Virtual Chalcogenide PV Conference 2020

25th - 28th May 2020 |Online

Advanced electrical characterization of ultra-thin CIGS solar cells in the dark

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➢ *Abstract*

The objective of this work is to ***show how electrical characterizations in the dark supported by simulations can provide sensitive analyses to understand different gains or losses of performances in ultra-thin CIGS PV*** *cells after different optimization and how they can provide useful information to the process for improvement.*

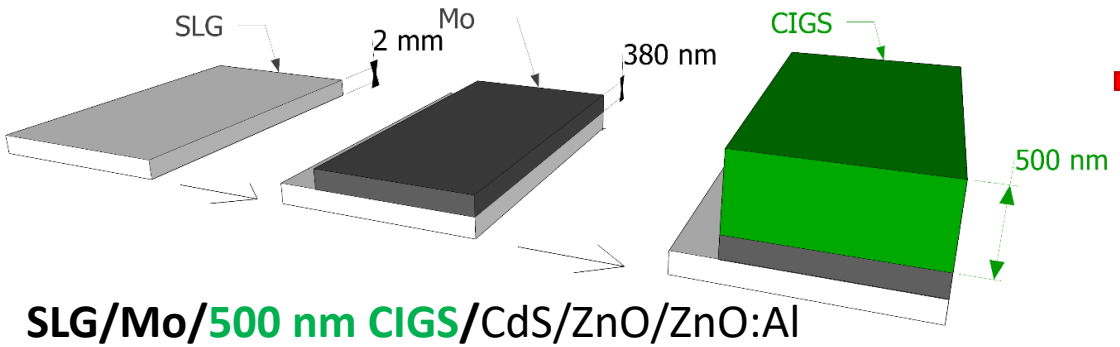
➢ Outline

- We will consider 3 series of experiments using **500nm thin-CIGS** absorbers **with/without grading** on **Mo**, on **Al_2O_3 passivation or on SLG/steel substrates**

- For each, the **parameters of I-V measurements** in the dark will be correlated with the **performances under illumination**.

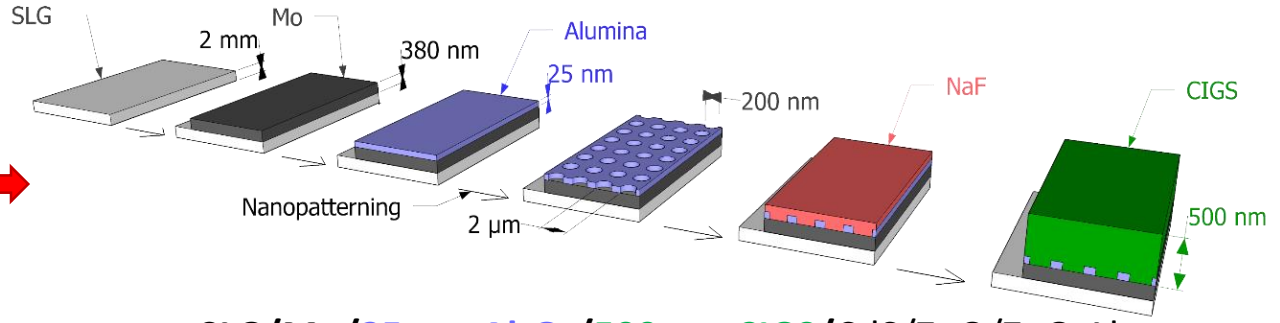
- However each will show that to understand some **degradation mechanisms**, **capacitance-voltage measurements** are also required, as well as the **help of simulations** to carefully and correctly interpret the origin of the defects, with the final objective to optimize the performances of the cells.

➢ Experiment details



SLG/Mo/500 nm CIGS/CdS/ZnO/ZnO:Al

With flat grading



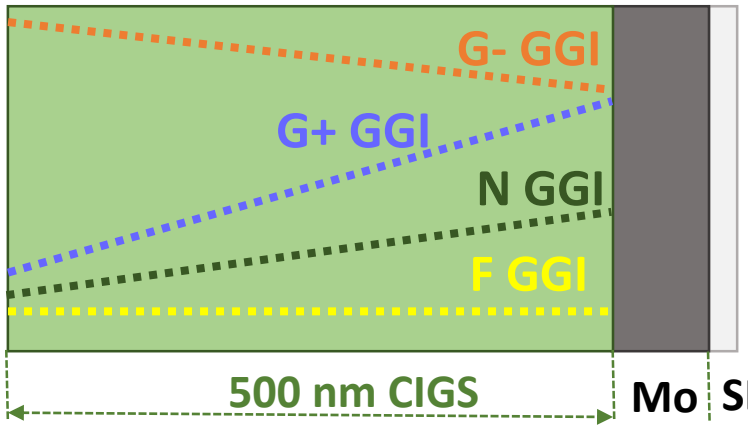
SLG/Mo/25 nm Al_2O_3/500 nm CIGS/CdS/ZnO/ZnO:Al

