HSTD 14

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Evaluation of dopant removal to design innovative LGADs: measurements and simulations

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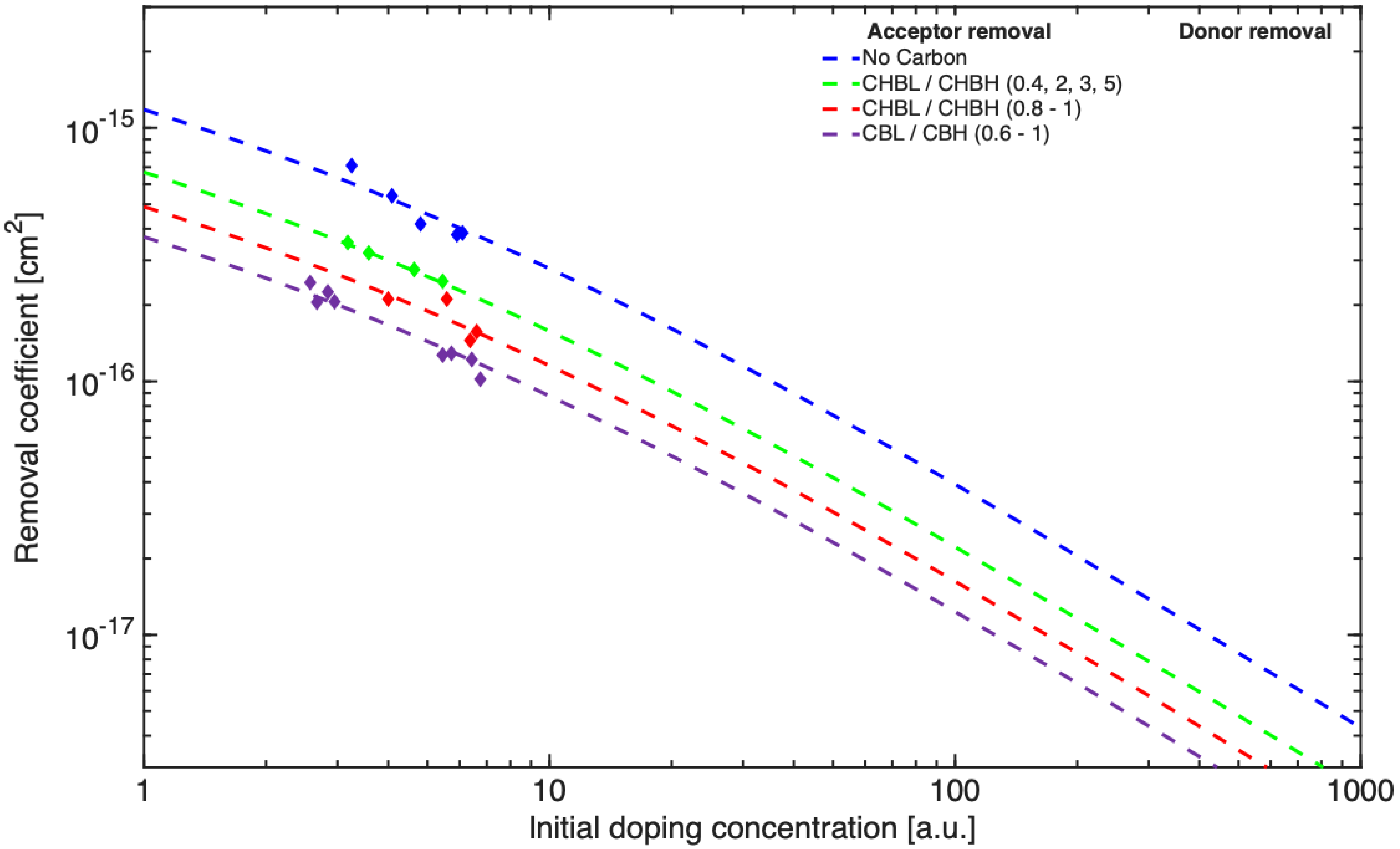
Defining the Challenge

Acceptor removal (→ lower gain → worse timing resolution) has been studied in detail for many years and is at the core of the LGADs' radiation hardness.



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$$N_{A,GL}(\Phi) = N_{A,GL}(0)e^{-c_A\Phi}$$

c_A from M. Ferrero et al., *An Introduction to Ultra-Fast Silicon Detectors (1st ed.)*, CRC Press (2021), doi:10.1201/9781003131946

Defining the Challenge

Donor removal is now becoming very interesting as it plays a crucial role in the functioning of **resistive LGADs** and compensated LGADs.

Donor removal = change in sheet resistance → could impact charge sharing and degrade spatial resolution.

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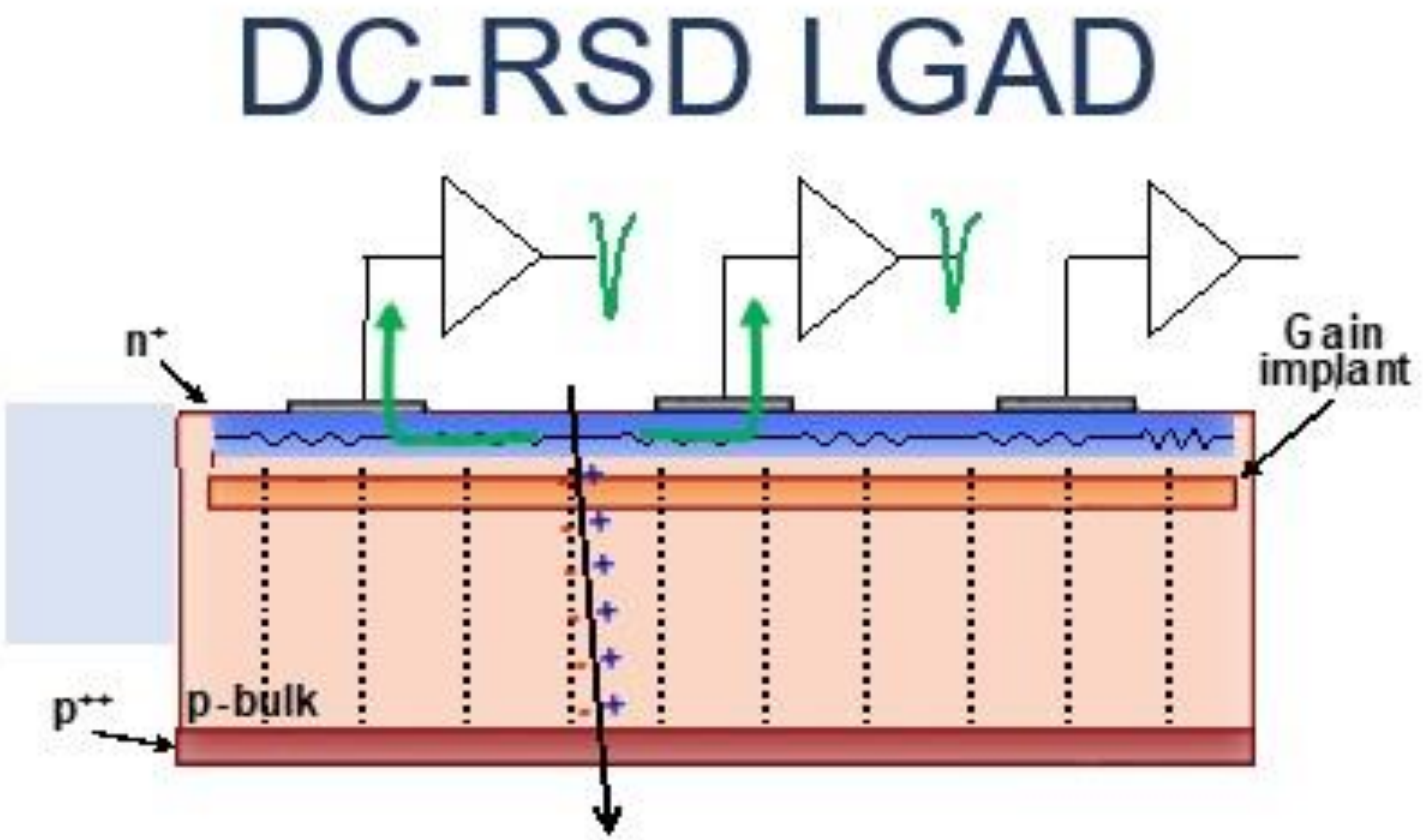
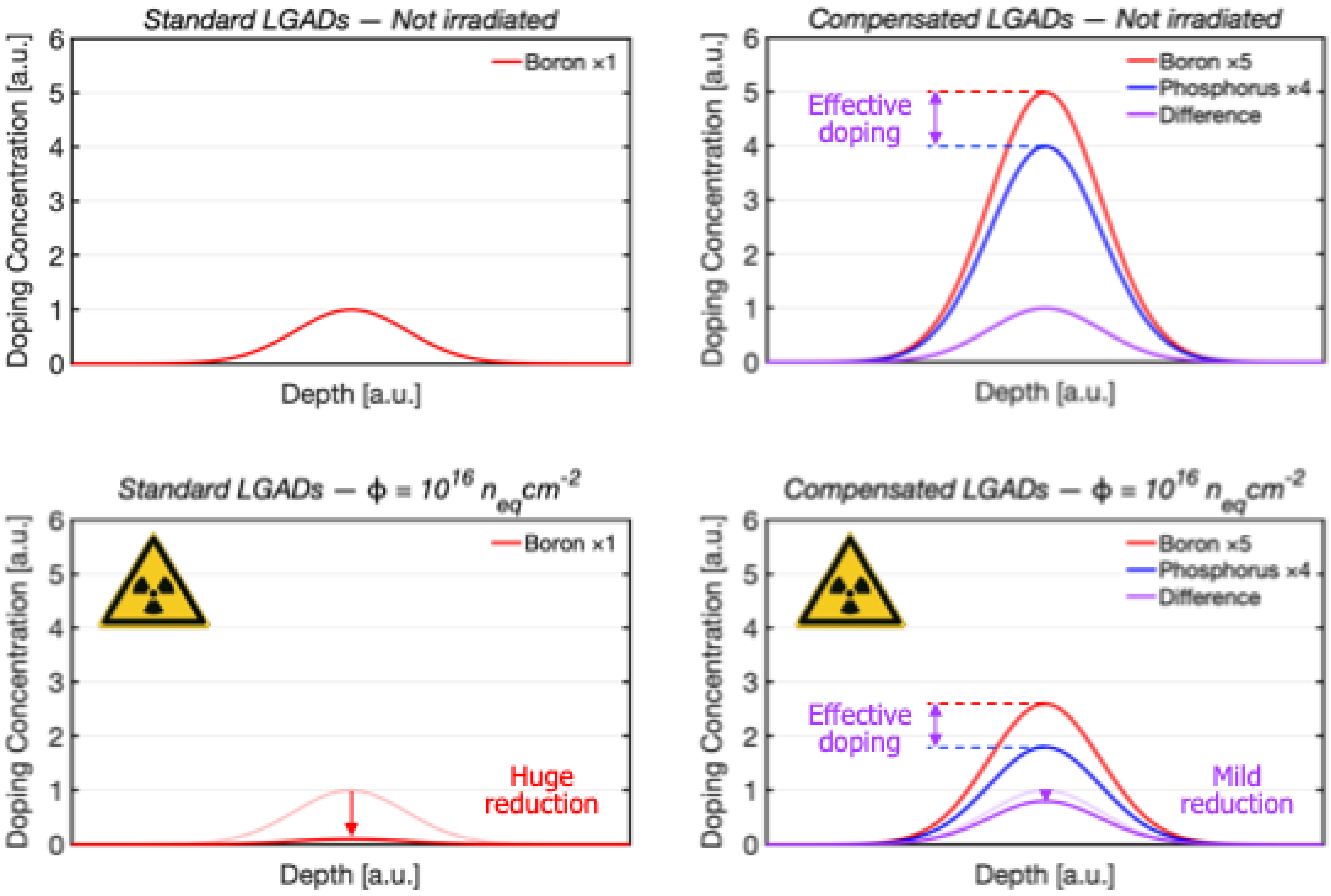


Defining the Challenge

Donor removal is now becoming very interesting as it plays a crucial role in the functioning of resistive LGADs and **compensated LGADs**.



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Defining the Challenge

Donor removal is now becoming very interesting as it plays a crucial role in the functioning of resistive LGADs and **compensated LGADs**.

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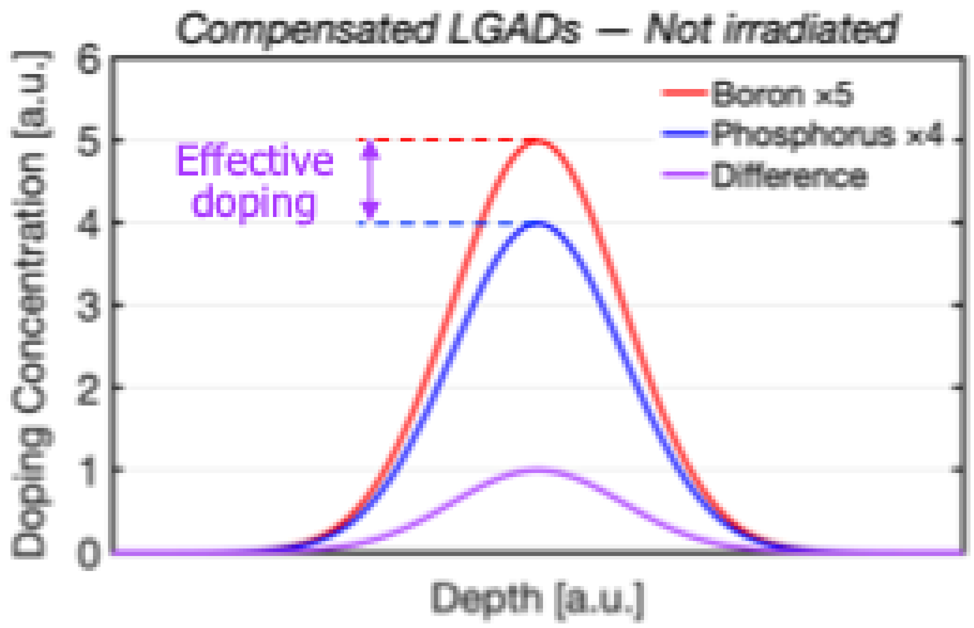
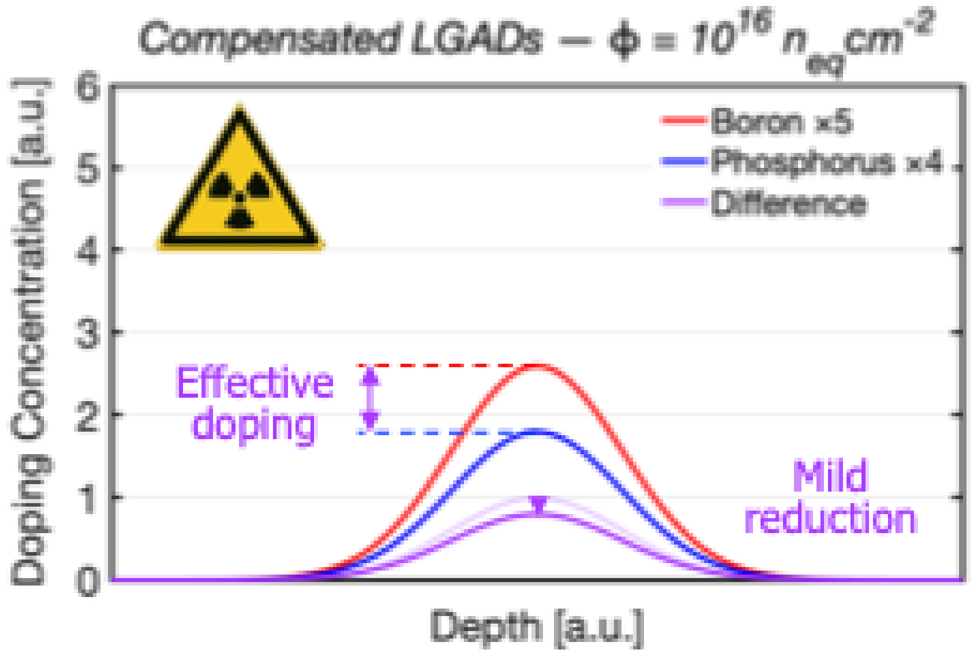
EXFLU1's split table

[a < b < c]
[2c < 3a]

Wafer #	Thickness	p+ dose	n+ dose	C dose
6	30	2 a	1	
7	30	2 b	1	
8	30	2 b	1	
9	30	2 c	1	
10	30	3 a	2	
11	30	3 b	2	
12	30	3 b	2	
13	30	3 b	2	1.0
14	30	3 c	2	
15	30	5 a	4	

Active thickness 30 μm





Extension of the Radiation Damage Model

"PerugiaModDoping"[1]

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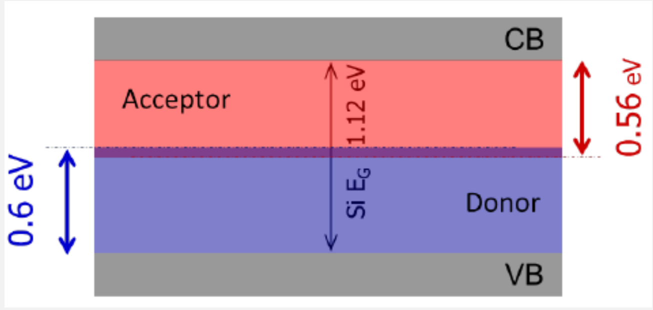
"**New University of Perugia**" Radiation Damage Model [2]

Surface damage (+ Q_{ox})

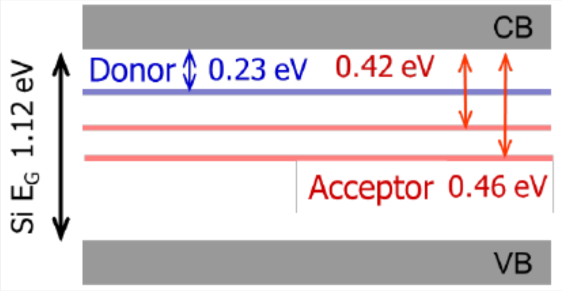
Type	Energy (eV)	Band width (eV)	Conc. (cm^{-2})
Acceptor	$E_C \le E_T \le E_C-0.56$	0.56	$D_{IT} = D_{IT}(\Phi)$
Donor	$E_V \le E_T \le E_V+0.6$	0.60	$D_{IT} = D_{IT}(\Phi)$



