets of models for “active edge” detectors
- We can predict the behaviour of these detectors in terms of Charge Collection Efficiency after irradiation

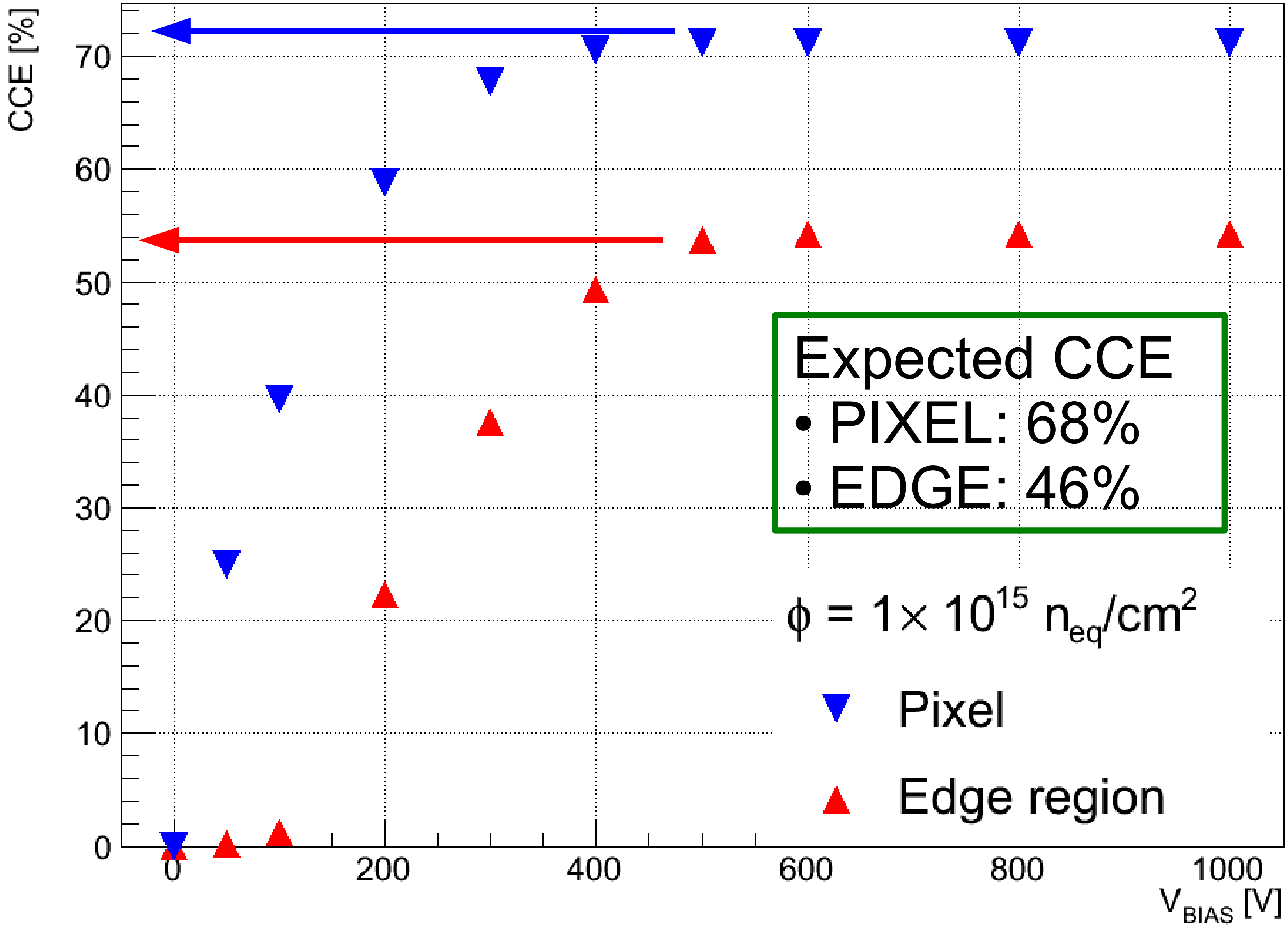


Two laser injection points

CCE in active edge detector



CCE in active edge detector



Expected CCE
- PIXEL: 68%
- EDGE: 46%

(5)

Conclusions & Outlook

- Good agreement between data and simulations for irradiated p-type sensors
- Need to understand better surface effects
  - ➔ In contact with M. Povoli in Trento and the Hamburg group
- Working on higher fluences
  - ➔ Waiting for bug fix from Silvaco Engineer
  - ➔ Need larger bias range for bias voltage
- Need to measure V_{GR} for irradiated diodes

Acknowledgements

- Maurice Glaser for the irradiations
- Michael Moll and Nicola Pacifico for letting me use their setup for measurements, and useful discussions
- Anna Macchiolo for the sensors and their related details
- Eckhart Fretwurst and Jiaguo Zhang for useful discussion on irradiation induced surface defects

References

(1) Radiation induced bulk damage mode by Pennicard et al.