Nanopatterning: ***With flat grading and NaF precursor***

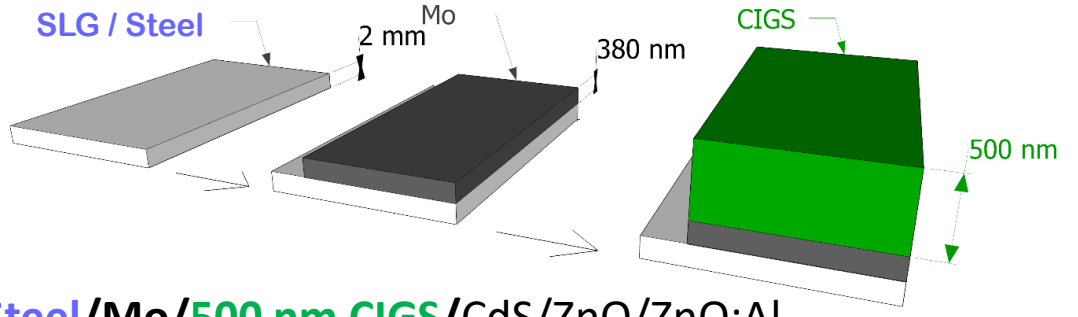
*contact opening width (**W = 200nm**)*

*hole pitch (**P = 2 µm**)*

Follow Pedro Salomé at 12h



Contact Wei-Chao (chen.weichao@angstrom.uu.se)

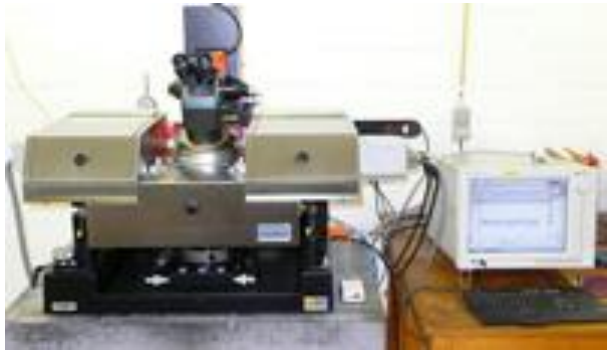


SLG vs Steel/Mo/500 nm CIGS/CdS/ZnO/ZnO:Al

With grading

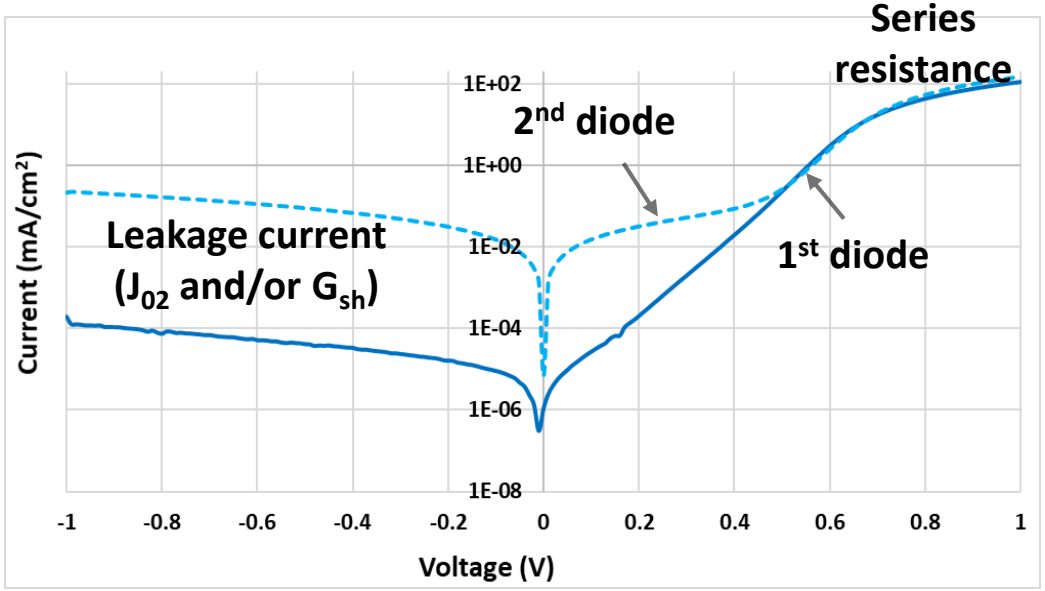
➢ Characterization details

The **dark *I-V* measurements** were performed at UCLouvain



Shielded *low signal PM8PS probe station +*
Keithley B1500a semiconductor device analyzer

Controlled temperature 25°C, in the dark



I-V measurement *(4 wires configuration)*
4 SMU up to 100 mA, ***10 fA resolution*** → The **two-diode model**

$$J(V) = J_{01}\left[exp\left(\frac{q(V-R_sJ)}{n_1kT}\right)-1\right] + J_{02}\left[exp\left(\frac{q(V-R_sJ)}{n_2kT}\right)-1\right] + \frac{V-R_sJ}{R_{sh}}$$

J_{01} *D_1 Diffusion* — J_{02} *D_2 Recombination* — R_{sh} *G_{sh} Shunt conductance*