+

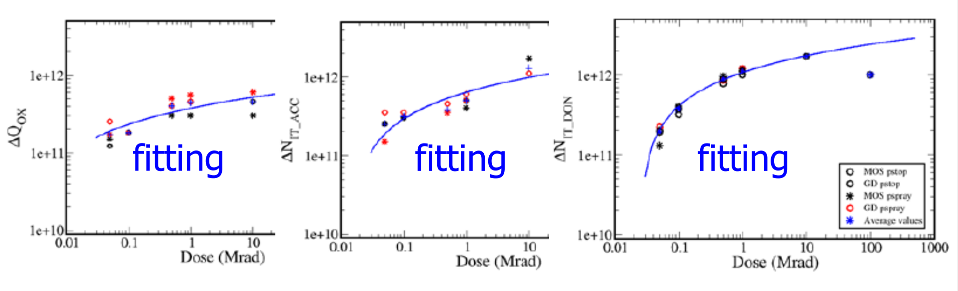
Bulk damage

Type	Energy (eV)	η (cm^{-1})	σ_n (cm^2)	σ_h (cm^2)
Donor	$E_C - 0.23$	0.006	2.3×10^{-14}	2.3×10^{-15}
Acceptor	$E_C - 0.42$	1.6	1×10^{-15}	1×10^{-14}
Acceptor	$E_C - 0.46$	0.9	7×10^{-14}	7×10^{-13}



- ✓ **Bulk damage** → **Traps concentrations** dependence upon the introduction rate **η** (defects concentration) and the **fluence** (**~ η×Φ**)
- ✓ **Surface damage** → **Traps** (N_{IT} interface trap density) and **oxide charge** (**Q_{ox}**) **concentrations** dependence upon the **fluence** as follow:

$$Q_{OX}(\phi) = Q_{OX}(0) + \Delta Q_{OX}(\phi)$$
$$N_{IT_{acc}} = N_{IT_{acc}}(0) + \Delta N_{IT_{acc}}(\phi)$$
$$N_{IT_{don}} = N_{IT_{don}}(0) + \Delta N_{IT_{don}}(\phi)$$



(a) ΔQ_{OX} (b) ΔN_{IT_ACC} (c) ΔN_{IT_DON}

Torino analytical parameterizations [3]

- **Gain Layer** (Acceptor Removal)

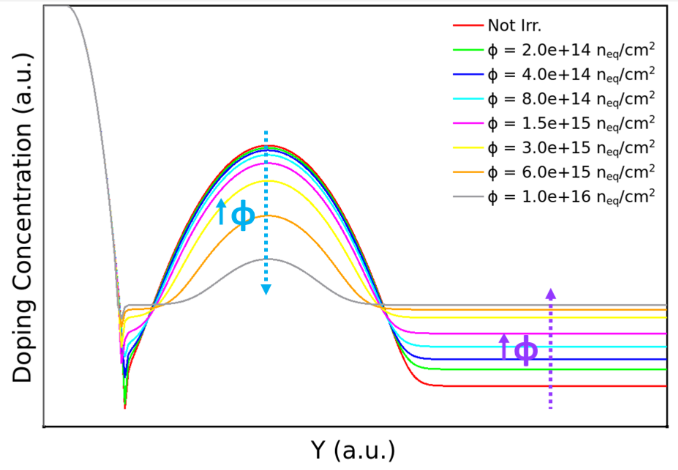
$$N^{peak}_{A,GL}(\Phi) = N_{A,GL}(0) \cdot e^{-c\cdot\Phi}$$

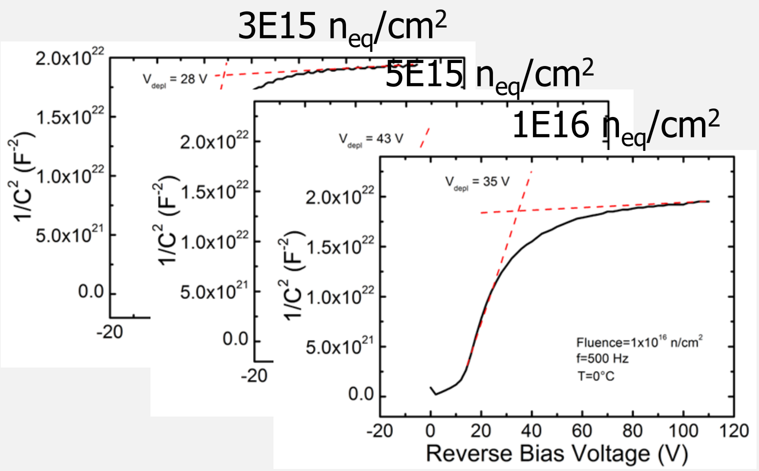
- **Bulk** (Acceptor Creation)
  - ✓ if $0 < \Phi \le 3e15\ n_{eq}/cm^2$

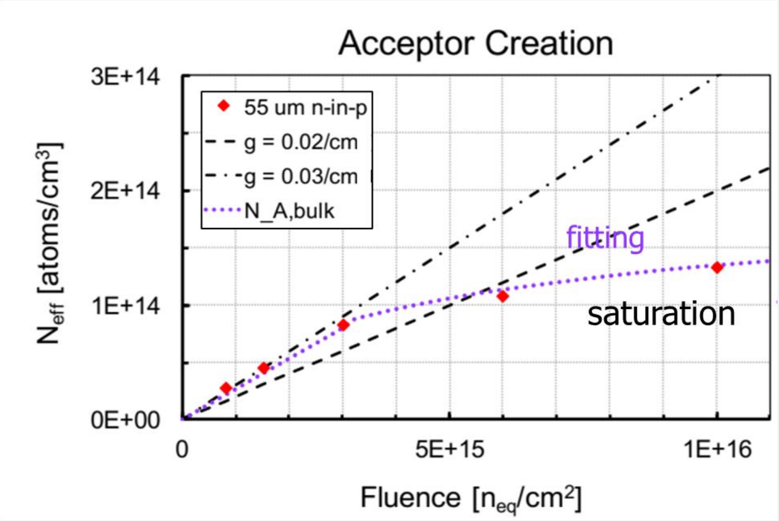
$$N_{A,bulk}(\Phi) = N_{A,bulk}(0) + g_c \cdot \Phi$$

  - ✓ if $\Phi > 3e15\ n_{eq}/cm^2$

$$N_{A,bulk}(\Phi) = 4{,}17e13 \cdot \ln(\Phi) - 1{,}41e15$$







TCAD simulation of **LGAD** device - **HPK**

✓ In collaboration with *INFN Torino*: **calibration/extension** of the previously developed models **by comparing** the **simulation findings** with **measurements** carried out on different classes of **LGAD** detectors.

✓ **Comparison** with **experimental data**, **before** and **after irradiation** (HPK2 production run, by HPK)

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"PerugiaModDoping"

- **Torino analytical parameterizations**
  - **Gain Layer** (Acceptor Removal)
  - **Bulk** (Acceptor Creation/Damage Saturation)
- **"New UNIPG"** TCAD Radiation Damage Model

Surface damage (+ Q_{ox})

Type	Energy (eV)	Band width (eV)	Conc. (cm^{-2})
Acceptor	$E_C \le E_T \le E_C-0.56$	0.56	$D_{IT} = D_{IT}(\Phi)$
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Bulk damage

Type	Energy (eV)	η (cm^{-1})	σ_n (cm^2)	σ_h (cm^2)
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Acceptor	E_C - 0.42	1.6	1×10^{-15}	1×10^{-14}
Acceptor	E_C - 0.46	0.9	7×10^{-14}	7×10^{-13}

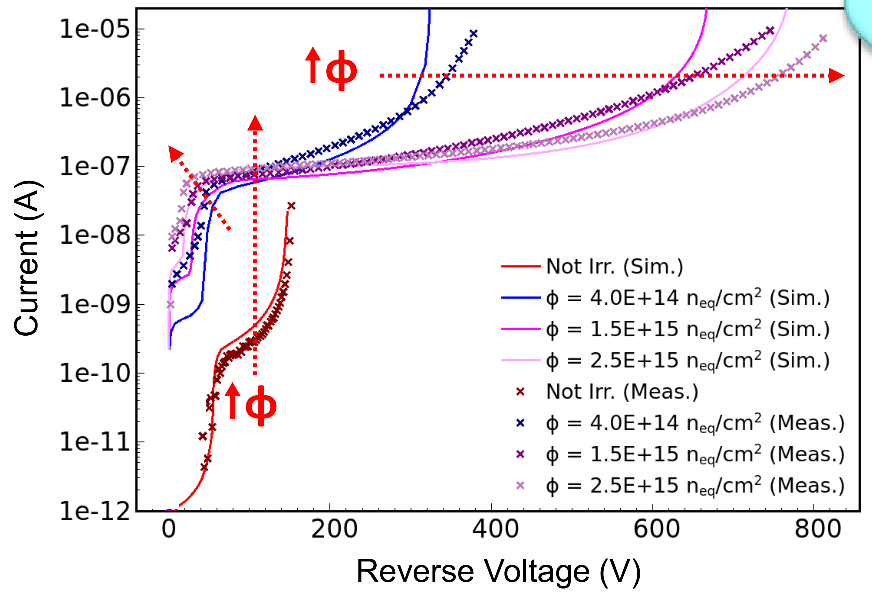
[6] R. V. Overstraeten et al., *Measurement of the ionization rates in diffused silicon p-n junctions*, SSE. 13, 1970.

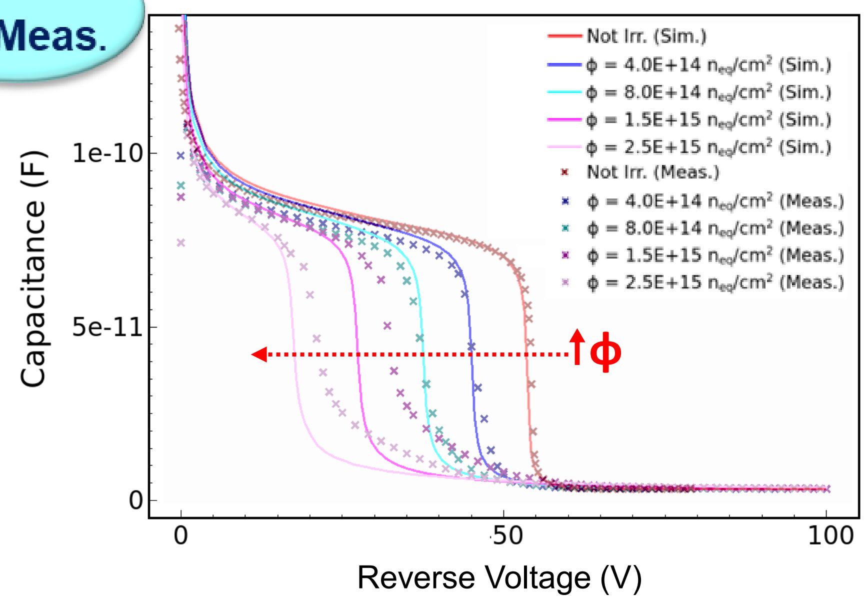
[7] E. C. Rivera, *Study of Impact Ionization Coefficients in Silicon With Low Gain Avalanche Diodes*, IEEE TED 70, 2023.

I-V, pre-irr @ 290 K, post-irr @ 248 K

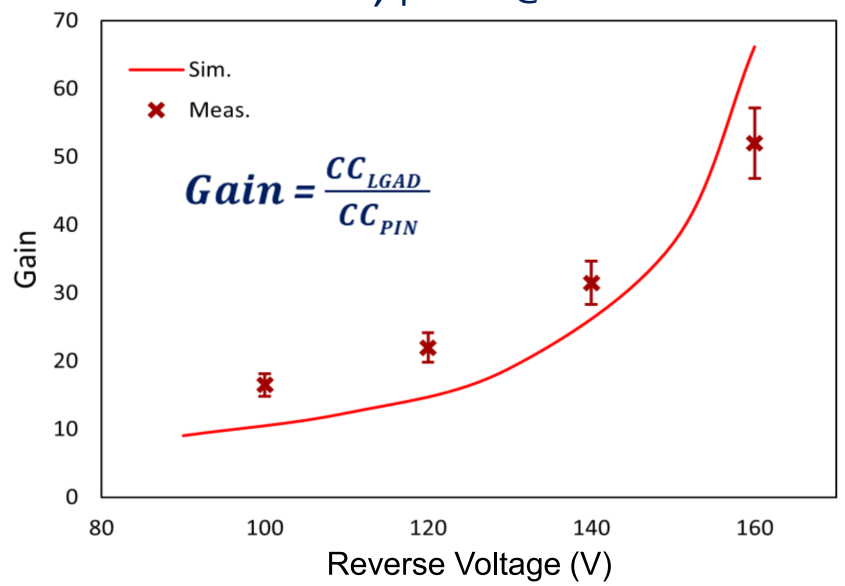
—— Simul. **x Meas.**

C-V, pre- & post-irr @ 298 K, 2 kHz

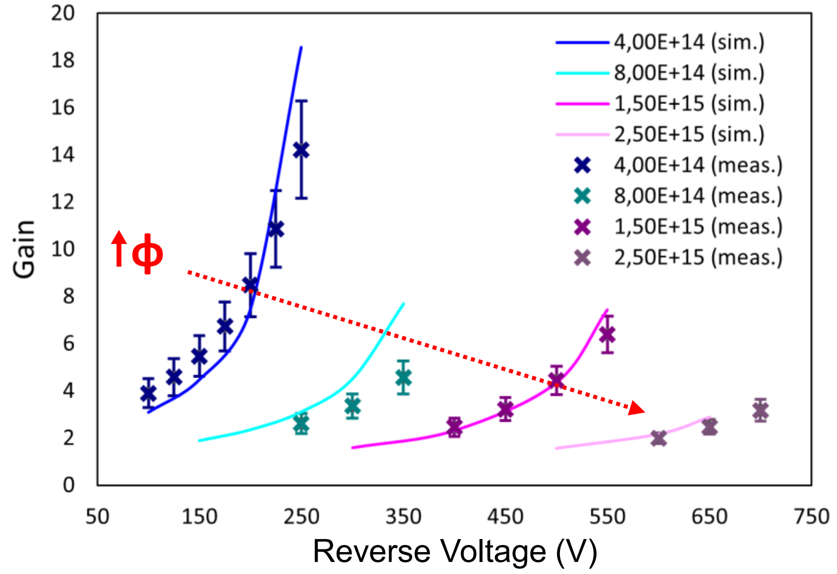




G-V, pre-irr @ 290 K



G-V, post-irr @ 248 K



vOv [6] & **Opt. vOv** [7] avalanche models. Electrical contact area **1,25 x 1,25 mm²**

Defining the Challenge, Designing the Approach

Donor removal is now becoming very interesting as it plays a crucial role in the functioning of resistive LGADs and compensated LGADs.

A Measurement – Simulation Synergy to Quantify Donor Removal at high initial concentrations ($N_D > 10^{15}$ atoms/cm^3)

Compensated LGADs

EXFLU1 batch samples offer an opportunity to study donor removal by reproducing in simulation the capacitance variation with irradiation.

These samples will also enable us to begin examining the interplay between donor removal and acceptor removal (How do the removal rates compare to each other?).

Van der Pauw test structures

A dedicated test structure for each implant under study to investigate donor and acceptor removal by examining the change in sheet resistance with irradiation with neutron (n) and protons (p).

EXFLU1 batch PGAIN and PPLUS test structures (TS) irradiated (n) and analysed

RSD2 batch NPLUS TS irradiated (n and p) and analysed;

DC-RSD1 batch NPLUS TS irradiated (n) and analysed;

NLGAD batch NGAIN TS will be analysed once FBK realises the batch.

EXFLU1 batch – Compensated LGADs

Wafer #	Thickness	p+ dose	n+ dose	C dose
6	30	2 a	1	
7	30	2 b	1	
8	30	2 b	1	
9	30	2 c	1	
10	30	3 a	2	
11	30	3 b	2	
12	30	3 b	2	
13	30	3 b	2	1.0
14	30	3 c	2	
15	30	5 a	4	

[a < b < c] & [2c < 3a]