(2) J. Zhang et al., Study of X-ray radiation damage in silicon sensors

(3) Micheal Moll's Ph.D. thesis

(4) D. Campbell, Frequency and temperature dependence of the depletion voltage from CV measurements for irradiated Si detectors

(5) G. Kramberger, Determination of effective trapping times for electrons and holes in irradiated silicons

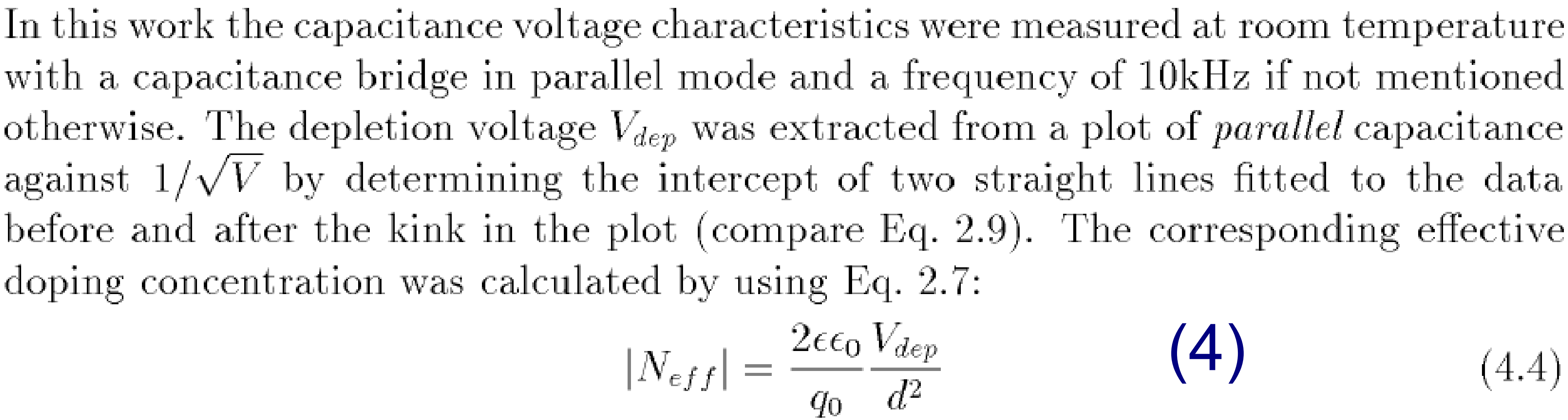
Backup

Summary

wafer	Vdep (V)	Neff (10^11cm^-3)	I @ Vdep + 50 V (nA)	taug (10^-5 s)
1	24	5.4	56	3.4
2	24	5.7	62	3.1
6	25	5.7	33	5.8
7	23	5.5	46	4.3
8	24	5.6	67	4.6
9	24	5.5	40	2.9
13	27	5.7	50	3.9
14	25	5.6	40	4.9