CV measurement
2 SMU from 1 KHz to 5 MHz with ***0.1 fF resolution***

Apparent doping Ncv

$$N_{cv} = -\frac{2}{q\varepsilon A^2\left[\frac{d(C^{-2})}{dV_{dc}}\right]}$$

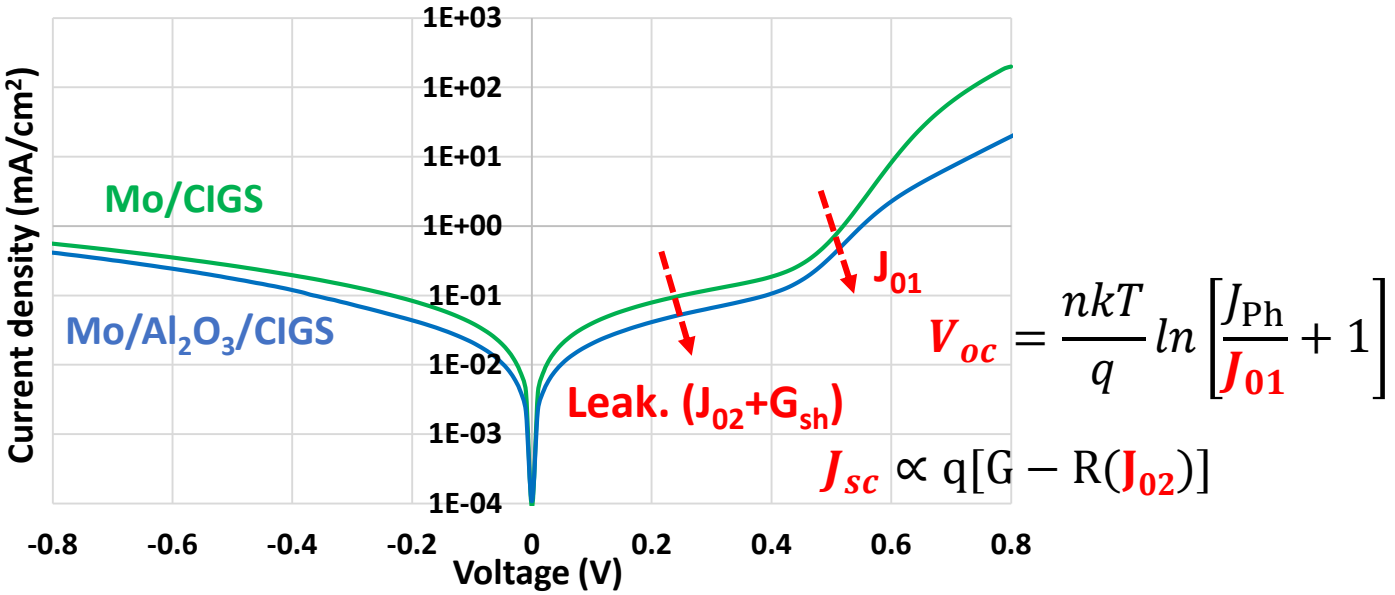
Depletion width (X)

$$C = \frac{\varepsilon A}{X}$$

V_{bi} extraction

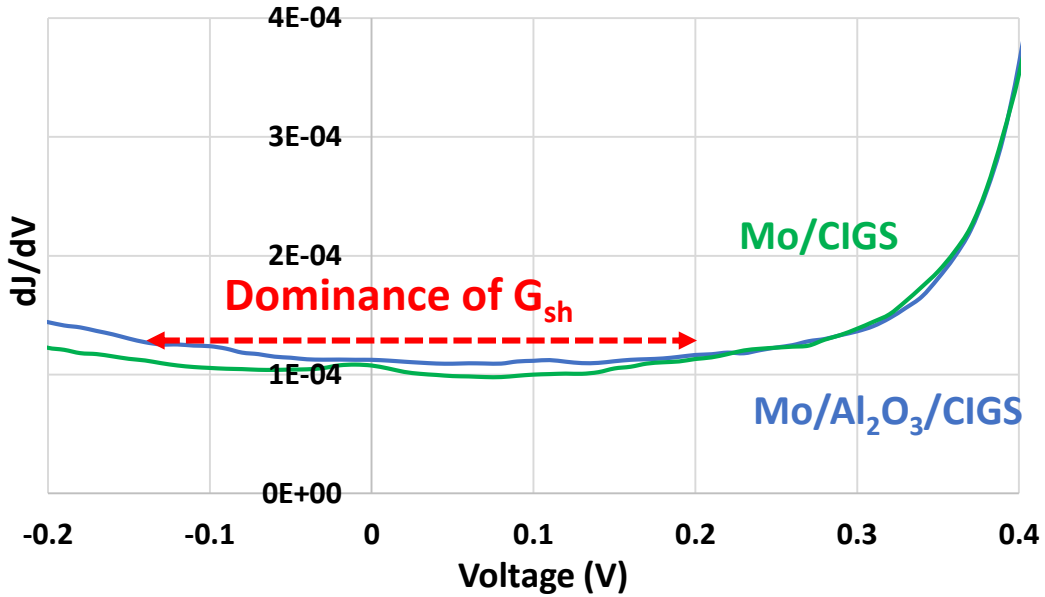
$$C^{-2} = \frac{2(V_{bi}-V_{dc})}{q\varepsilon A^2 N_A}$$