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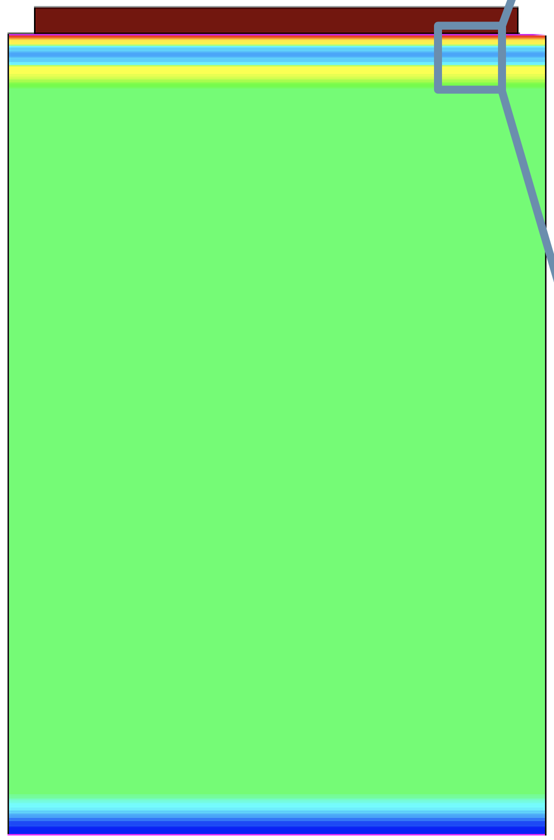
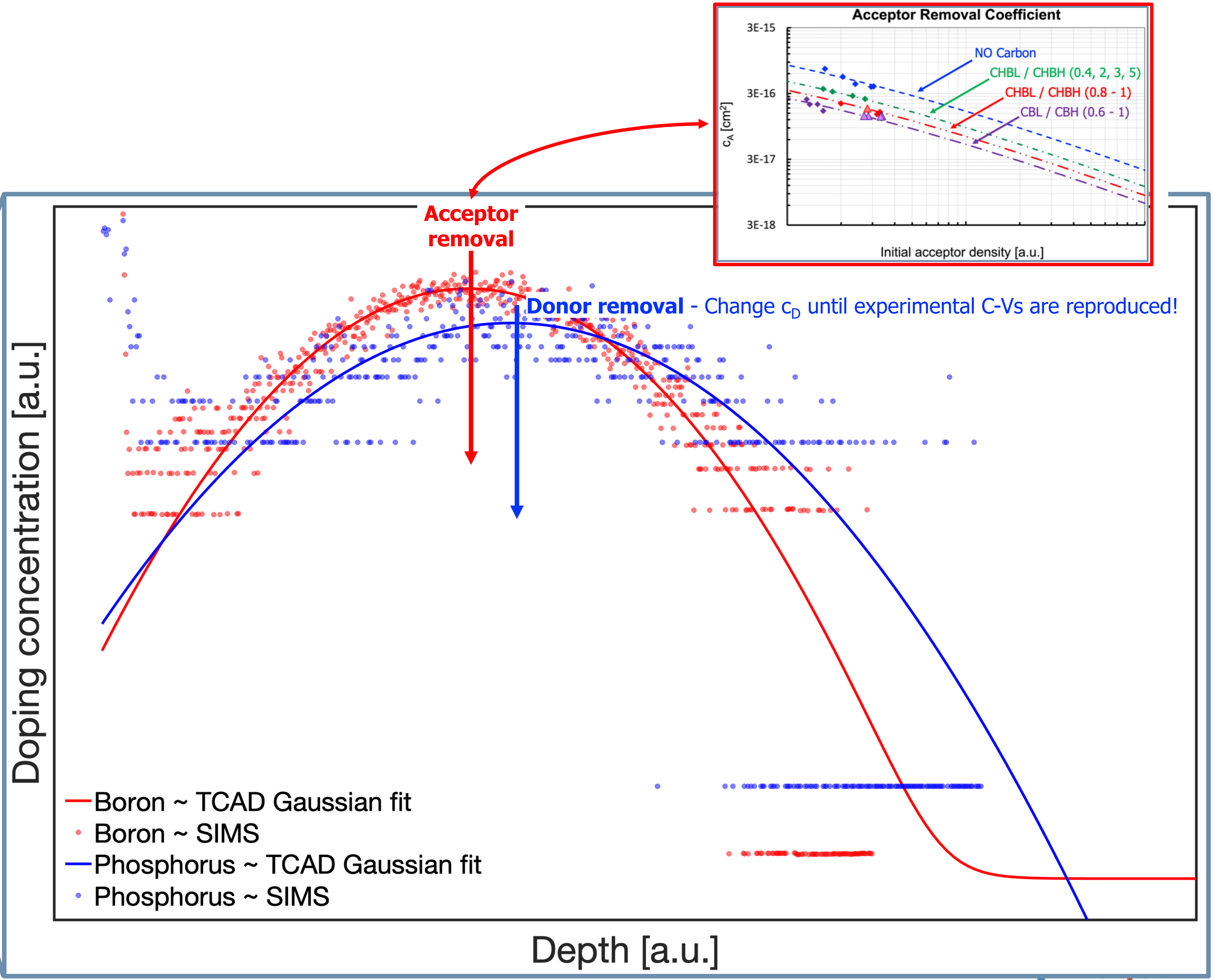
Single pad Compensated LGAD





EXFLU1 batch – Compensated LGADs

Wafer #	Thickness	p+ dose	n+ dose	C dose
12	30	3 b	2	
13	30	3 b	2	1.0

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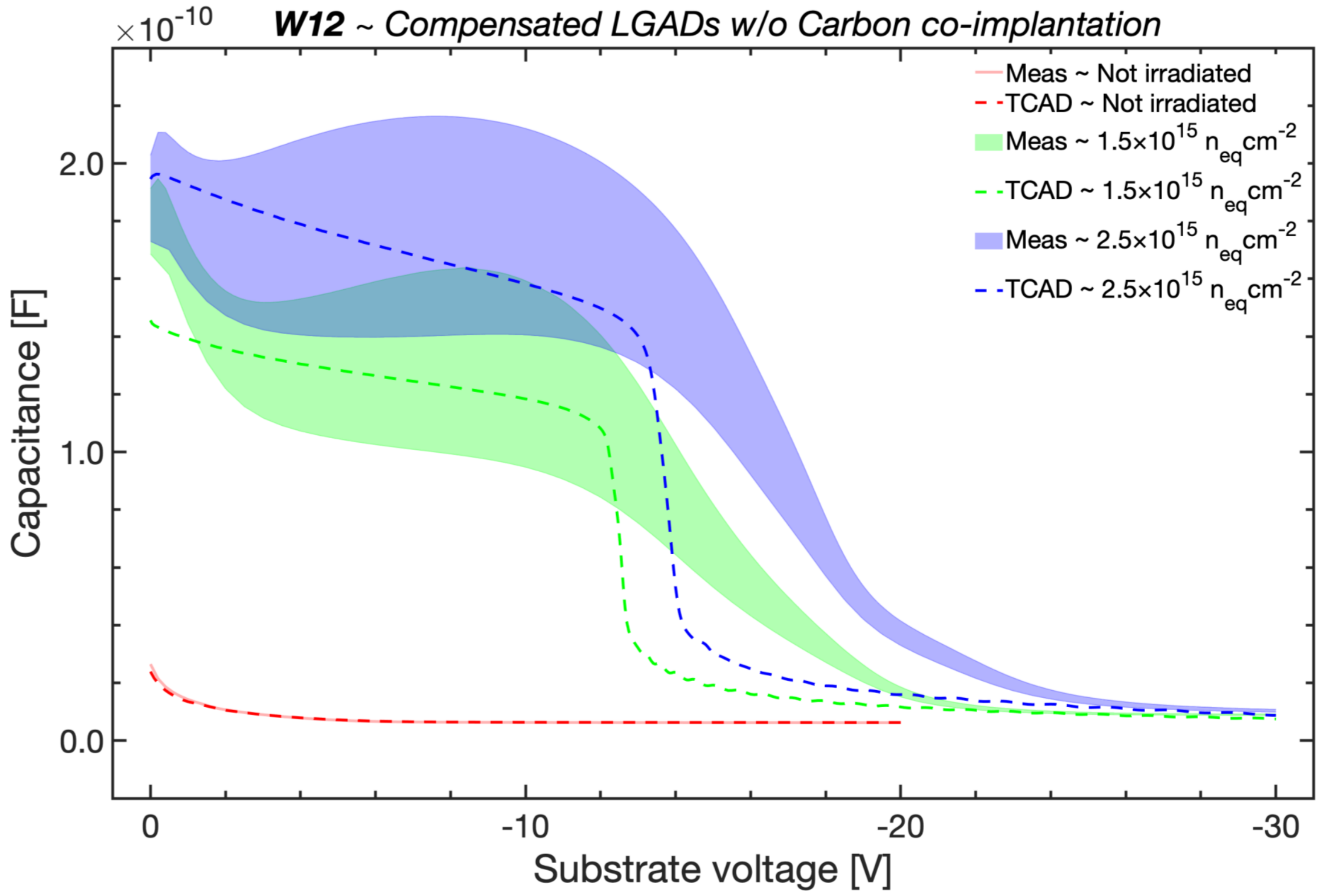
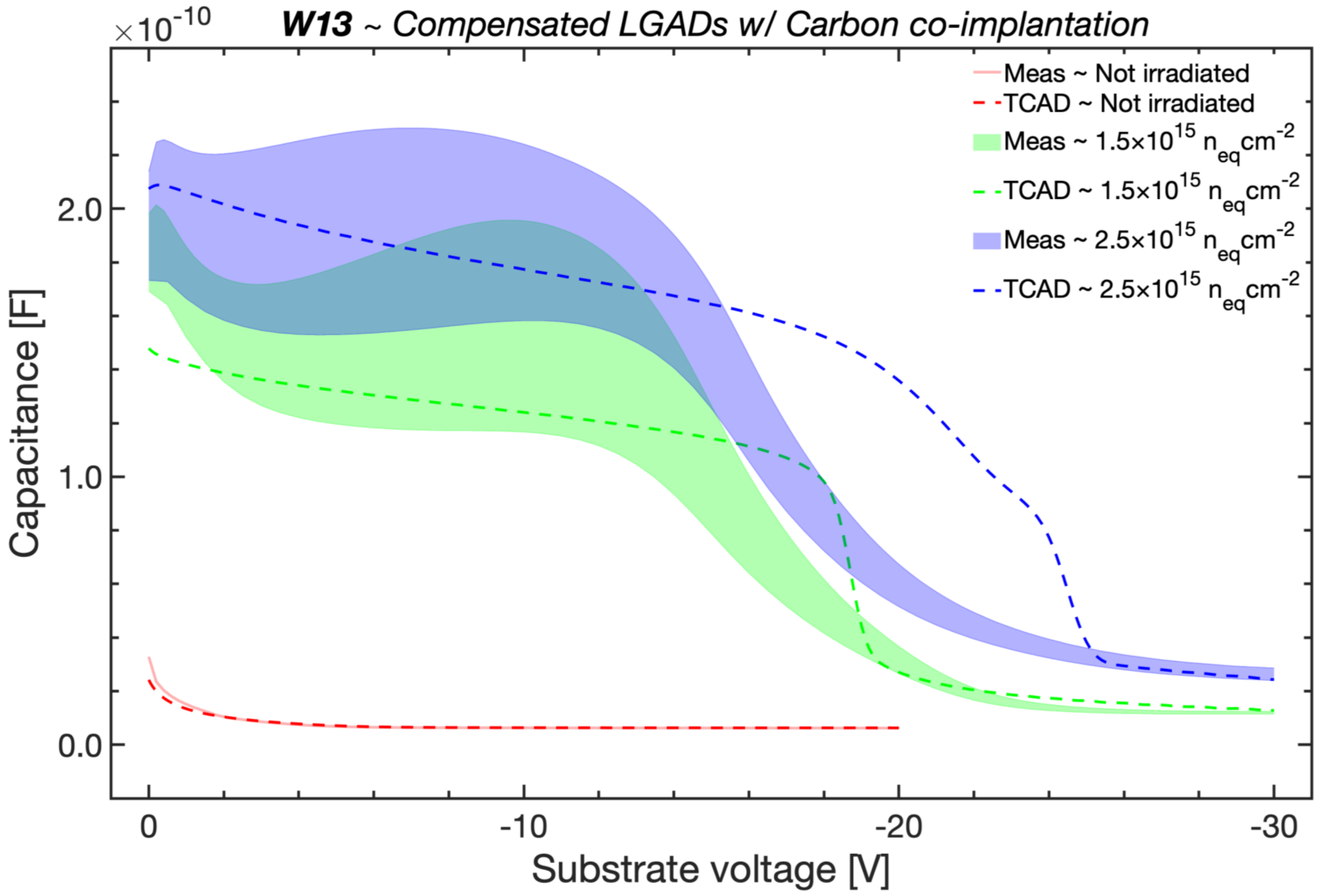
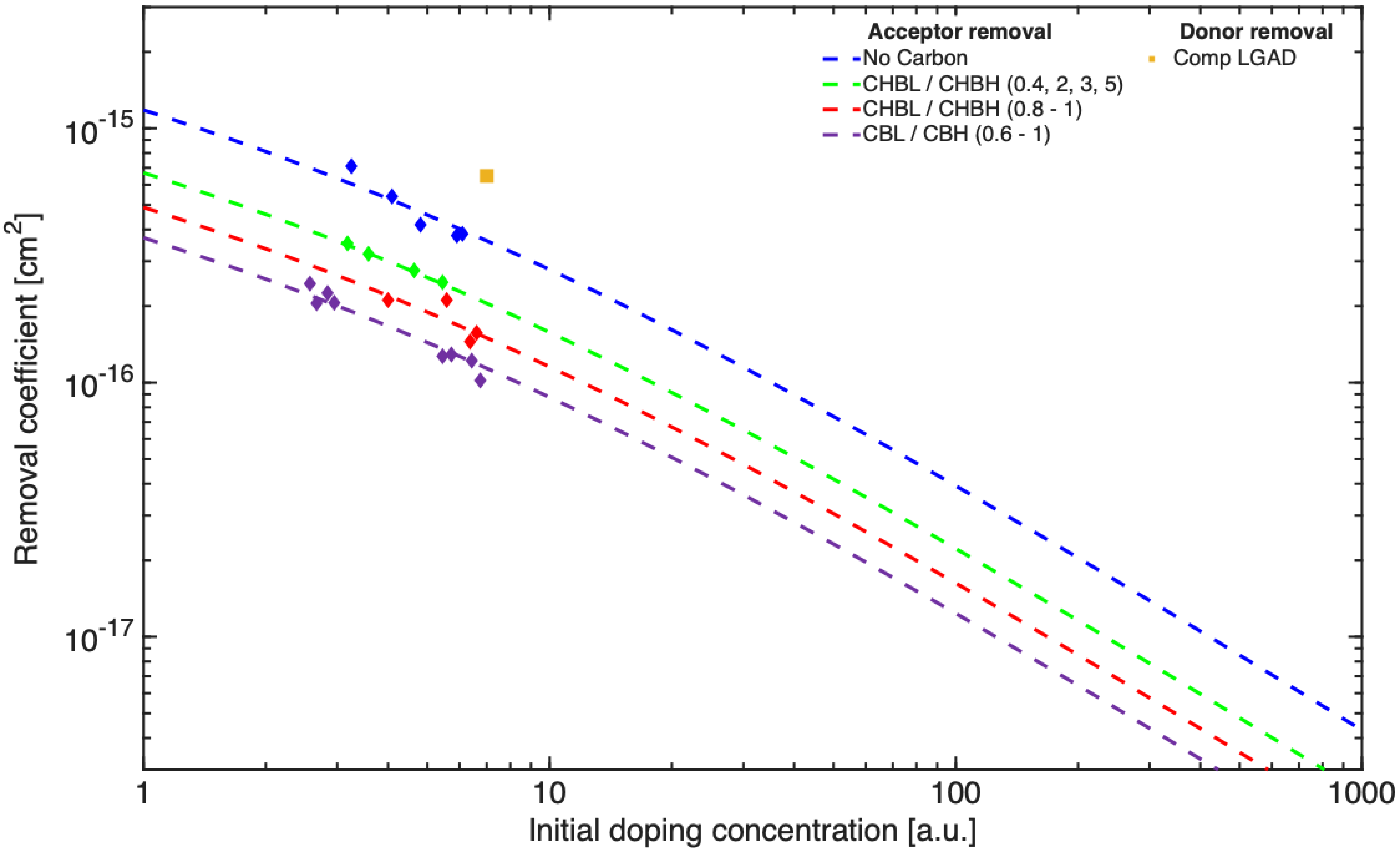




By exploiting the experimental acceptor removal coefficient $c_A = 2.50 \cdot 10^{-16}$ cm², agreement with C-V measurements is achieved using a donor removal coefficient $c_D = 6.50 \cdot 10^{-16}$ cm².

By exploiting the extracted c_D ($6.50 \cdot 10^{-16}$ cm²) and the experimental $c_A = 8.26 \cdot 10^{-17}$ cm² for the carbonated gain implant, a good agreement between measurements and simulations was achieved.

c_D extracted from compensated LGADs



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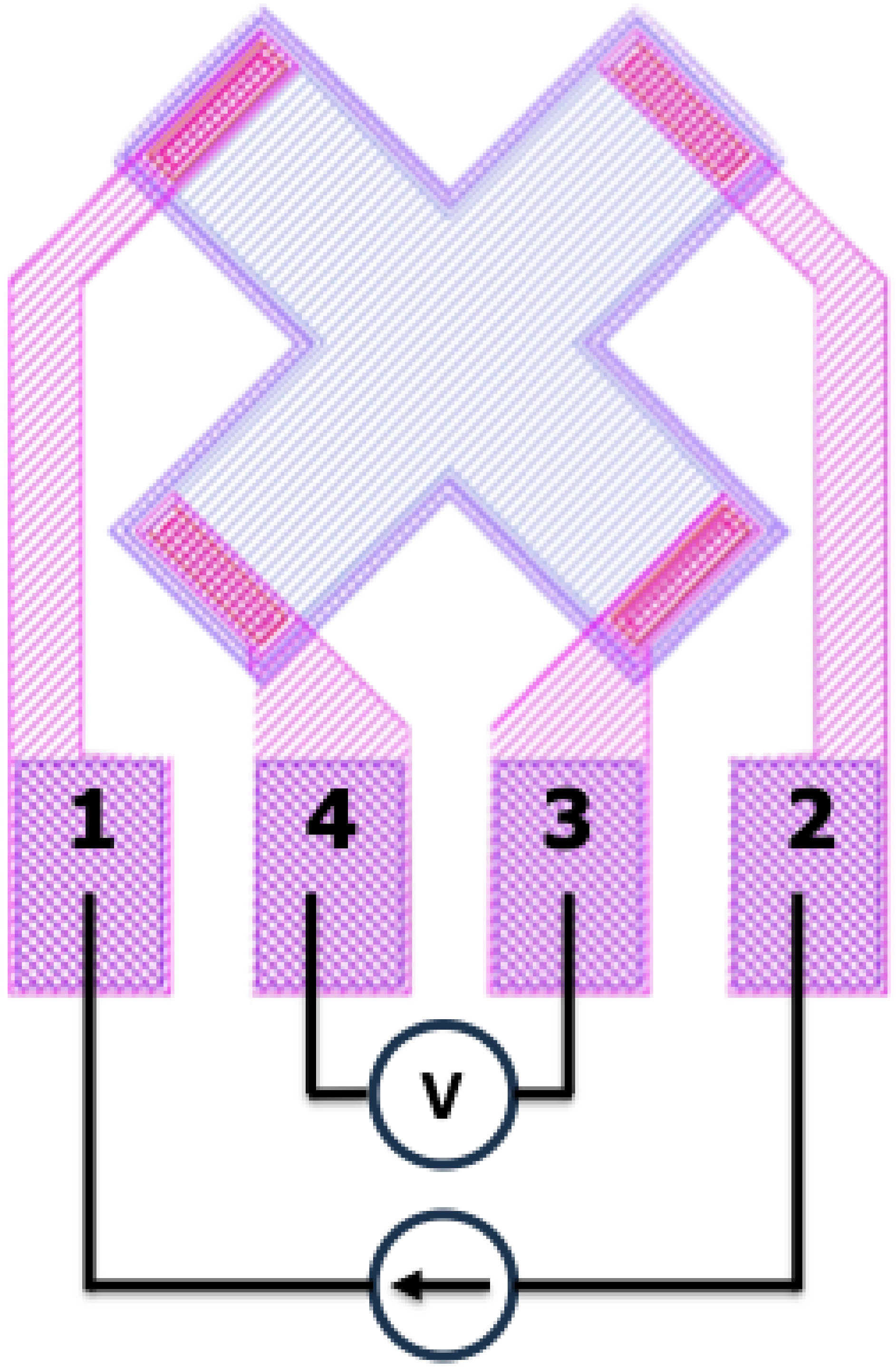
Van der Pauw test structure