- Not be irradiated

N_{eff} & U_{dep}

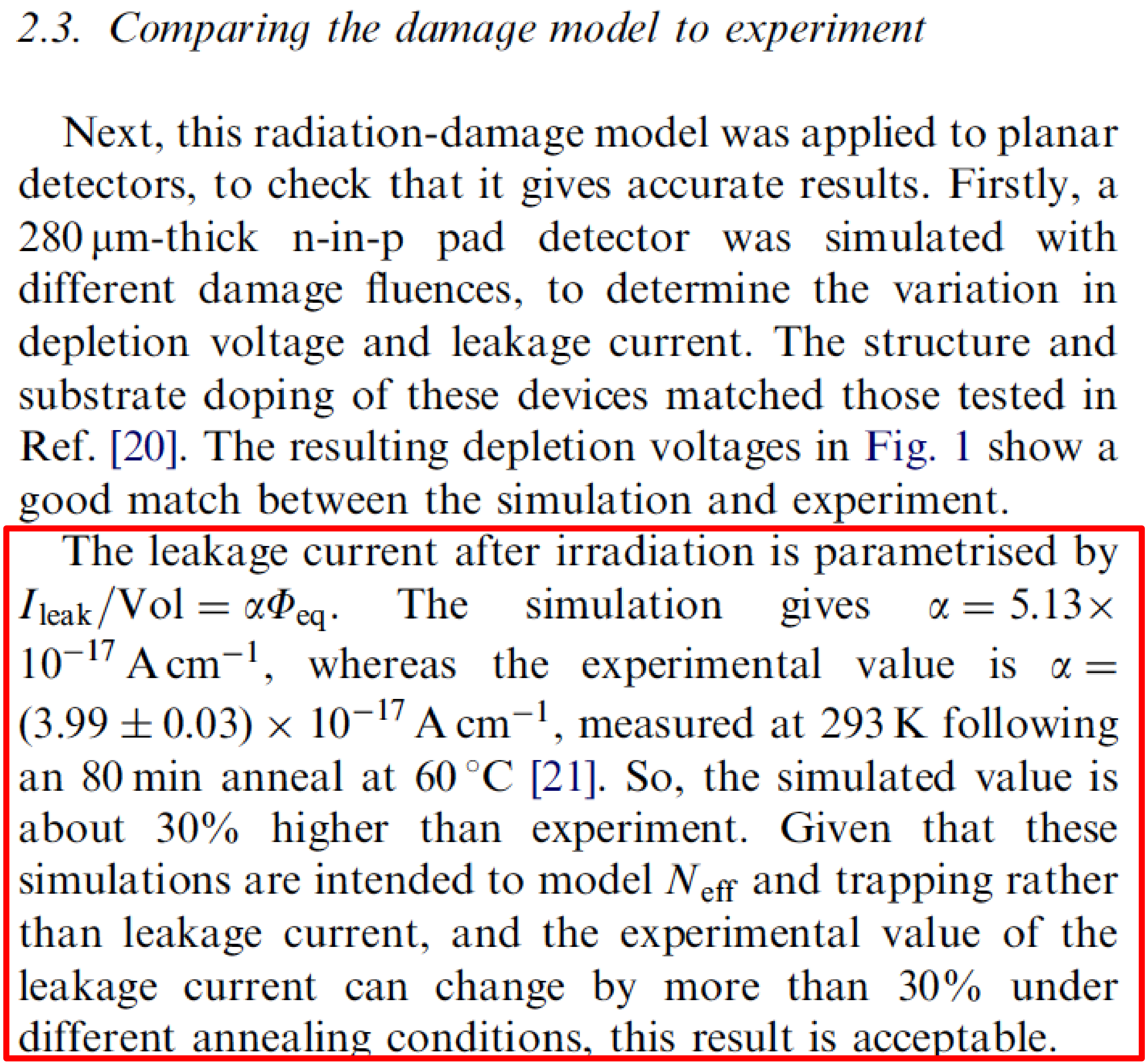


In this work the capacitance voltage characteristics were measured at room temperature with a capacitance bridge in parallel mode and a frequency of 10kHz if not mentioned otherwise. The depletion voltage V_{dep} was extracted from a plot of *parallel* capacitance against $1/\sqrt{V}$ by determining the intercept of two straight lines fitted to the data before and after the kink in the plot (compare Eq. 2.9). The corresponding effective doping concentration was calculated by using Eq. 2.7:

$$|N_{eff}| = \frac{2\epsilon\epsilon_0}{q_0}\frac{V_{dep}}{d^2} \qquad (4.4)$$

(4)

Pennicard *et al.* simulations



2.3. *Comparing the damage model to experiment*

Next, this radiation-damage model was applied to planar detectors, to check that it gives accurate results. Firstly, a 280 μm-thick n-in-p pad detector was simulated with different damage fluences, to determine the variation in depletion voltage and leakage current. The structure and substrate doping of these devices matched those tested in Ref. [20]. The resulting depletion voltages in Fig. 1 show a good match between the simulation and experiment.

The leakage current after irradiation is parametrised by $I_{\mathrm{leak}}/\mathrm{Vol} = \alpha\Phi_{\mathrm{eq}}$. The simulation gives $\alpha = 5.13 \times 10^{-17}\,\mathrm{A\,cm^{-1}}$, whereas the experimental value is $\alpha = (3.99 \pm 0.03) \times 10^{-17}\,\mathrm{A\,cm^{-1}}$, measured at 293 K following an 80 min anneal at 60 °C [21]. So, the simulated value is about 30% higher than experiment. Given that these simulations are intended to model N_{eff} and trapping rather than leakage current, and the experimental value of the leakage current can change by more than 30% under different annealing conditions, this result is acceptable.