➢ Characterization results: current - voltage (*J-V*) Mo/CIGS vs Mo/Al_2O_3/CIGS



$$V_{oc} = \frac{nkT}{q} ln\left[\frac{J_{\mathrm{Ph}}}{J_{01}} + 1\right]$$

$$J_{sc} \propto q[G - R(J_{02})]$$



Electrical parameters	Dark parameters						Parameters under illumination*			
	J_{01} (mA/cm²)	J_{02} (mA/cm²)	n_1	n_2	R_s (Ω.cm²)	R_{sh} (Ω.cm²)	J_{sc} (mA/cm²)	V_{oc} (V)	FF (%)	Eff (%)
Mo/CIGS	7.13E-05	2.06E-02	2.02	5.63	0.69	2.11E+03	21.4	573.1	66.5	8.15
Mo/Al_2O_3	4.20E-05	6.68E-03	2.12	3.68	1.84	3.86E+03	24.3	609.1	64.7	9.50

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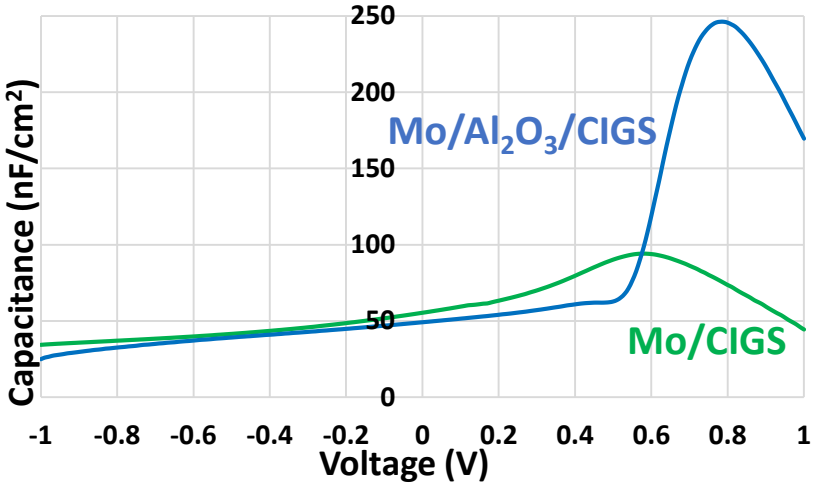
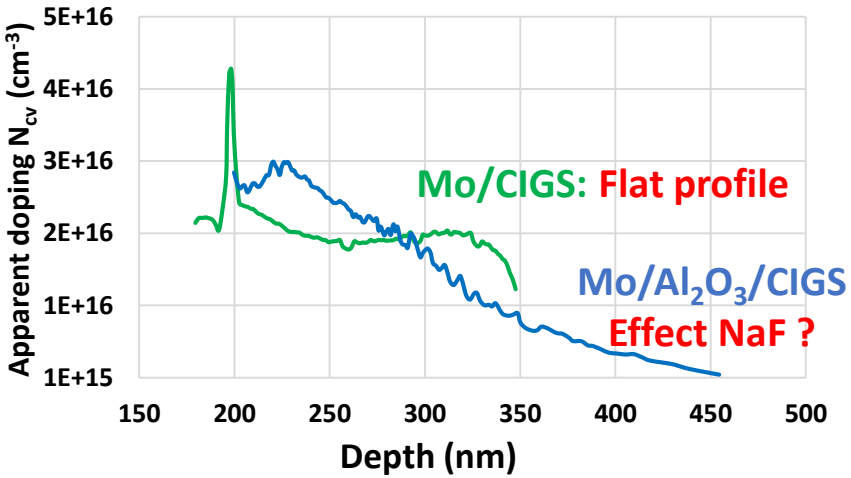
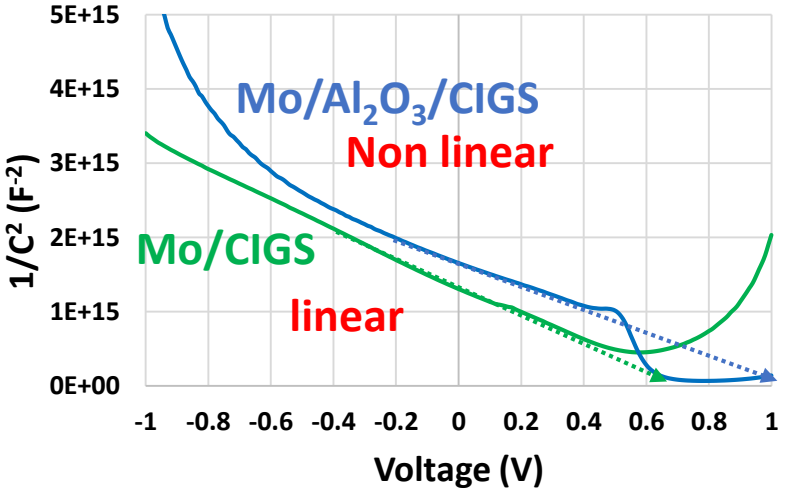
➢ Characterization results: capacitance - voltage *(C-V)* Mo/CIGS vs $Mo/Al_2O_3/CIGS$