MEASUREMENT SETUP



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STEP1 Apply a known current $\mathbf{I_{12}}$

STEP2 Measure the voltage difference $\mathbf{V_{34}}$

STEP3 Calculate the sheet resistance as

$$R_{sh} = \frac{\pi}{\ln(2)} \frac{V_{34}}{I_{12}}$$

Beware of substrate's parasitic contribution

Van der Pauw test structure

MEASUREMENT SETUP

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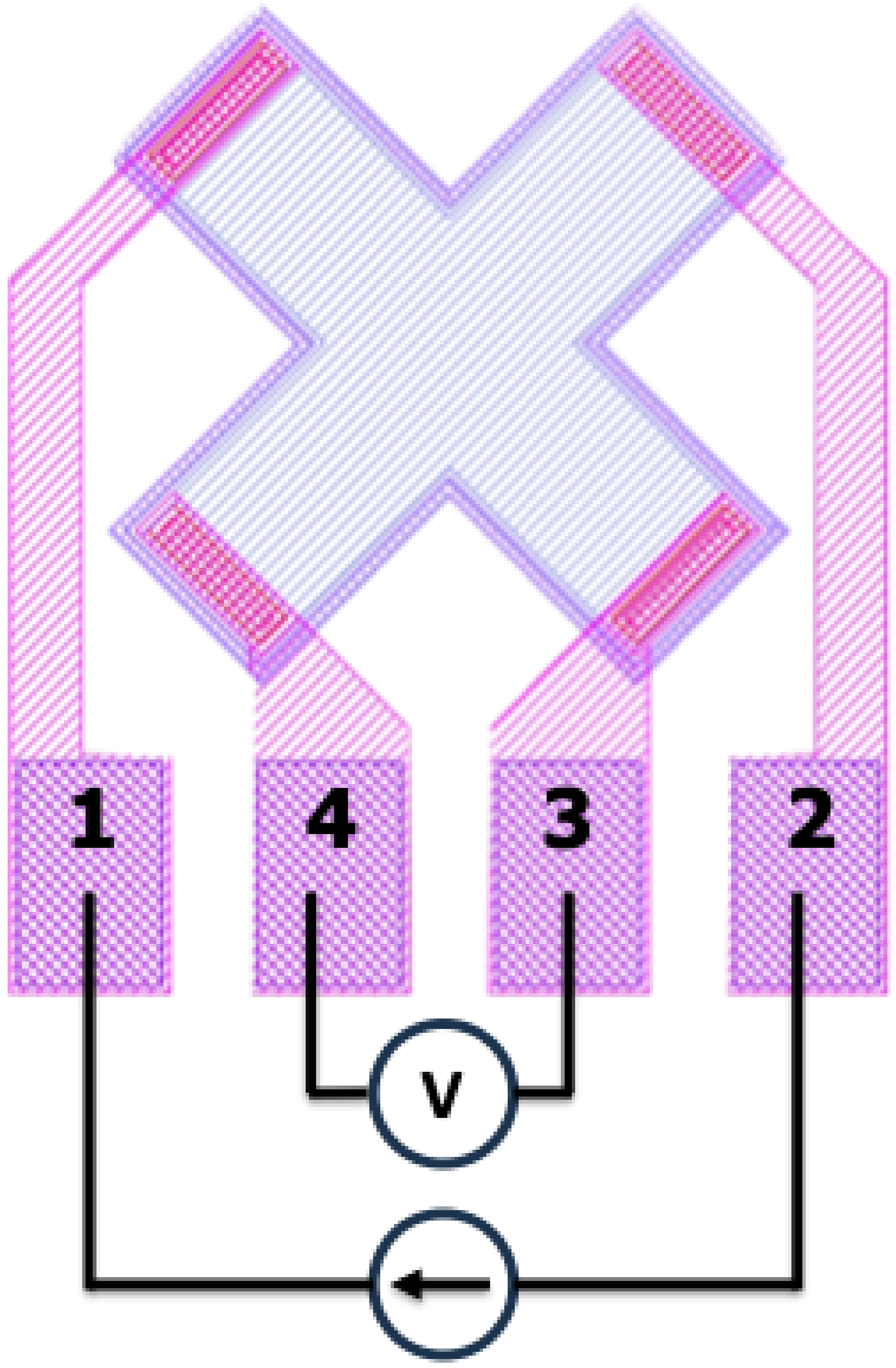

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STEP3 Calculate the sheet resistance as

$$R_{sh} = \frac{\pi}{\ln(2)} \frac{V_{34}}{I_{12}}$$

Beware of substrate's parasitic contribution

SIMULATION SETUP

Synopsys® Sentaurus Technology CAD (TCAD) enriched with the New University of Perugia radiation damage model

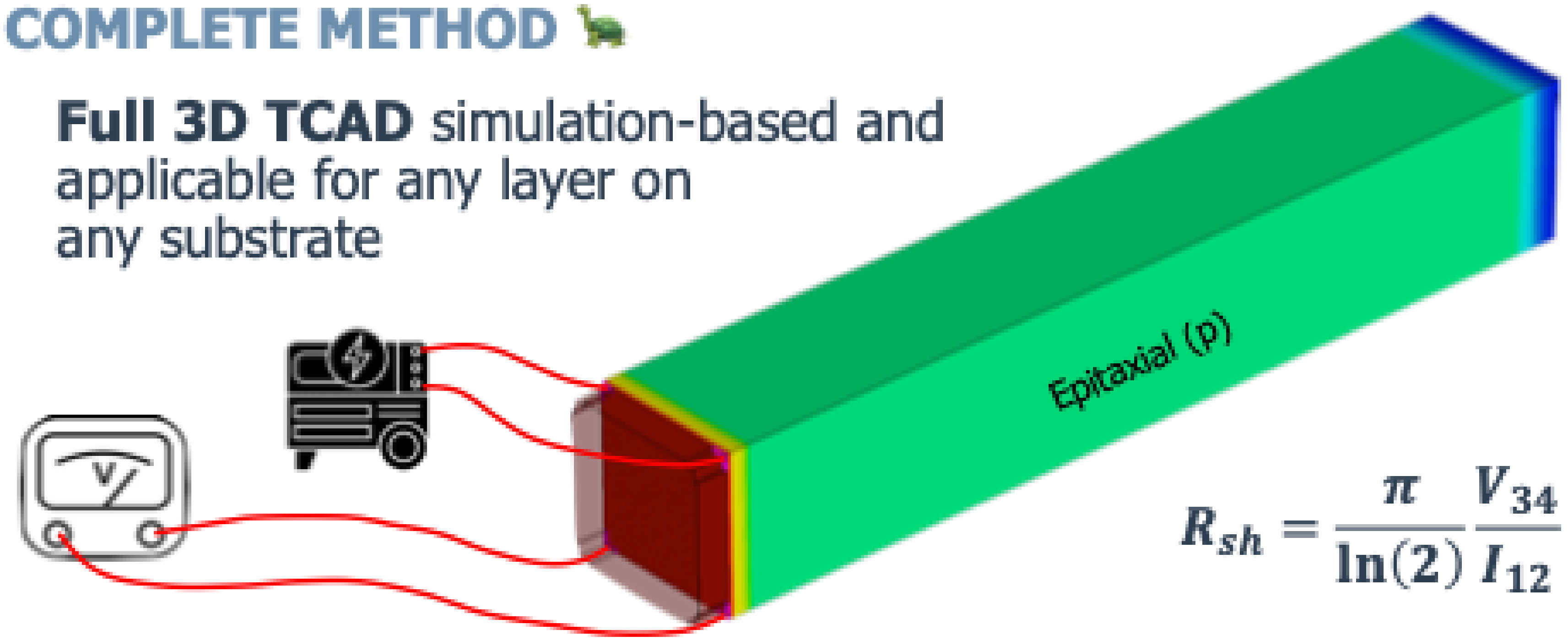
FAST METHOD

Analytical and only for *p*-layers on a *n*-substrate or *n*-layers on p-substrates (

$$R_{sh} = \left[\int_0^d q\left[n(x)\mu_n(x) + p(x)\mu_p(x)\right]dx\right]^{-1}$$

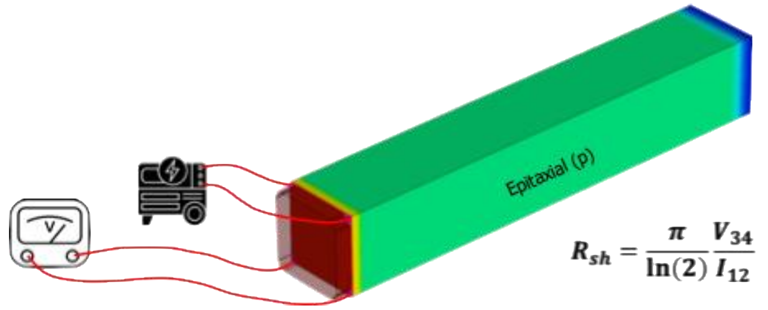
COMPLETE METHOD

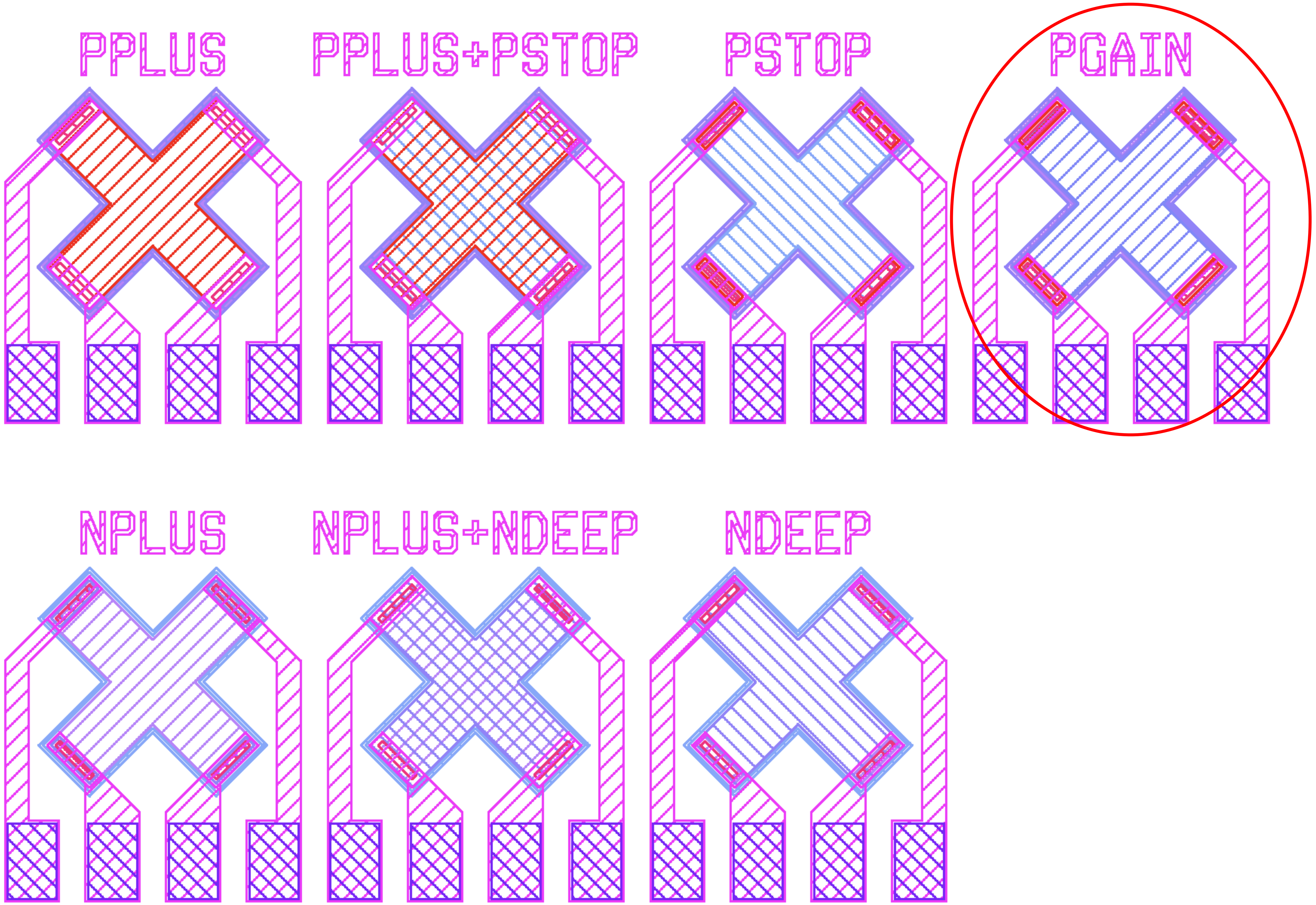
Full 3D TCAD simulation-based and applicable for any layer on any substrate



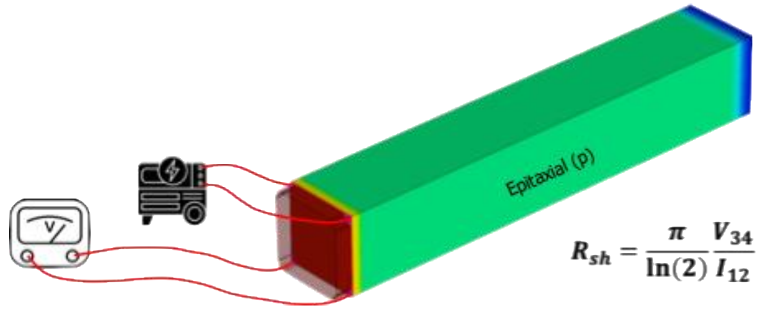
$$R_{sh} = \frac{\pi}{\ln(2)} \frac{V_{34}}{I_{12}}$$

EXFLU1 batch - PGAIN

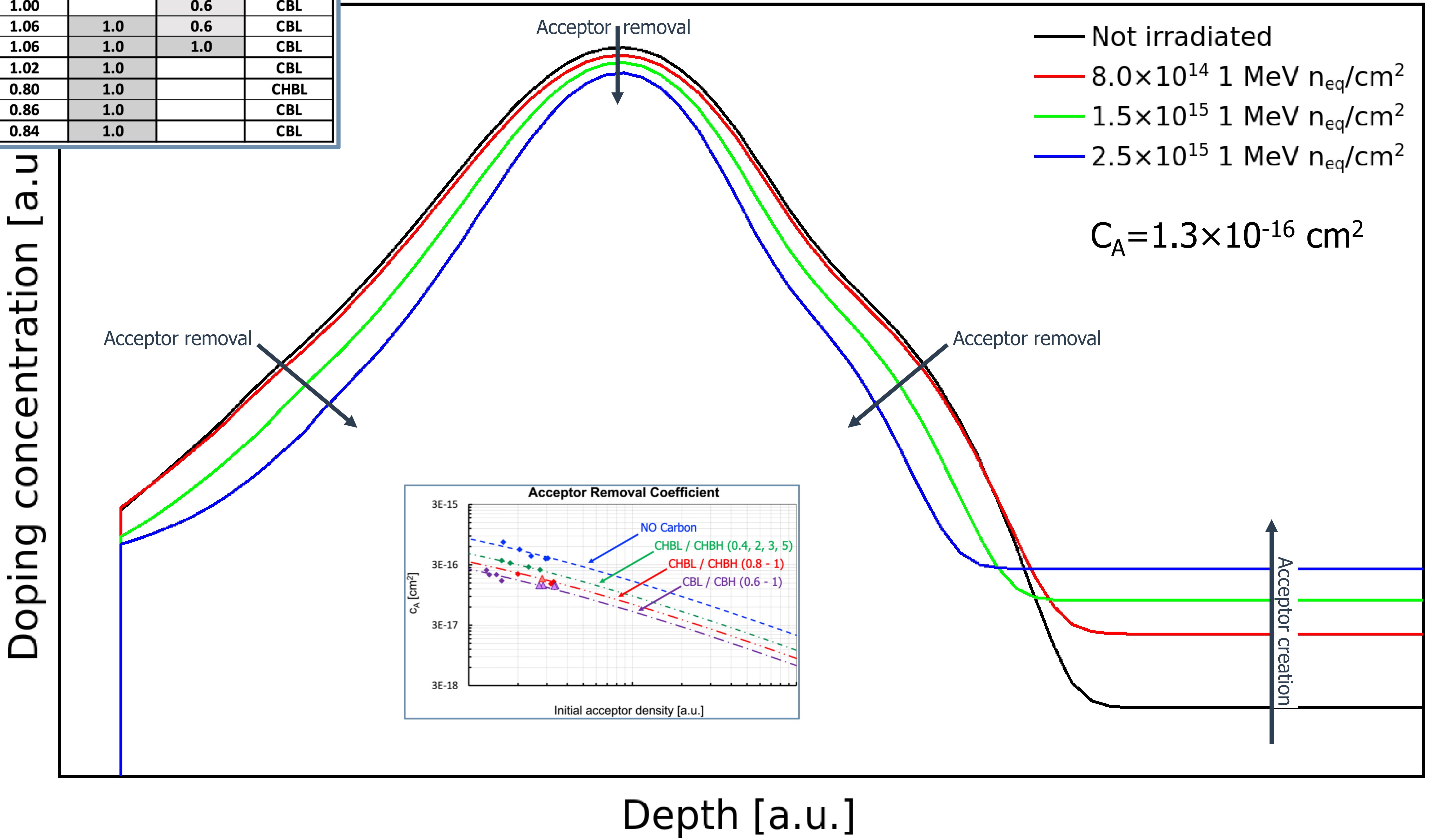




EXFLU1 batch - PGAIN



Wafer #	Thickness	p+ dose	C dose	C shield	Diffusion
1	45	1.04	1.0		CBL
2 *	45	1.00		0.6	CBL
3 *	45	1.06	1.0	0.6	CBL
4 *	45	1.06	1.0	1.0	CBL
5	30	1.02	1.0		CBL
16	20	0.80	1.0		CHBL
17	20	0.86	1.0		CBL
18	15	0.84	1.0		CBL