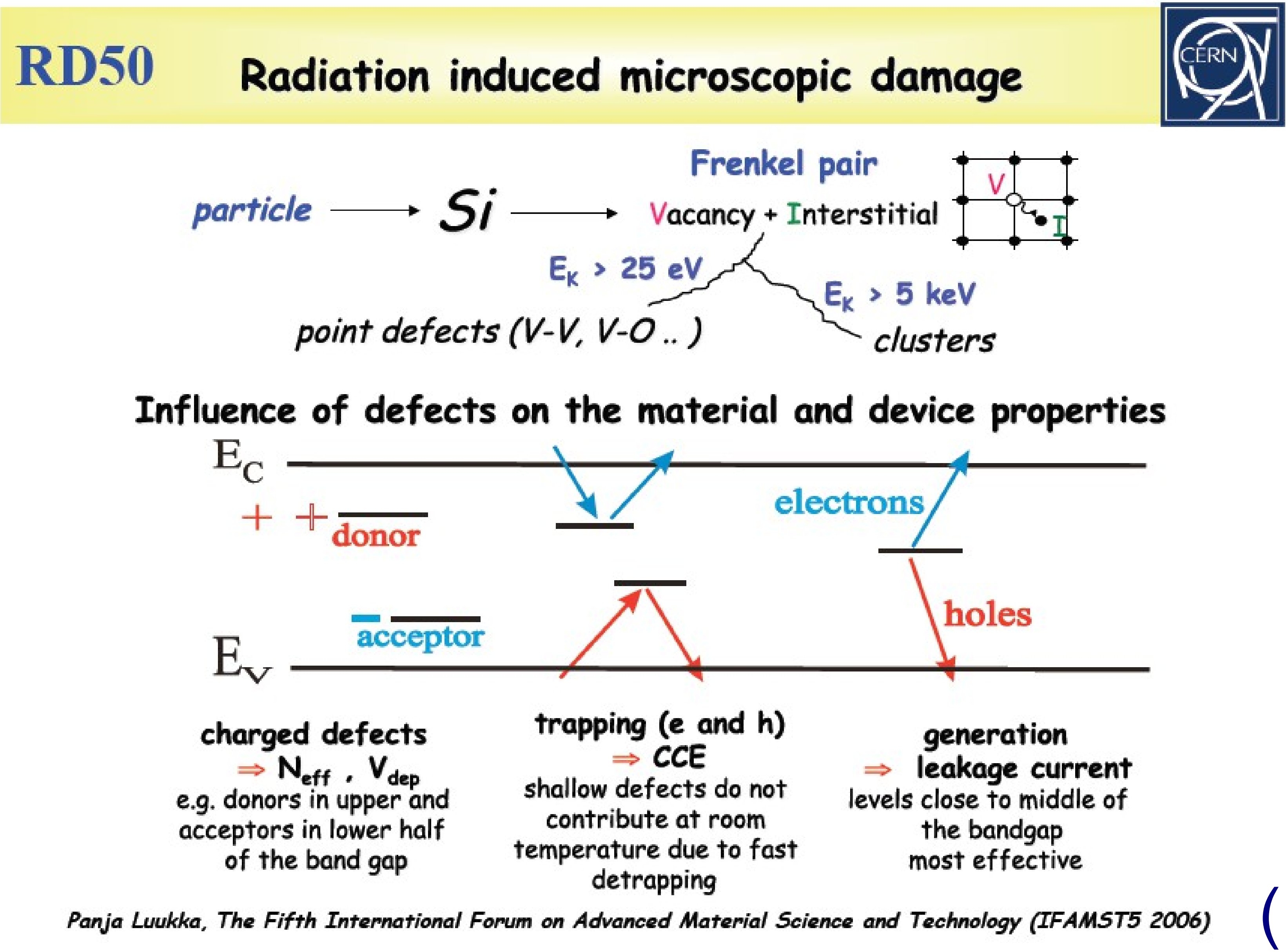
(2)