$$V_{oc} = \frac{nkT}{q} ln\left[\frac{(N_A + \Delta n)\Delta n}{n_i^2}\right]$$

$$C^{-2} = \frac{2(V_{bi} - V_{dc})}{q\varepsilon A^2 N_A}$$

Electrical parameters	Dark parameters			Parameters under illumination*			
	$N_{app(0\ V)}$ (cm^{-3})	X (nm)	$V_{bi\ (0\ V)}$ (eV)	J_{sc} (mA/cm^2)	V_{oc} (V)	FF (%)	Eff (%)
Mo/CIGS	2.30E16	217.41	0.76	21.4	573.1	66.5	8.15
$Mo/Al_2O_3/CIGS$	2.70E16	244.72	1.07	24.3	609.1	64.7	9.50

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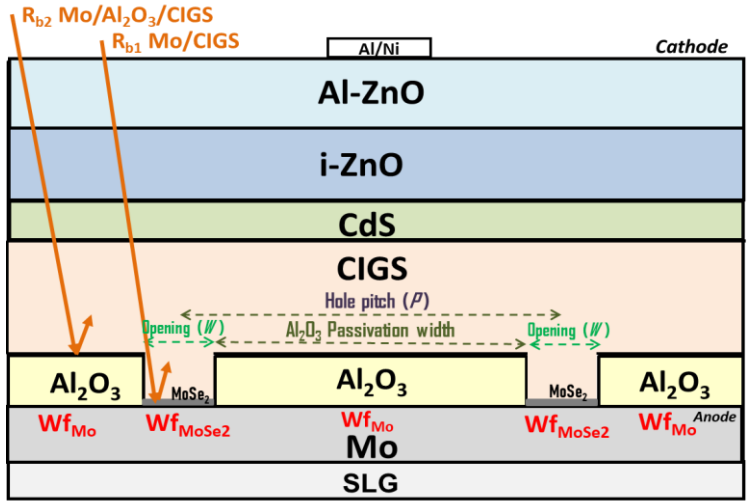
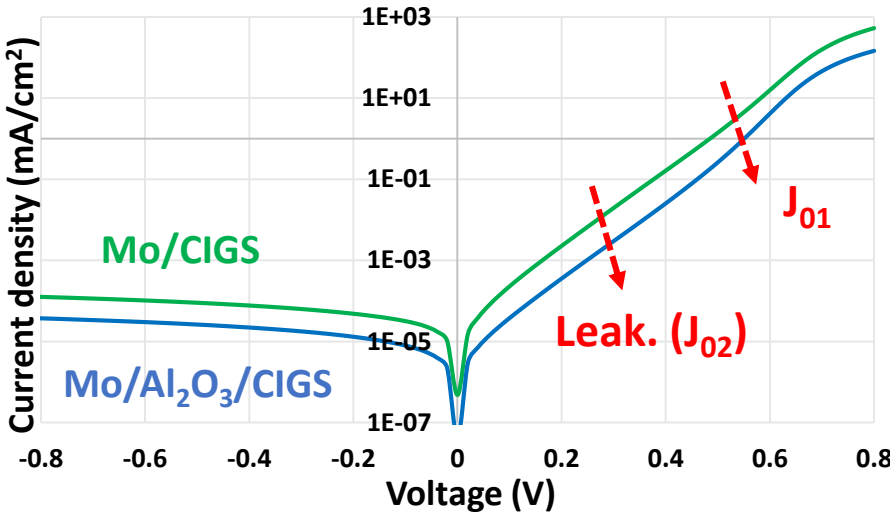
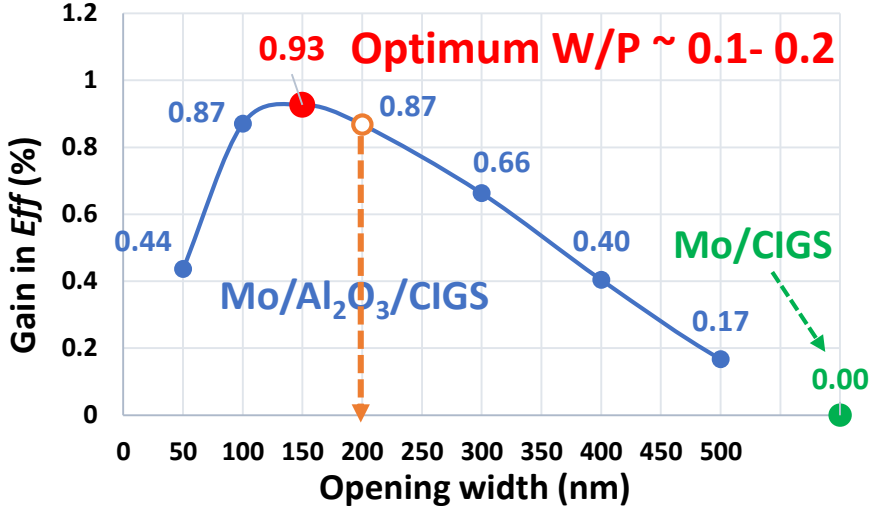
➢ ATLAS 2D Simulation: current - voltage Mo/CIGS vs Mo/Al_2O_3/CIGS