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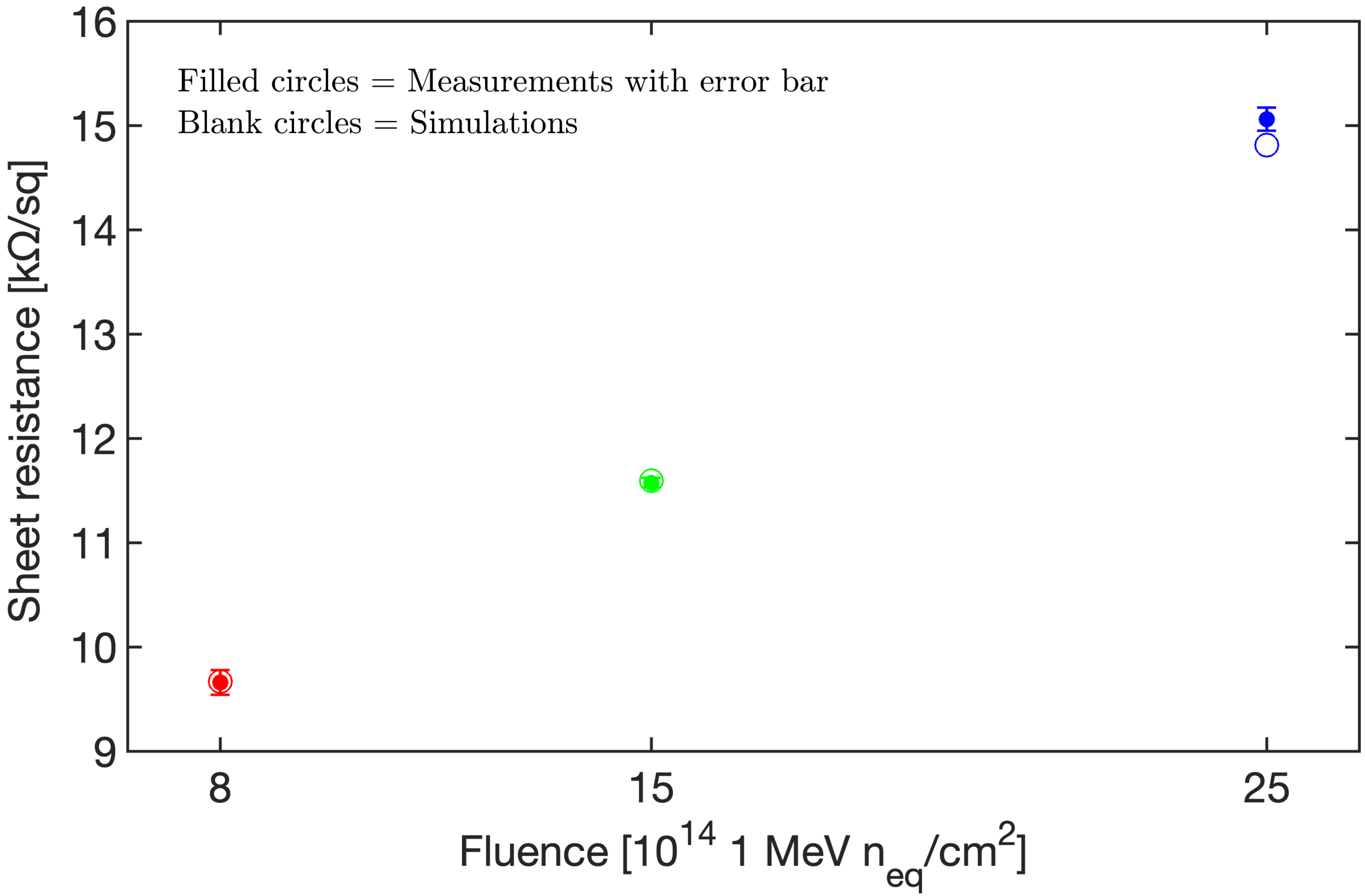
EXFLU1 batch — PGAIN — TCAD Measurements



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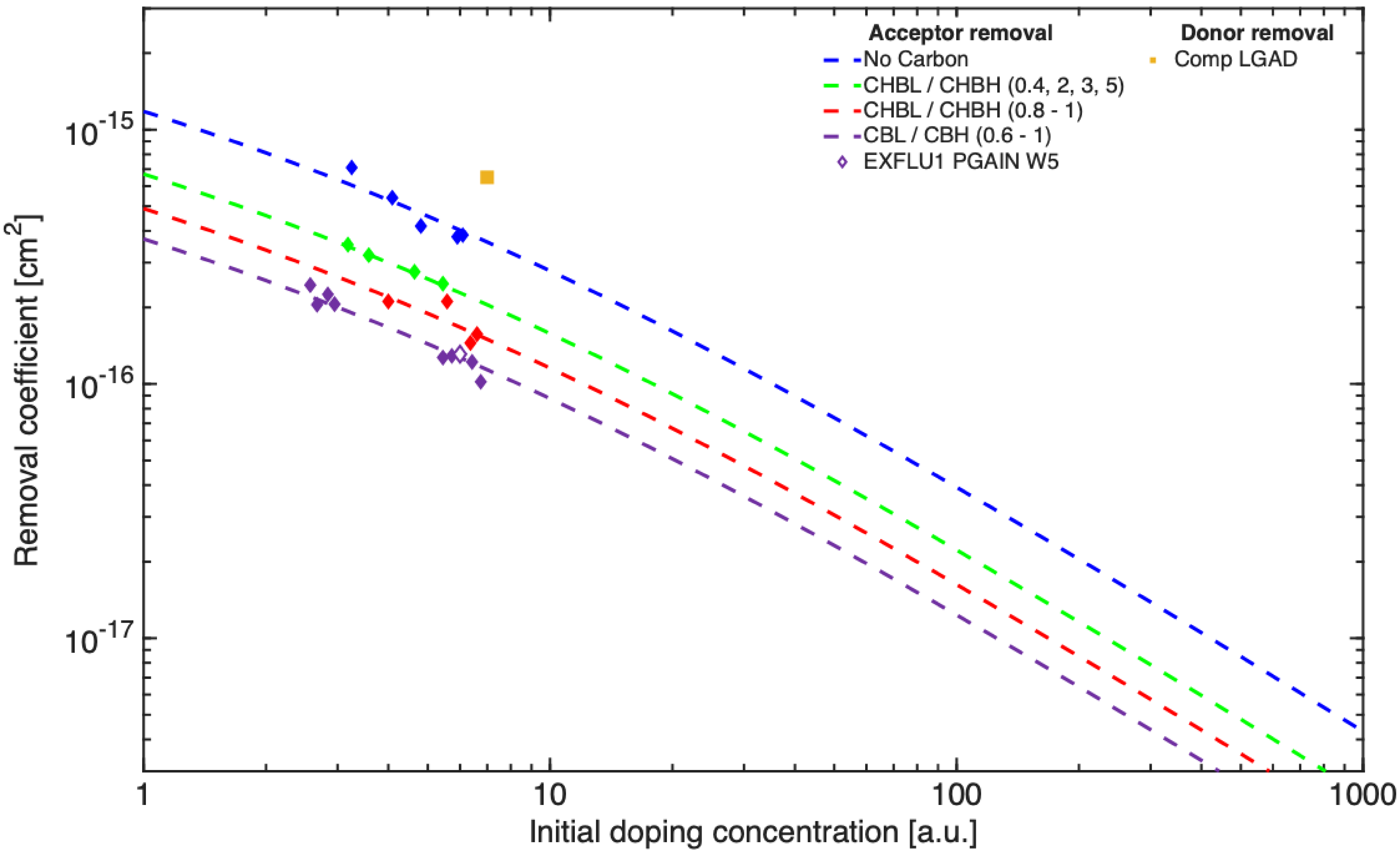
c_A extracted from compensated PGAIN



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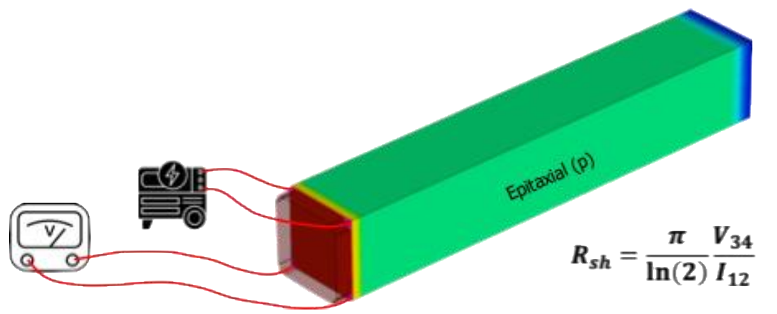
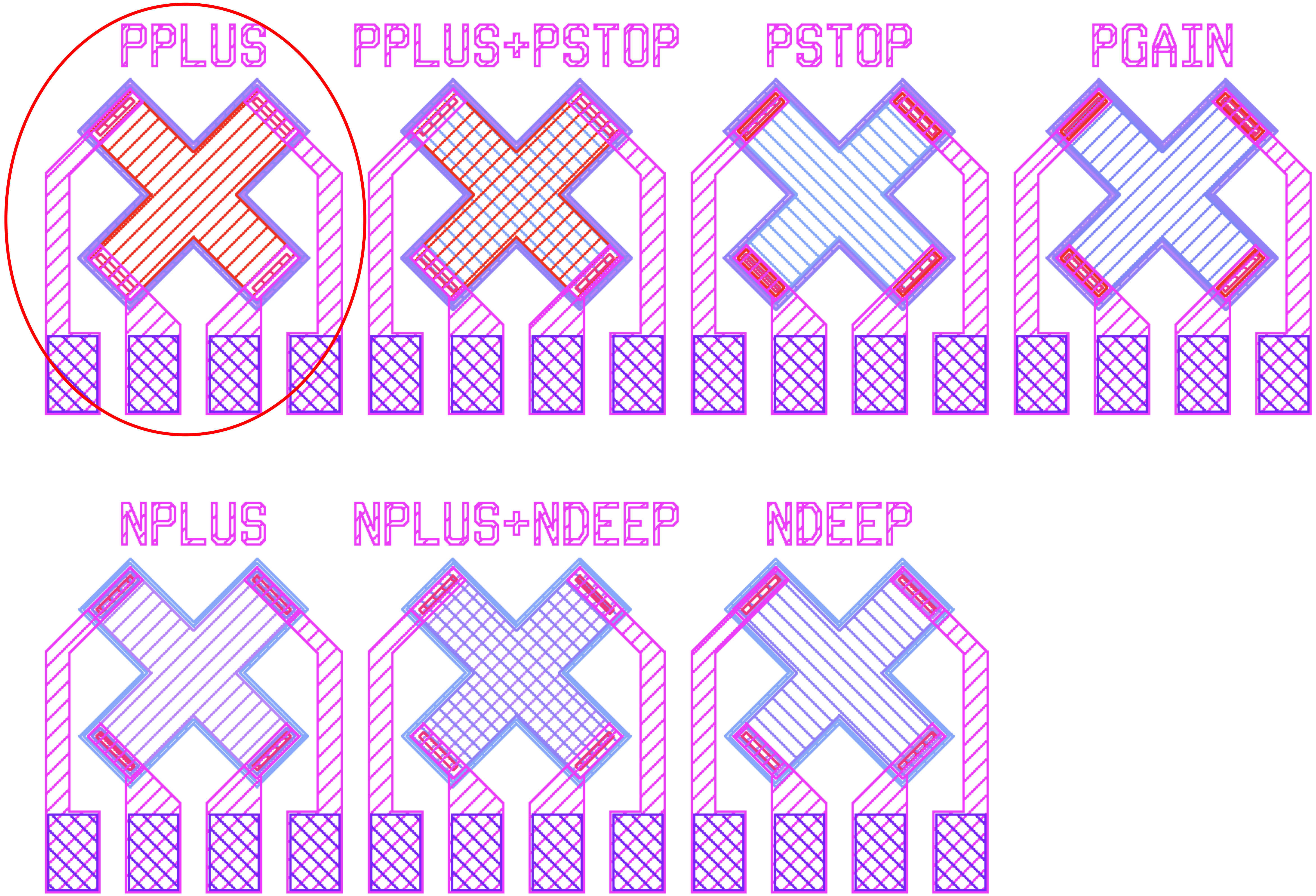
EXFLU1 batch - PPLUS





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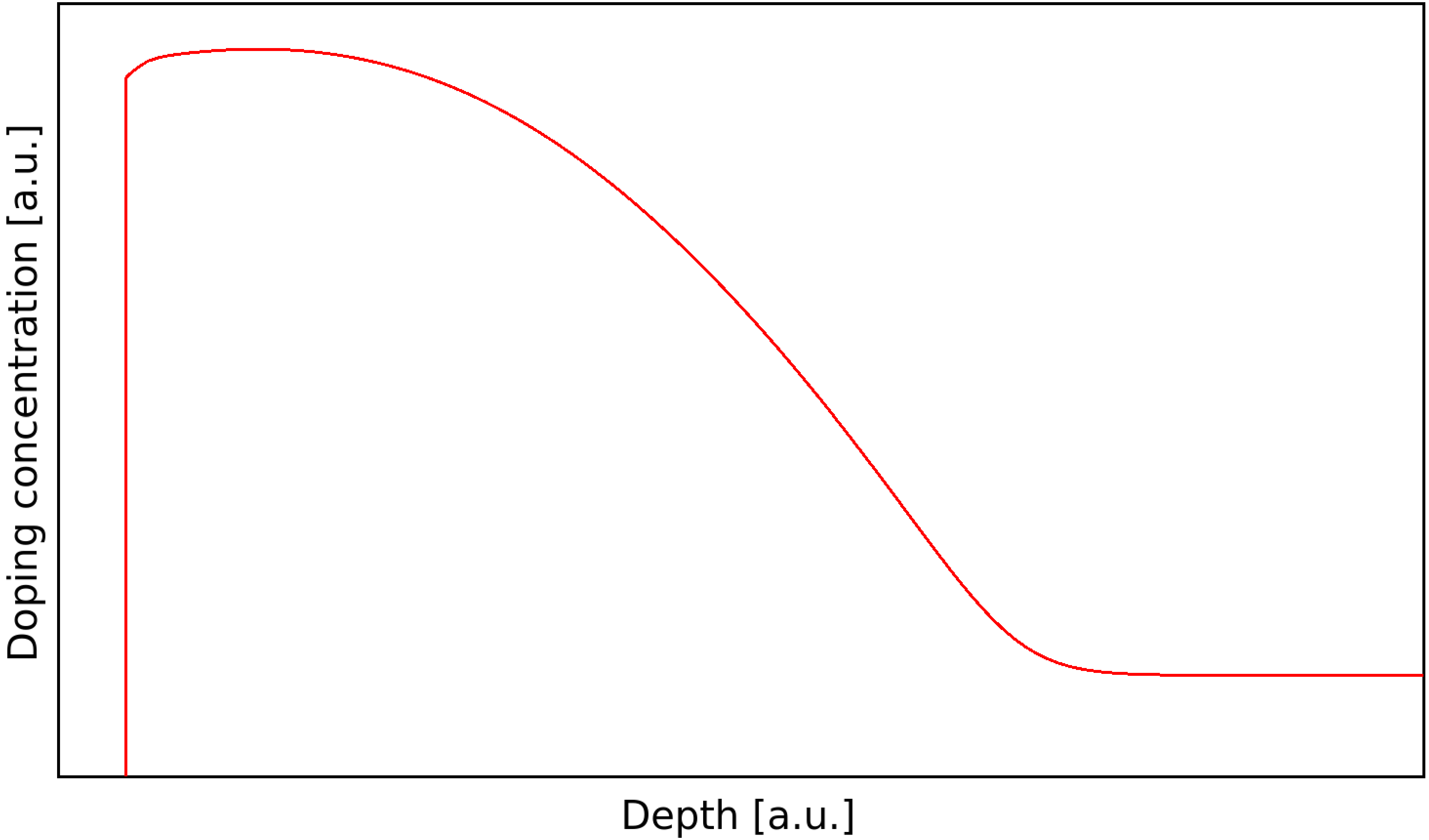
PPLUS profiles before irradiation



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EXFLU1- Experimental data - PPLUS

Wafer #	Thickness	p+ dose	n+ dose	C dose
6	30	2 a	1	
7	30	2 b	1	
8	30	2 b	1	
9	30	2 c	1	
10	30	3 a	2	
11	30	3 b	2	
12	30	3 b	2	
13	30	3 b	2	1.0
14	30	3 c	2	
15	30	5 a	4	

[a < b < c] & [2c < 3a]