Trapping and CCE

- Trapping time: $\frac{1}{\tau_{\mathrm{eff}_{e,h}}} = \beta_{e,h} \Phi_{eq}$
- Linear coefficient for electrons: $\beta_e = (4.2 \pm 0.3) \times 10^{-16}\ \mathrm{cm}^2/\mathrm{ns}$
- For uniform deposition across the bulk:

$$CCE = \frac{\lambda}{w}[1 - e^{-\frac{\lambda}{w}}]$$

- With $\lambda = v_{sat} * \tau_{eff}$ the charge trapping distance and *w* the bulk thickness



RD50 Radiation induced microscopic damage

particle → Si → Frenkel pair

Vacancy + Interstitial

V

I

$E_K > 25$ eV

$E_K > 5$ keV

point defects (V-V, V-O ..)

clusters

Influence of defects on the material and device properties

E_C

E_V

donor

acceptor

electrons

holes

charged defects
⇒ N_{eff} , V_{dep}
e.g. donors in upper and acceptors in lower half of the band gap

trapping (e and h)
⇒ CCE
shallow defects do not contribute at room temperature due to fast detrapping

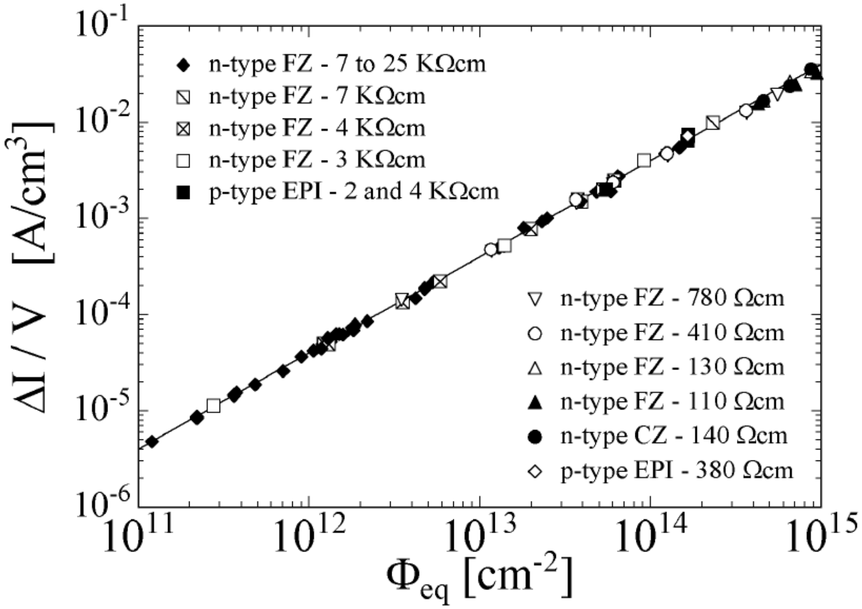
generation
⇒ leakage current
levels close to middle of the bandgap most effective

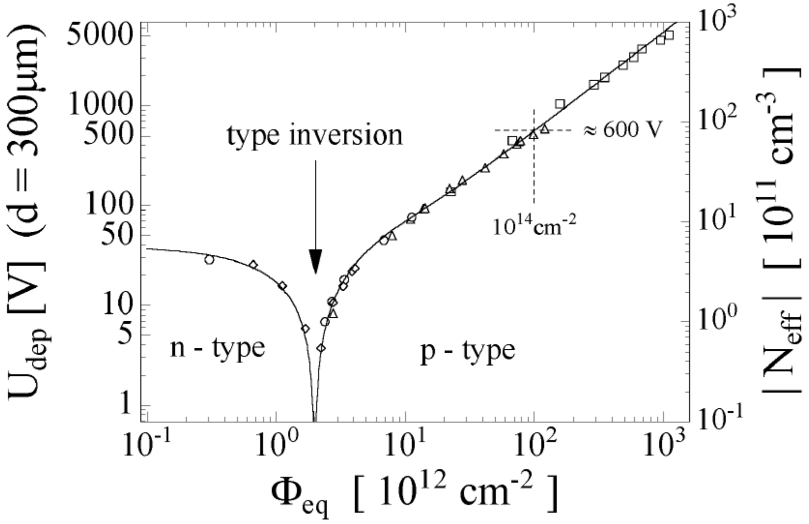
Panja Luukka, The Fifth International Forum on Advanced Material Science and Technology (IFAMST5 2006)

(1)

Observables and effects

- The leakage current increase is prop. to ϕ
- The U_{dep} increases is prop. to ϕ after type inversion
- The defects acts as trapping centers





(4)