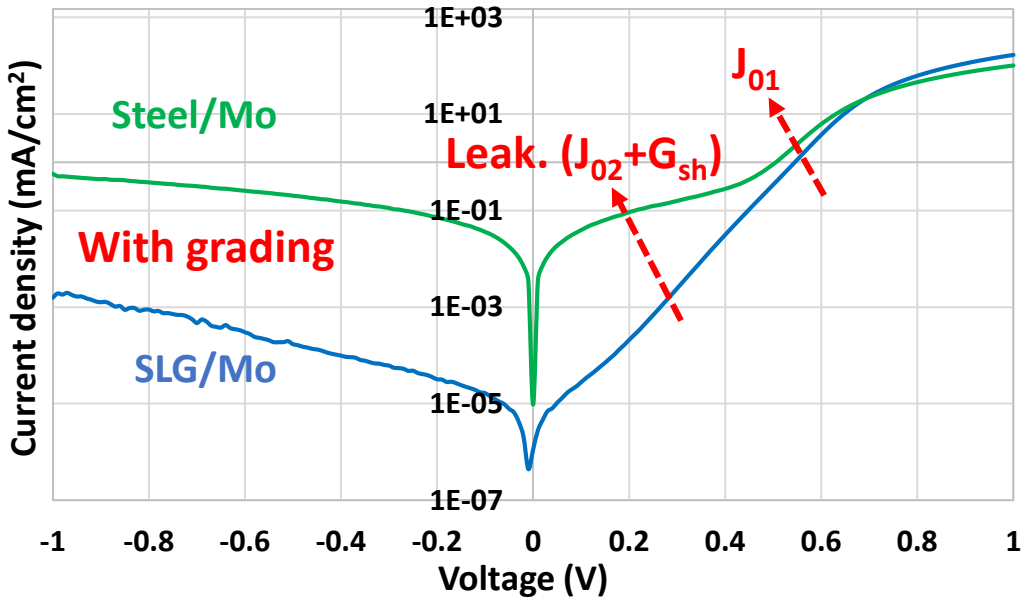
Without R_{sh}

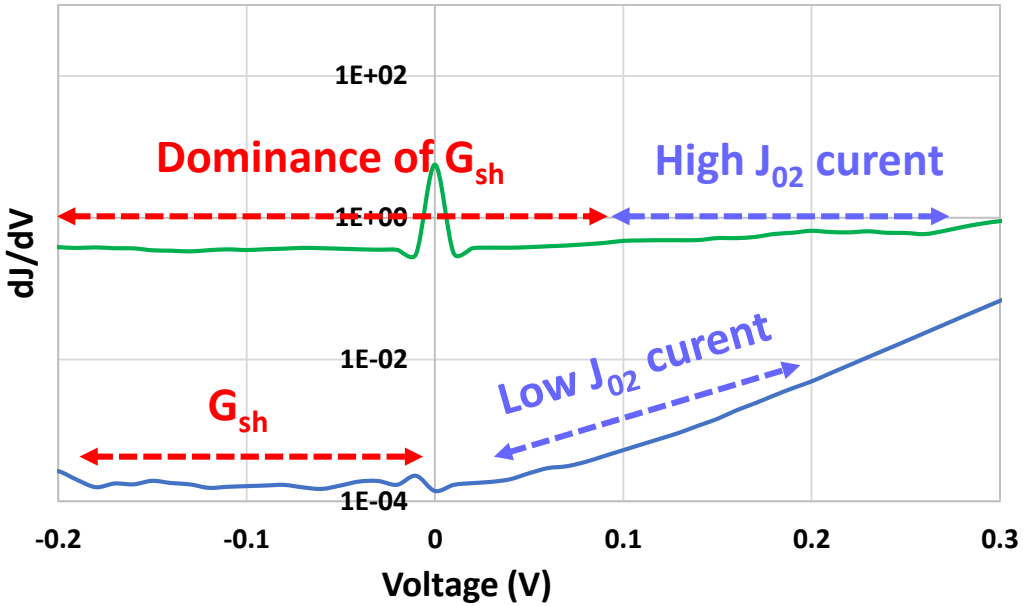




Electrical parameters	Dark parameters					Parameters under illumination			
	J_{01} (mA/cm²)	J_{02} (mA/cm²)	n_1	n_2	R_s (Ω.cm²)	J_{sc} (mA/cm²)	V_{oc} (V)	FF (%)	Eff (%)
Mo/CIGS	3.70E-05	2.40E-04	1.21	1.64	0.83	26.62	659.79	76.15	13.38
Mo/Al_2O_3	1.99E-06	4.02E-05	1.45	1.92	2.14	28.13	700.74	72.75	14.34