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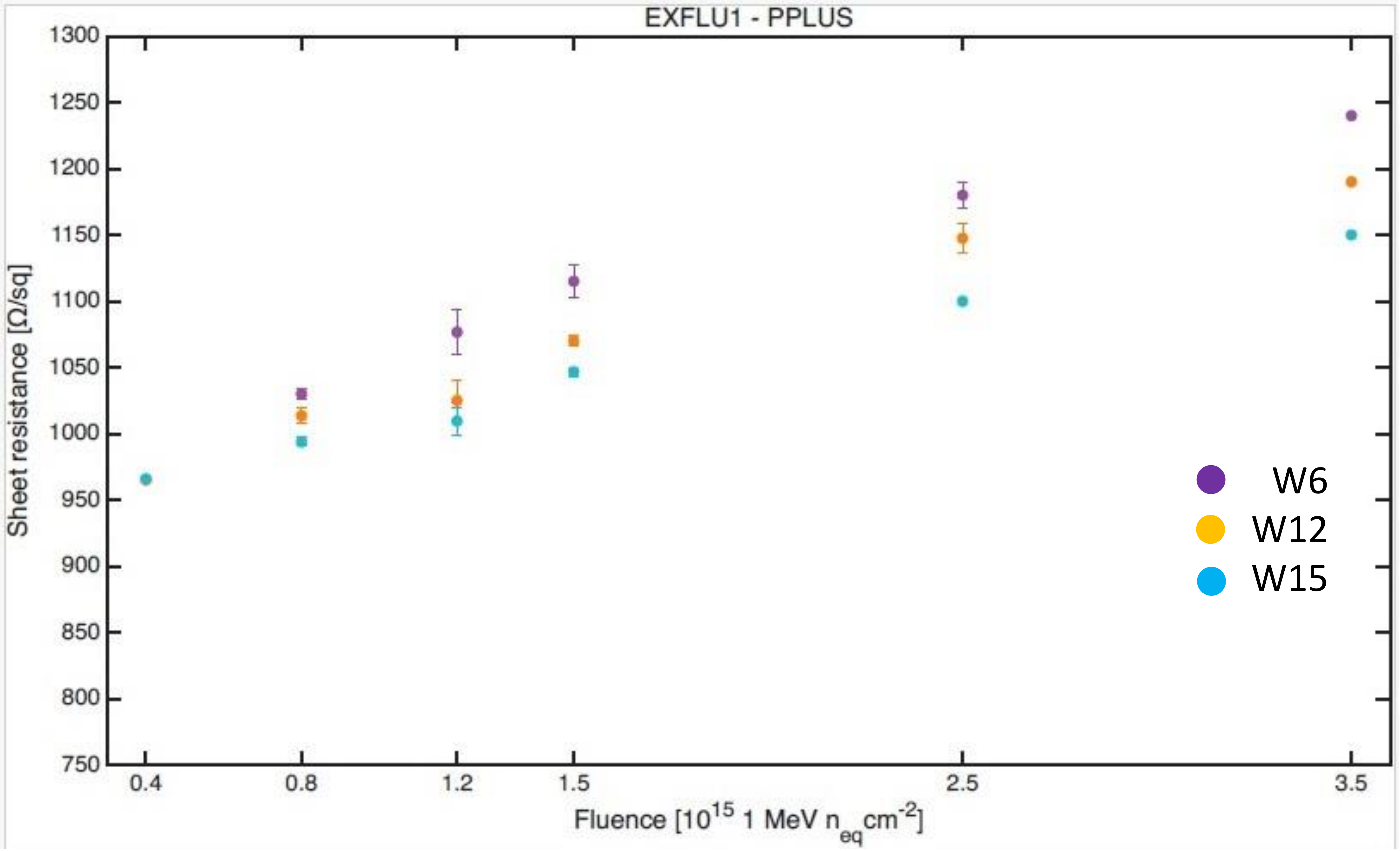
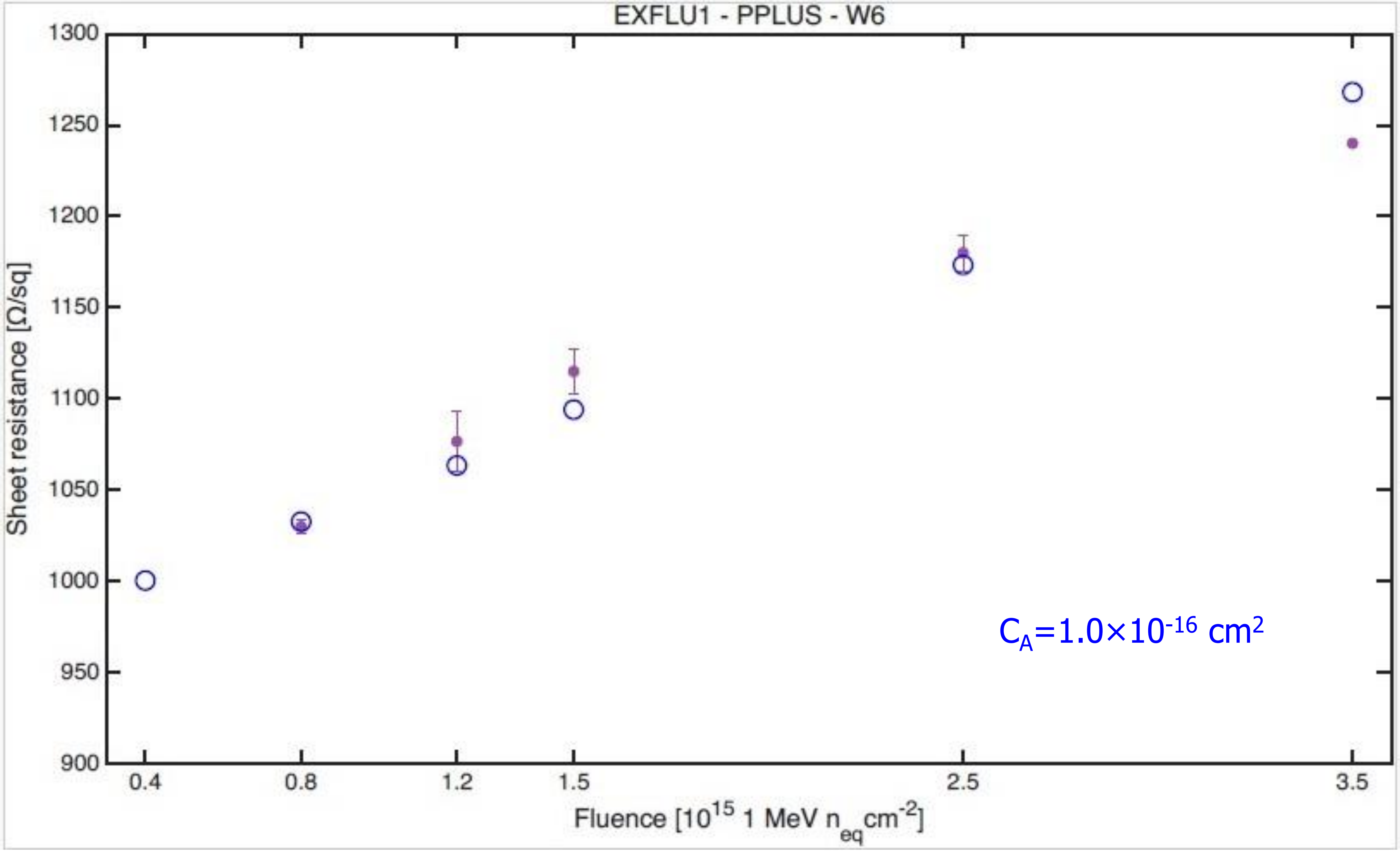


Sim vs meas – PPLUS - W6



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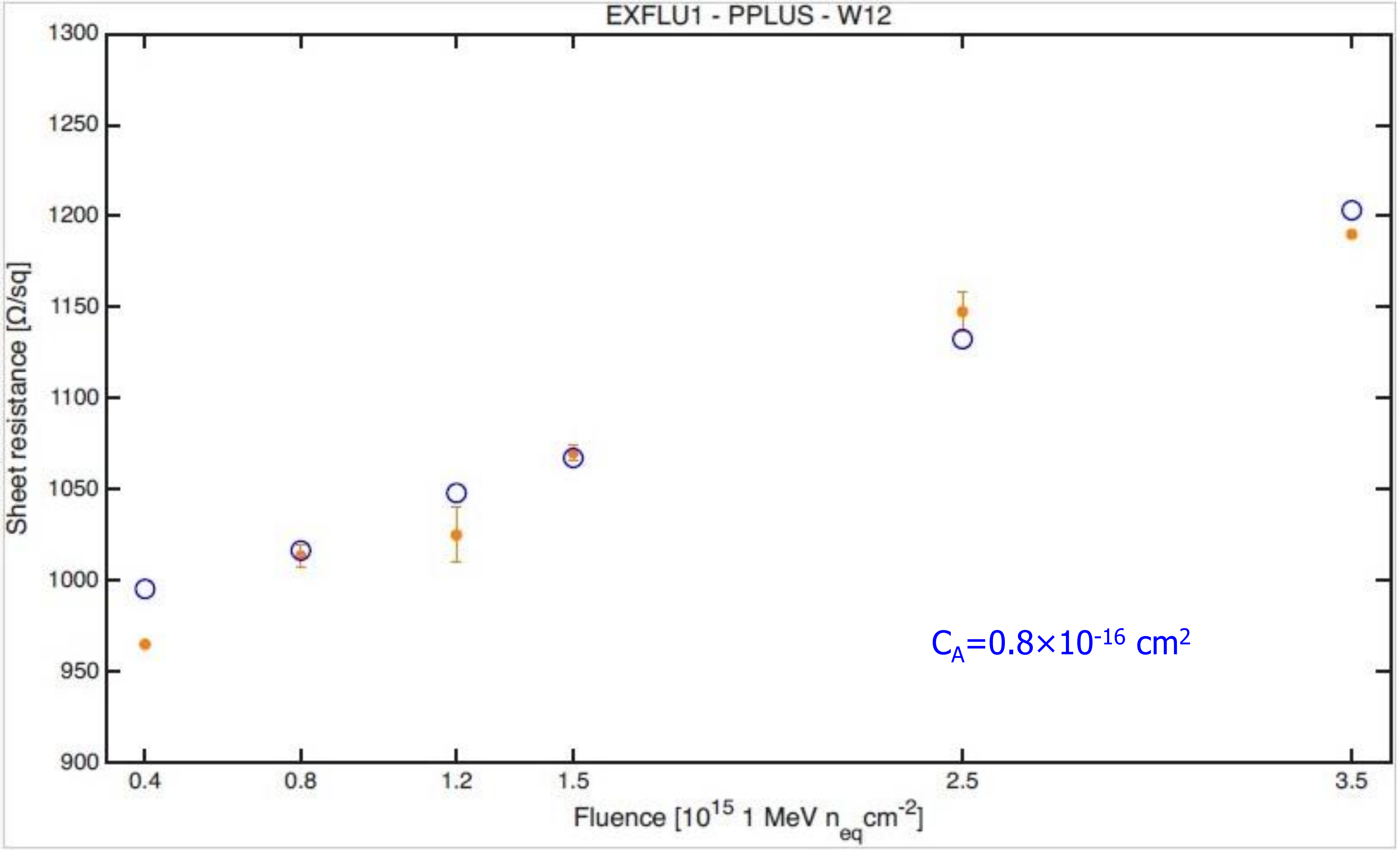
Sim vs meas – PPLUS – W12



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Sim vs meas – PPLUS – W15

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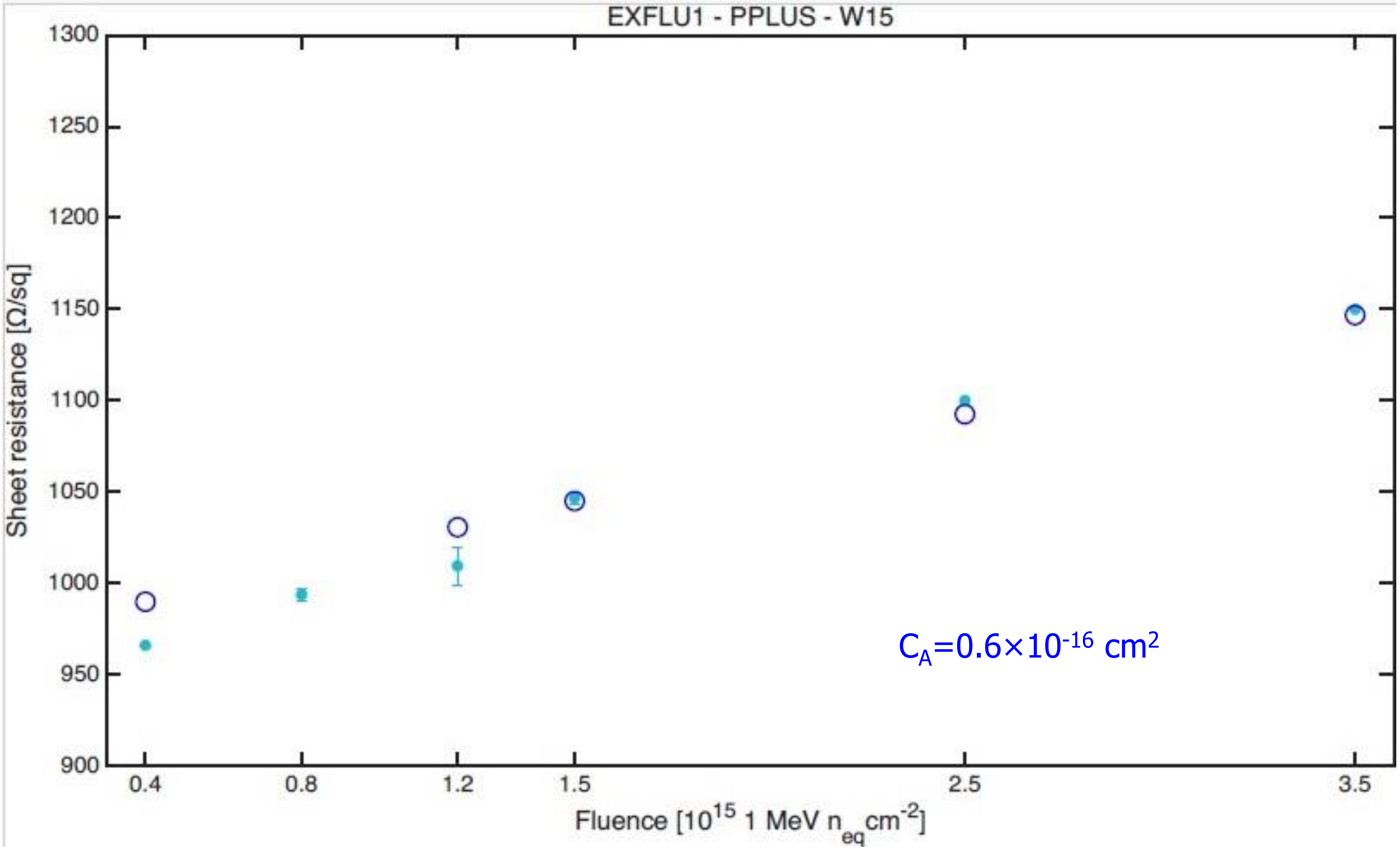
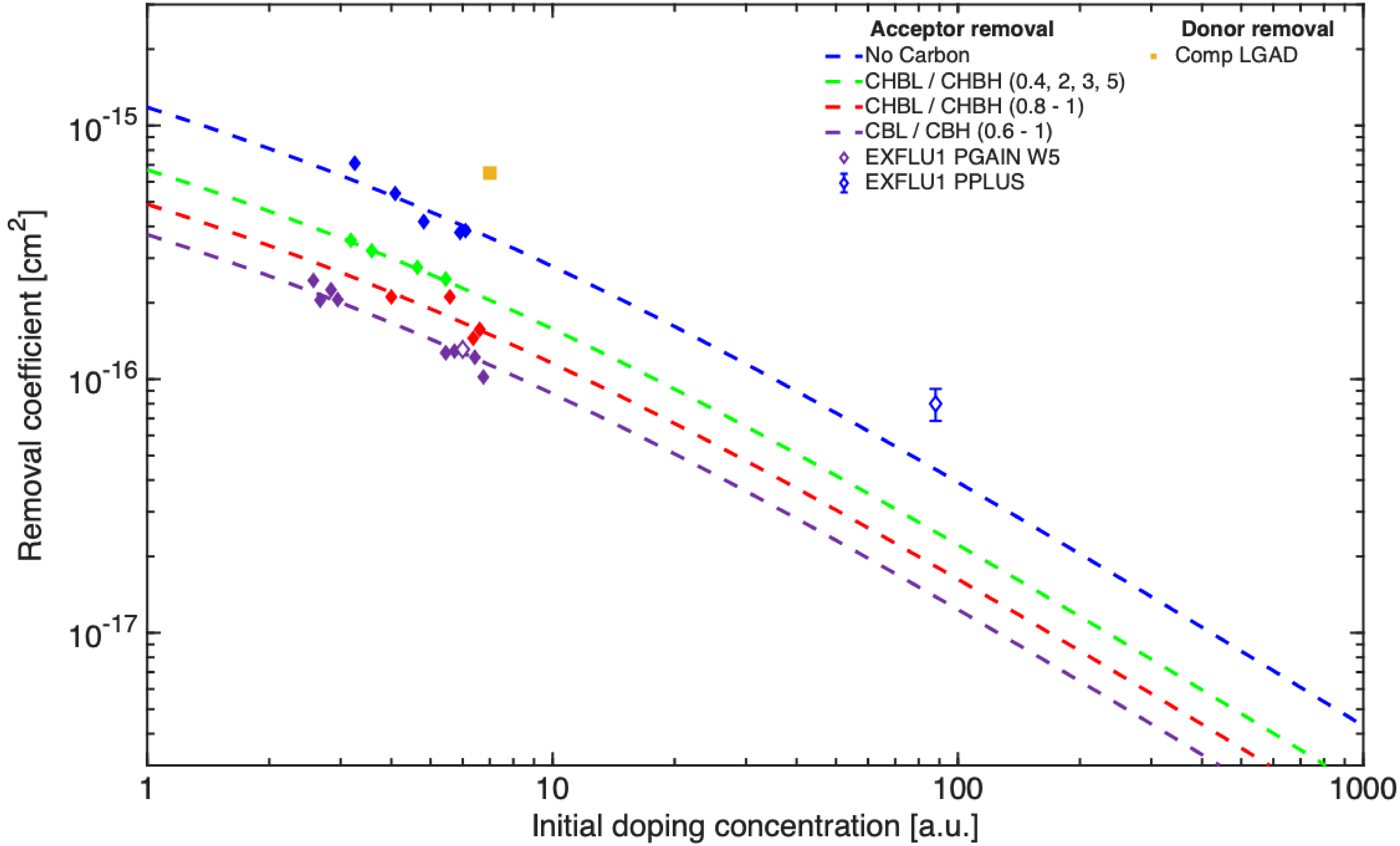


$C_A = 0.6 \times 10^{-16}$ cm^2

c_A extracted from compensated PPLUS



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RSD2 batch — NPLUS

Wafer n.	Sub	Carbon	NPLUS Dose	Dose PGAIN	Met. Thickness
1	Si-Si 55um	N	0.25	2.4	thick
2	Si-Si 55um	N	0.25	2.4	normal
3	Si-Si 55um	N	0.25	2.45	normal
4	Si-Si 55um	N	0.25	2.5	normal
5	Si-Si 55um	N	0.5	2.5	normal
6	epi 45 um	N	0.5	2.5	normal
7	Si-Si 55um	N	0.5	2.45	normal
8	epi 45 um	N	0.5	2.4	normal
9	epi 45 um	N	0.5	2.4	normal
10	epi 45 um	Y (1)	0.5	2.4	normal
11	epi 45 um	N	1	2.4	normal
12	epi 45 um	Y (0.8)	1	2.4	normal
13	Si-Si 55um	N	1	2.45	normal
14	epi 45 um	N	1	2.45	normal
15	Si-Si 55um	N	1	2.35	normal

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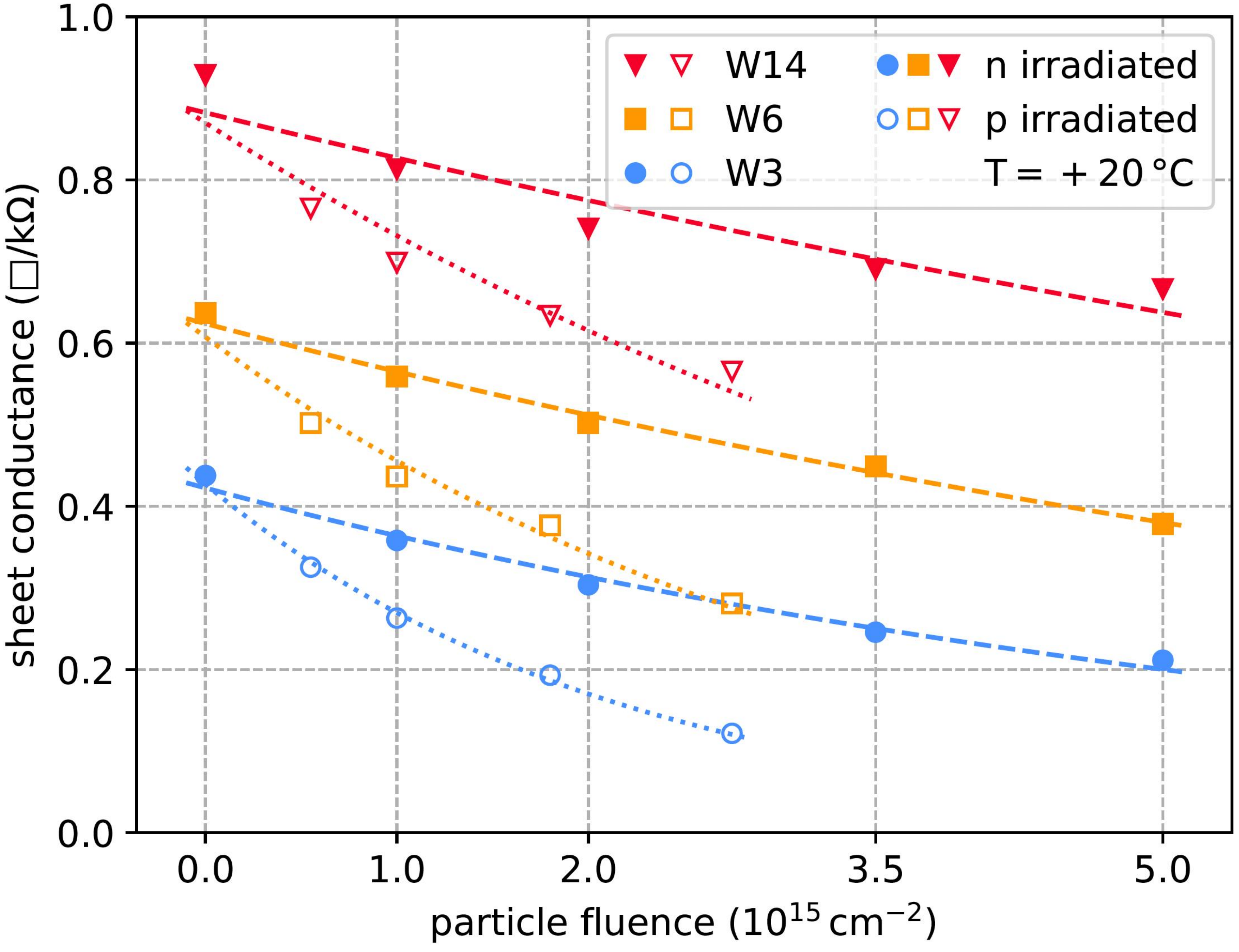

RSD2 batch — NPLUS

c_D donor removal coefficient values $[10^{-16}\ \mathrm{cm}^2]$				
Location	Irradiation	W3	W6	W14
KIT	Neutron	1.5 ± 0.2	1.0 ± 0.2	0.6 ± 0.2
	Proton	4.6 ± 0.4	2.9 ± 0.4	1.7 ± 0.3
Perugia	Neutron	1.6 ± 0.2	1.0 ± 0.2	0.7 ± 0.1
	Proton	4.7 ± 0.6	2.9 ± 0.4	1.7 ± 0.3

Wafer n.	Sub	Carbon	NPLUS Dose	Dose PGAIN	Met. Thickness
1	Si-Si 55um	N	0.25	2.4	thick
2	Si-Si 55um	N	0.25	2.4	normal
3	Si-Si 55um	N	0.25	2.45	normal
4	Si-Si 55um	N	0.25	2.5	normal
5	Si-Si 55um	N	0.5	2.5	normal
6	epi 45 um	N	0.5	2.5	normal
7	Si-Si 55um	N	0.5	2.45	normal
8	epi 45 um	N	0.5	2.4	normal
9	epi 45 um	N	0.5	2.4	normal
10	epi 45 um	Y (1)	0.5	2.4	normal
11	epi 45 um	N	1	2.4	normal
12	epi 45 um	Y (0.8)	1	2.4	normal
13	Si-Si 55um	N	1	2.45	normal
14	epi 45 um	N	1	2.45	normal
15	Si-Si 55um	N	1	2.35	normal

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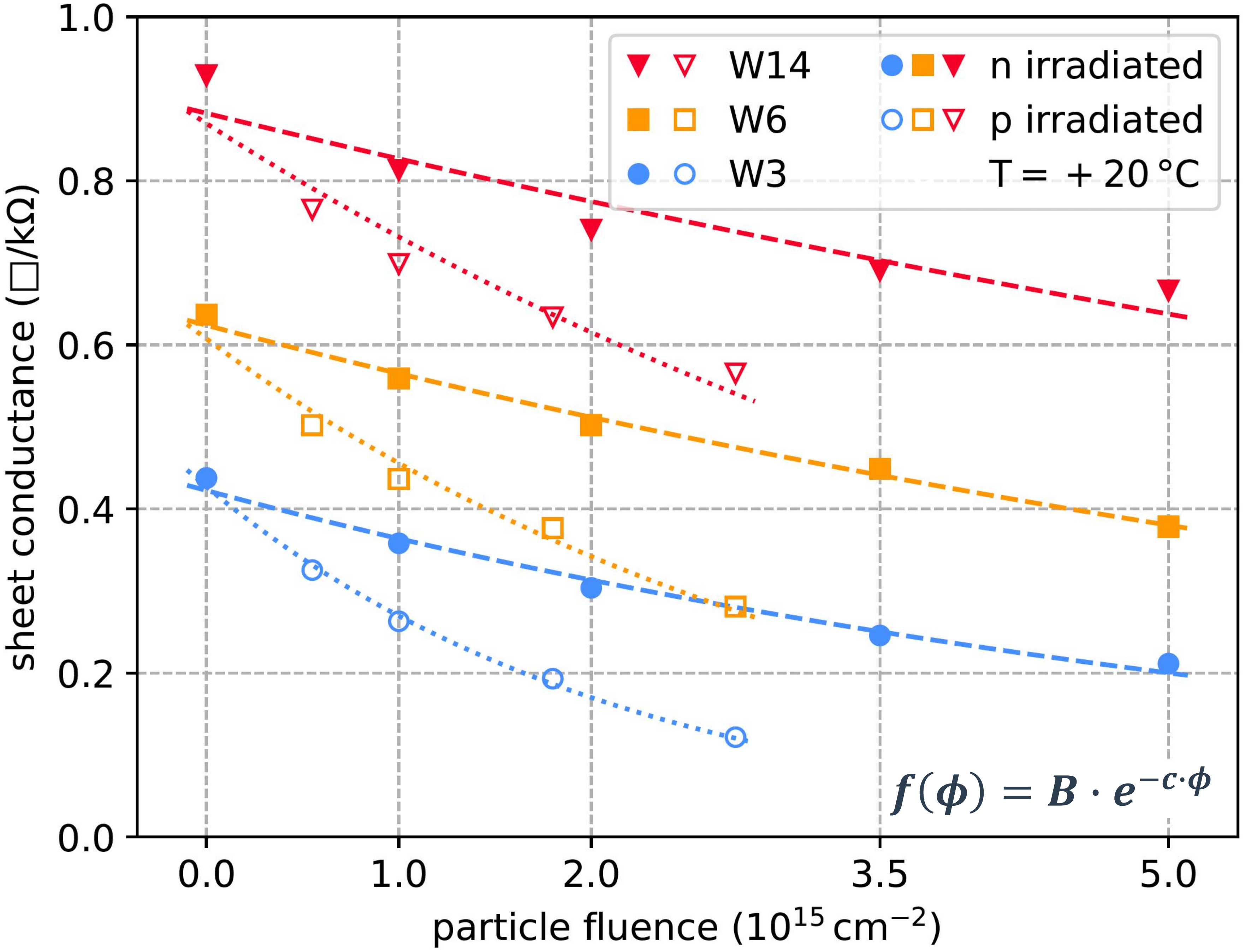

NPLUS profiles before irradiation

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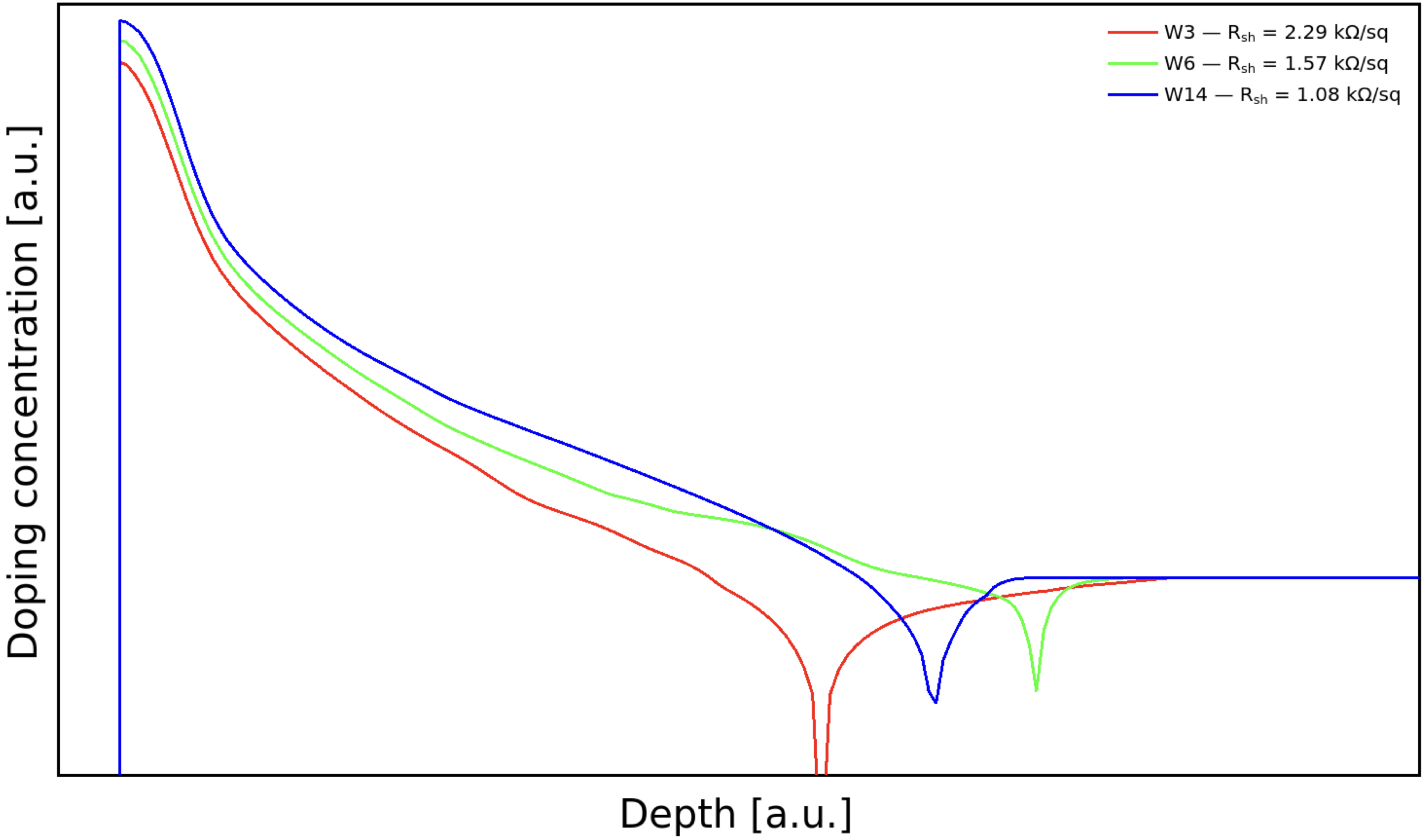

RSD2 NPLUS W3 — Neutron Proton

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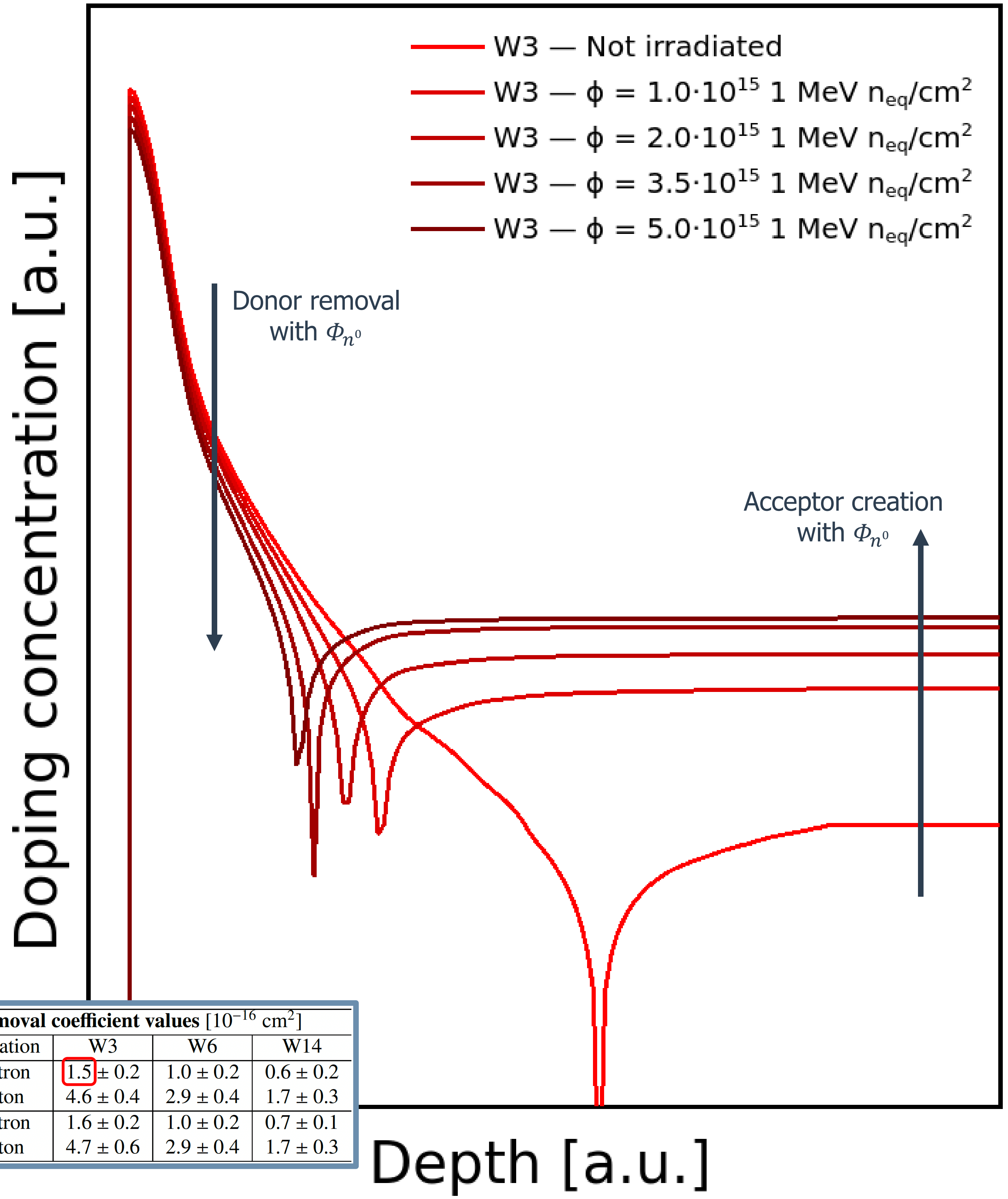
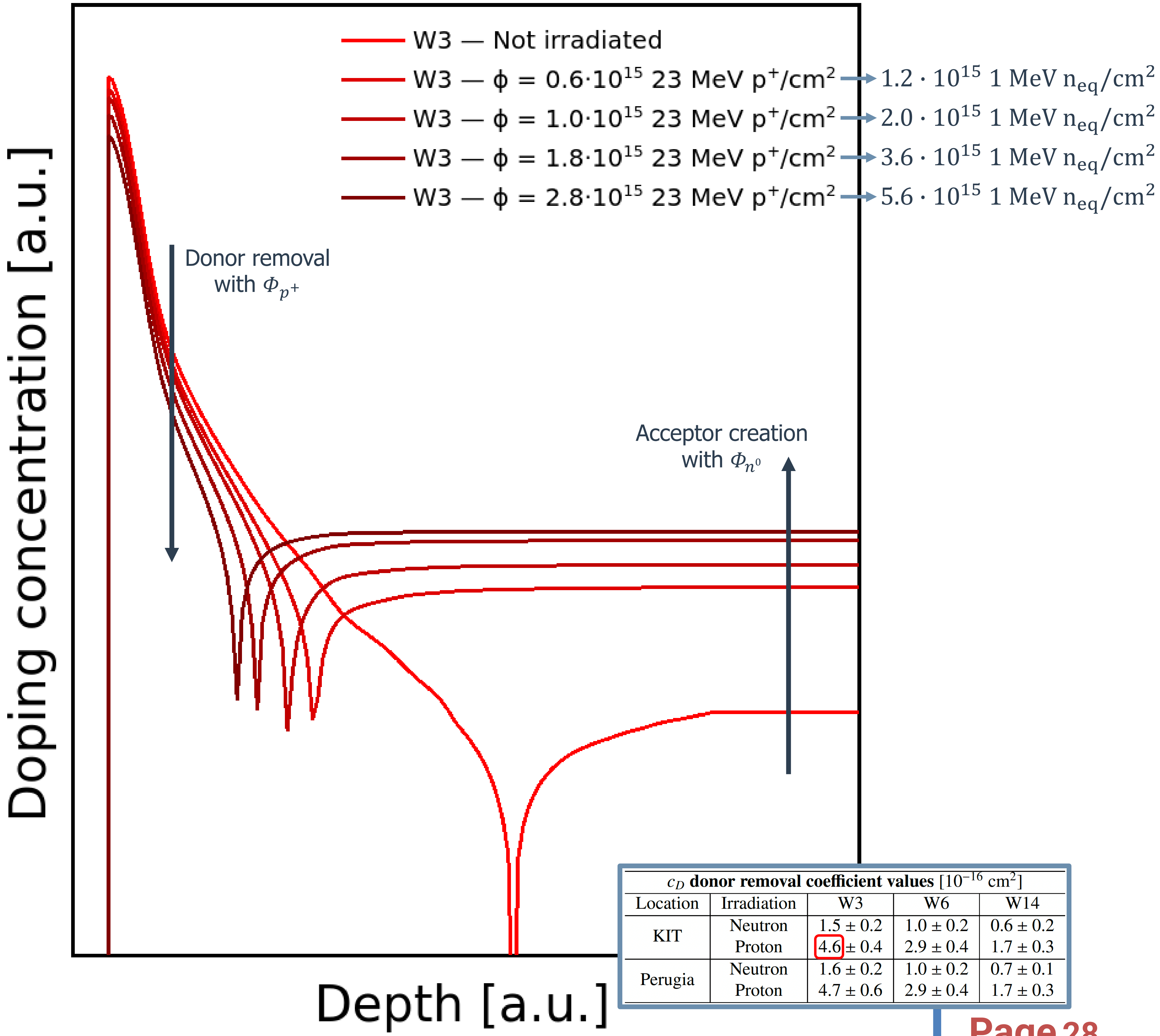
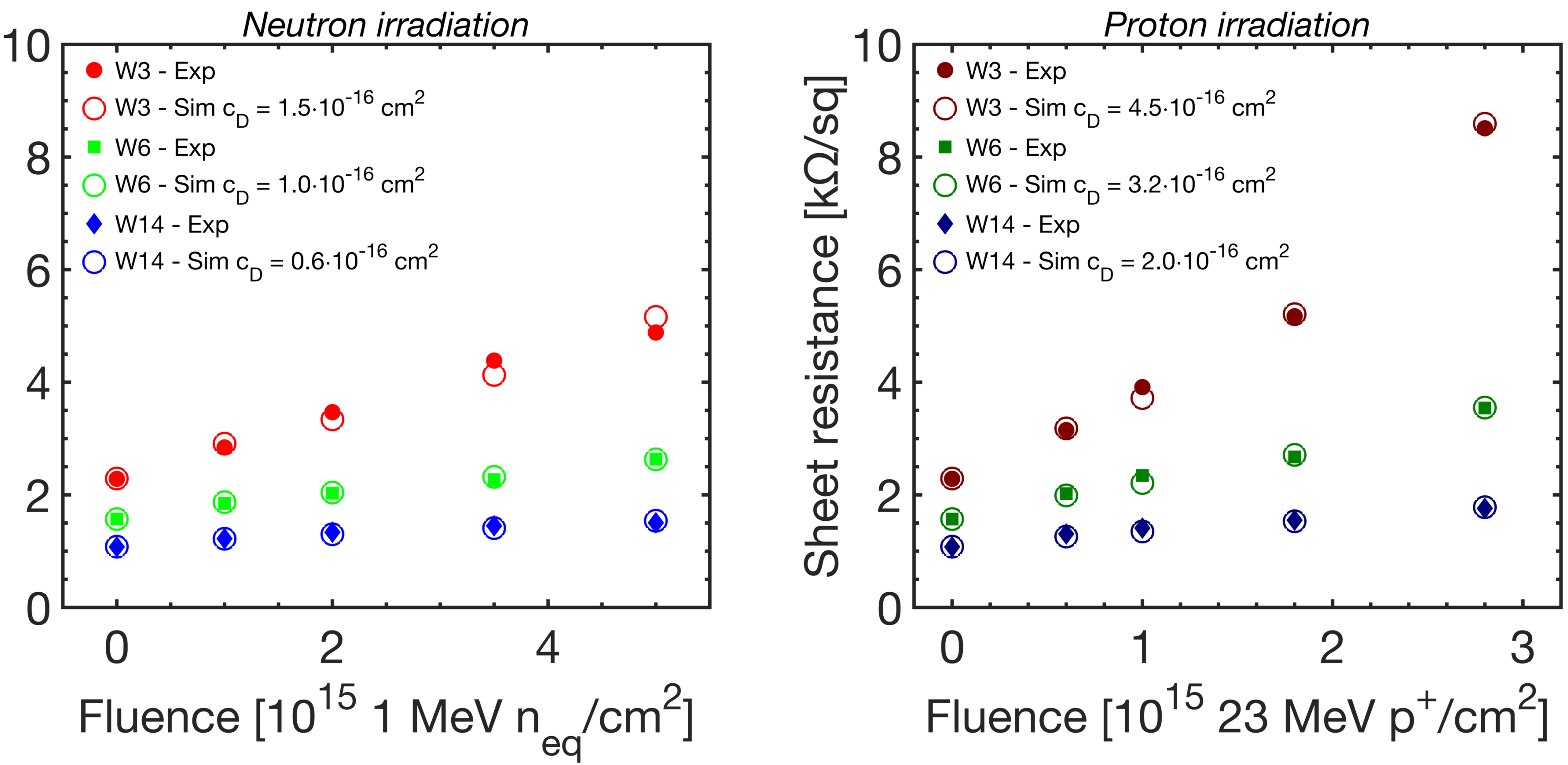