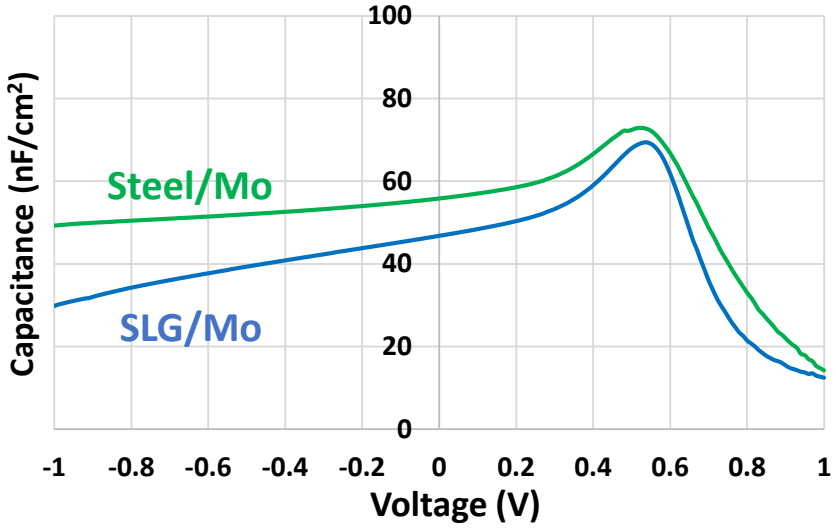
➢ Characterization results : current - voltage (*J-V*) SLG/Mo vs Steel/Mo

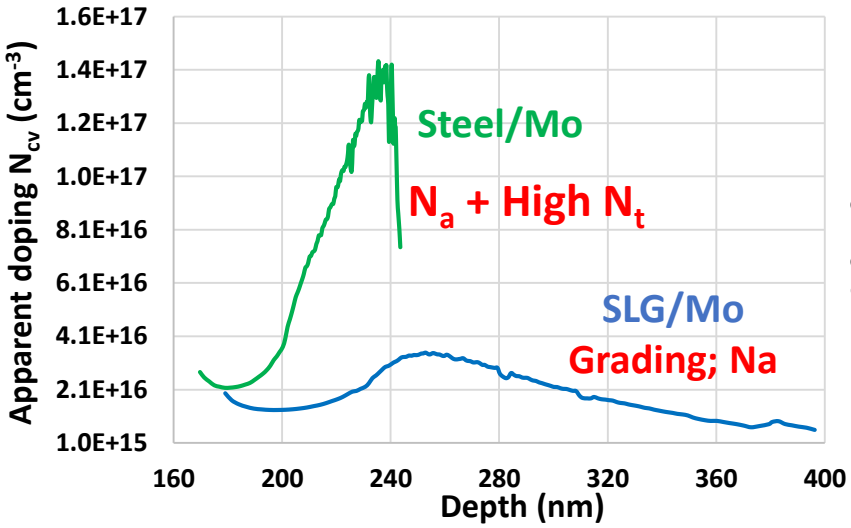


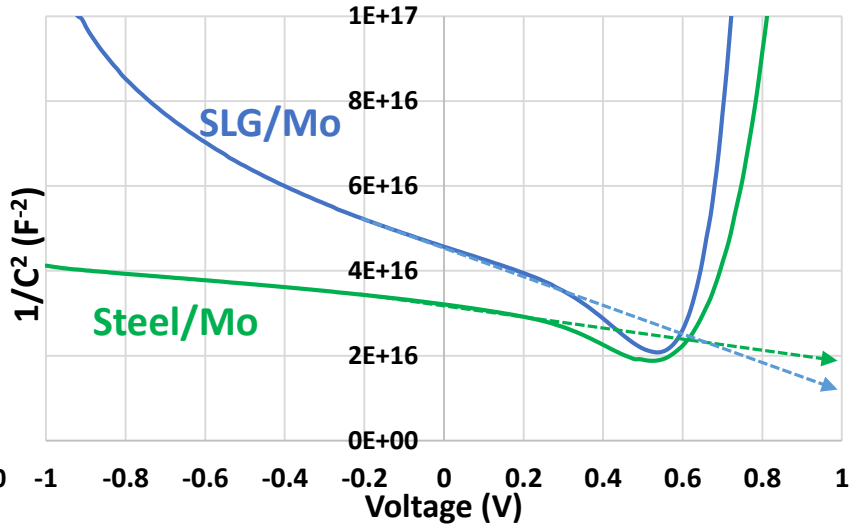


Electrical parameters	Dark parameters						Parameters under illumination			
	J_{01} (mA/cm²)	J_{02} (mA/cm²)	n_1	n_2	R_s (Ω.cm²)	R_{sh} (Ω.cm²)	J_{sc} (mA/cm²)	V_{oc} (V)	FF (%)	Eff (%)
SLG/Mo	2.37E-06	3.79E-06	1.62	1.91	1.77	3.23E+05	23.61	0.674	74.20	11.78
Steel/Mo	2.19E-04	2.02E-02	2.27	5.15	3.46	1.59E+03	22.78	0.641	73.85	10.78