c_D donor removal coefficient values [10^{-16} cm^2]				
Location	Irradiation	W3	W6	W14
KIT	Neutron	1.5 ± 0.2	1.0 ± 0.2	0.6 ± 0.2
	Proton	4.6 ± 0.4	2.9 ± 0.4	1.7 ± 0.3
Perugia	Neutron	1.6 ± 0.2	1.0 ± 0.2	0.7 ± 0.1
	Proton	4.7 ± 0.6	2.9 ± 0.4	1.7 ± 0.3



c_D donor removal coefficient values [10^{-16} cm^2]				
Location	Irradiation	W3	W6	W14
KIT	Neutron	1.5 ± 0.2	1.0 ± 0.2	0.6 ± 0.2
	Proton	4.6 ± 0.4	2.9 ± 0.4	1.7 ± 0.3
Perugia	Neutron	1.6 ± 0.2	1.0 ± 0.2	0.7 ± 0.1
	Proton	4.7 ± 0.6	2.9 ± 0.4	1.7 ± 0.3

RSD2 batch — NPLUS — TCAD   Measurements



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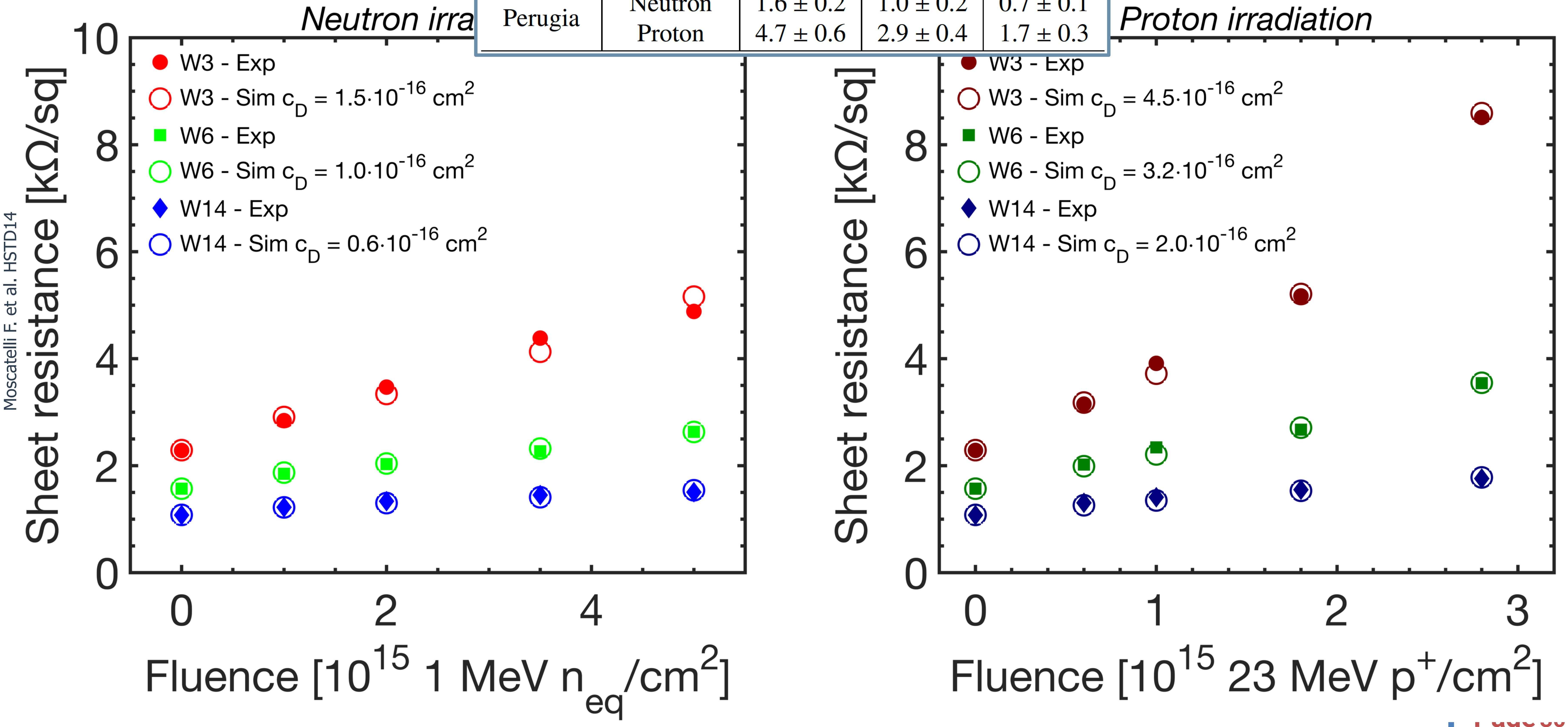
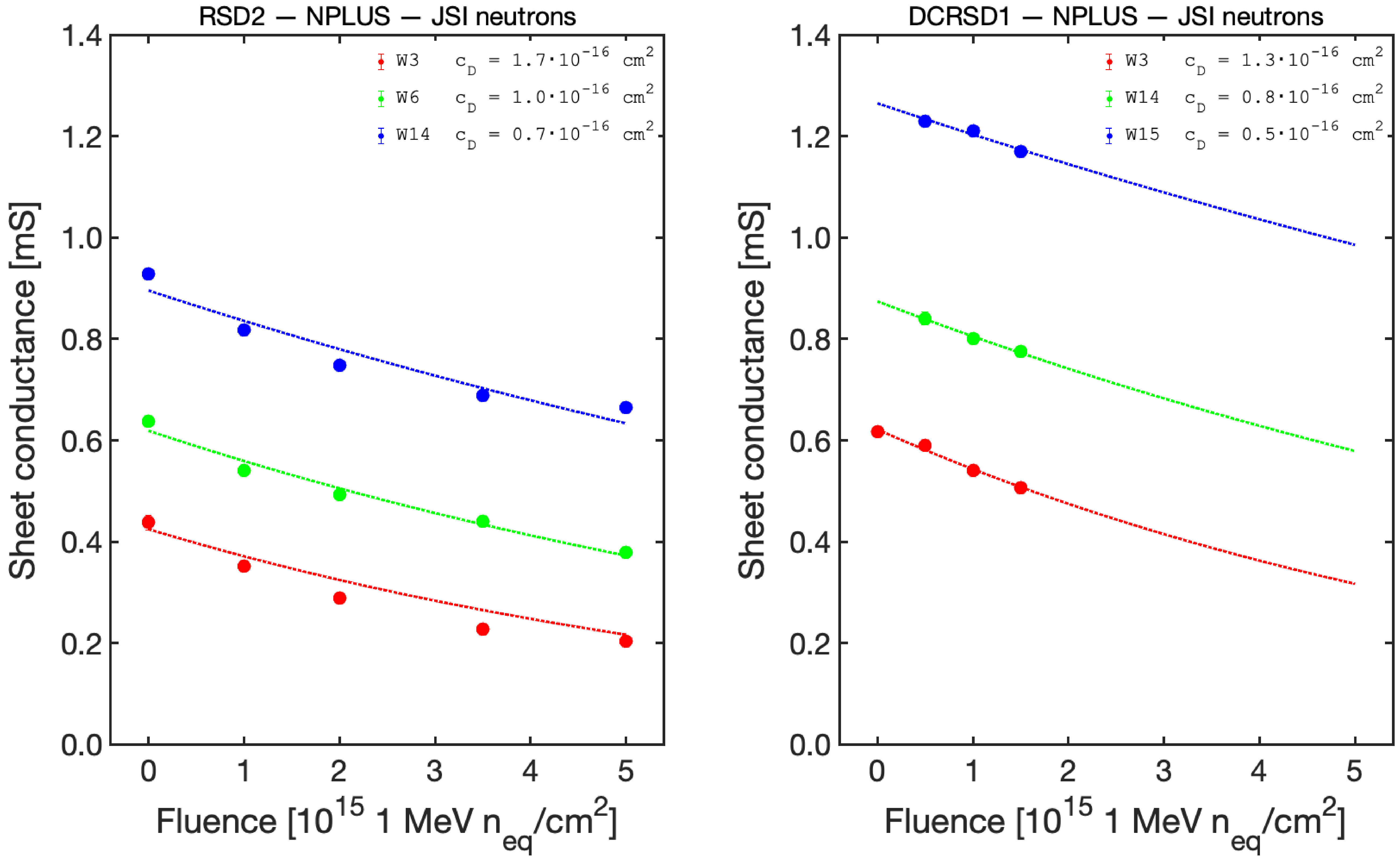
RSD2 batch — NPL ... nts

c_D **donor removal coefficient values** [10^{-16} cm^2]				
Location	Irradiation	W3	W6	W14
KIT	Neutron	1.5 ± 0.2	1.0 ± 0.2	0.6 ± 0.2
	Proton	4.6 ± 0.4	2.9 ± 0.4	1.7 ± 0.3
Perugia	Neutron	1.6 ± 0.2	1.0 ± 0.2	0.7 ± 0.1
	Proton	4.7 ± 0.6	2.9 ± 0.4	1.7 ± 0.3



New DC-RSD1 batch — NPLUS — TCAD   Measurements



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c_D extracted from NPLUS

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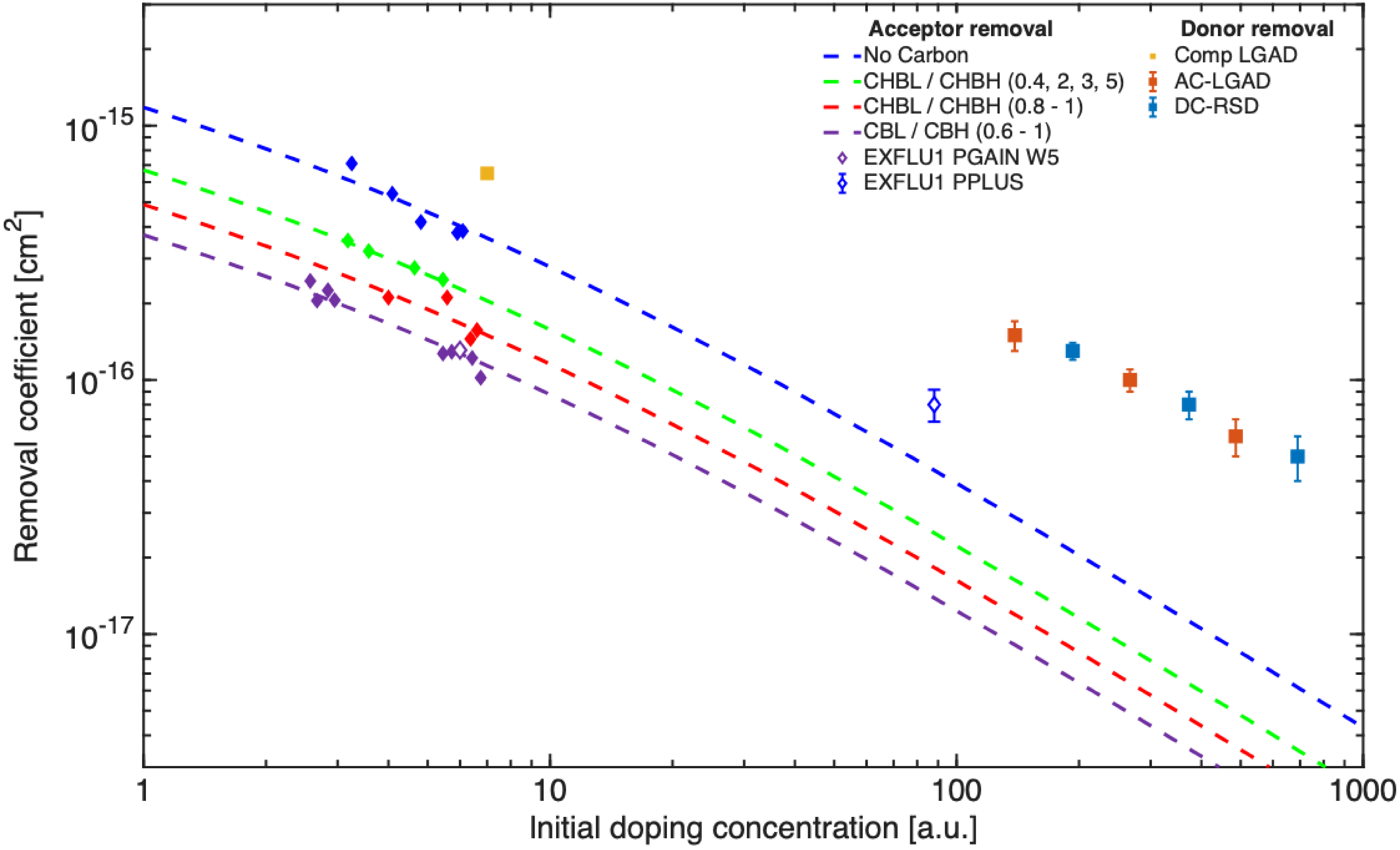

Conclusion

Doping removal can be estimated via **changes in sheet resistance** under irradiation:

- **For surface implants of opposite conductivity to the substrate:** van der Pauw measurements alone are sufficient;
- **For deep and/or same conductivity type implants:** simulation is required to interpret van der Pauw measurements.

Preliminary analyses indicate:

- **Correlation** between **C-V** and **van der Pauw** extracted **removal coefficients;**
- **A more pronounced donor removal than acceptor removal.**

New analyses (EXFLU1, RSD2, DC-RSD1, NLGAD) aim **to** strengthen and **validate these results.**

Thank you for your attention!

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