➢ Characterization results : capacitance - voltage *(C-V)* SLG/Mo vs Steel/Mo







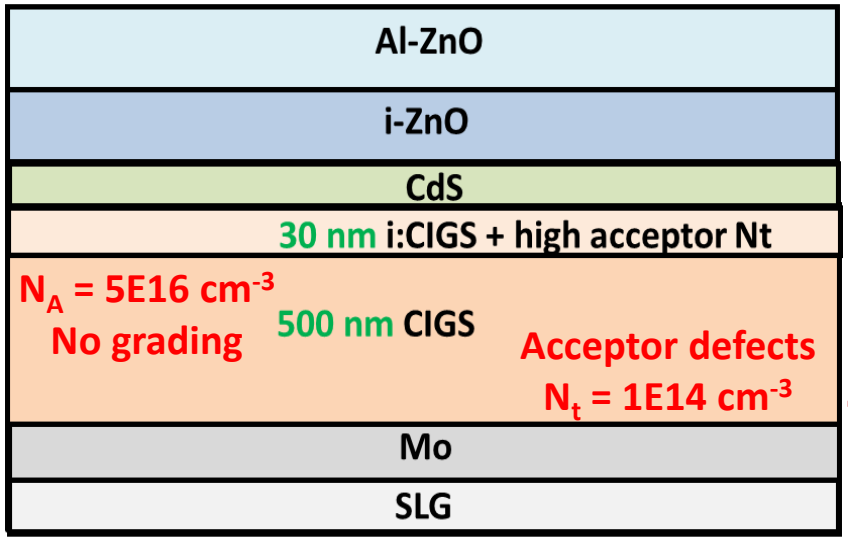
Another approach to decouple N_a and N_t is necessary

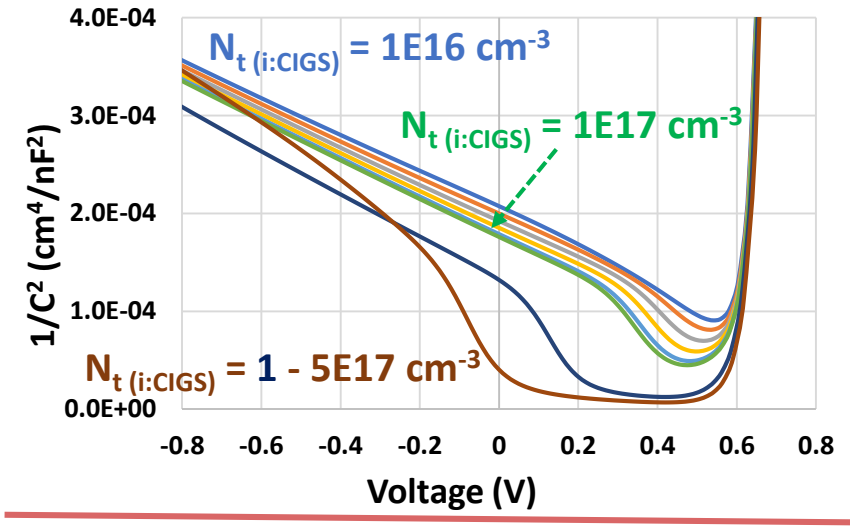
$$C^{-2} = \frac{2(V_{bi} - V_{dc})}{q\varepsilon A^2 N_A}$$

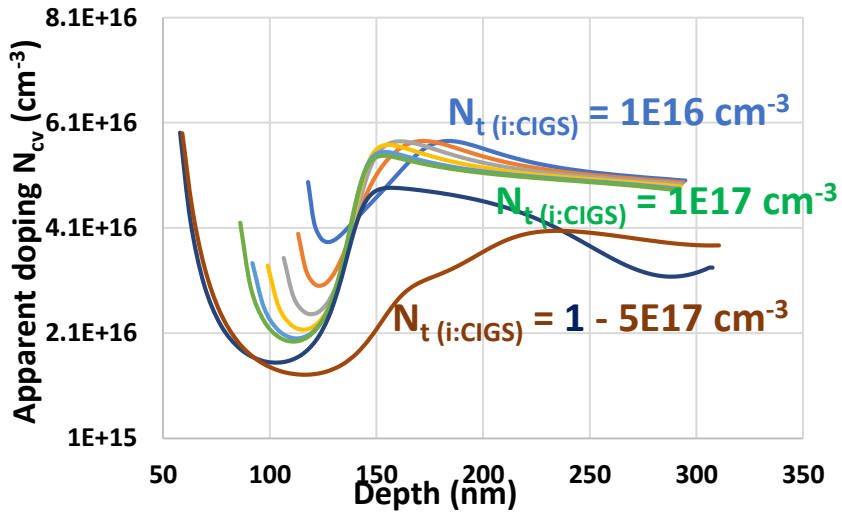
$$V_{oc} = \frac{nkT}{q} ln\left[\frac{(N_A + \Delta n)\Delta n}{n_i^2}\right]$$

Electrical parameters	Dark parameters			Parameters under illumination			
	$N_{app(0\ V)}$ (cm^{-3})	X (nm)	$V_{bi\ (0\ V)}$ (eV)	J_{sc} (mA/cm^2)	V_{oc} (V)	FF (%)	Eff (%)
SLG/Mo	2.30E16	257.20	1.41	23.61	0.674	74.20	11.78
Steel/Mo	1.12E17	215.64	2.52	22.78	0.641	73.85	10.78

➢ SCAPS 1D Simulation: Bulk defects



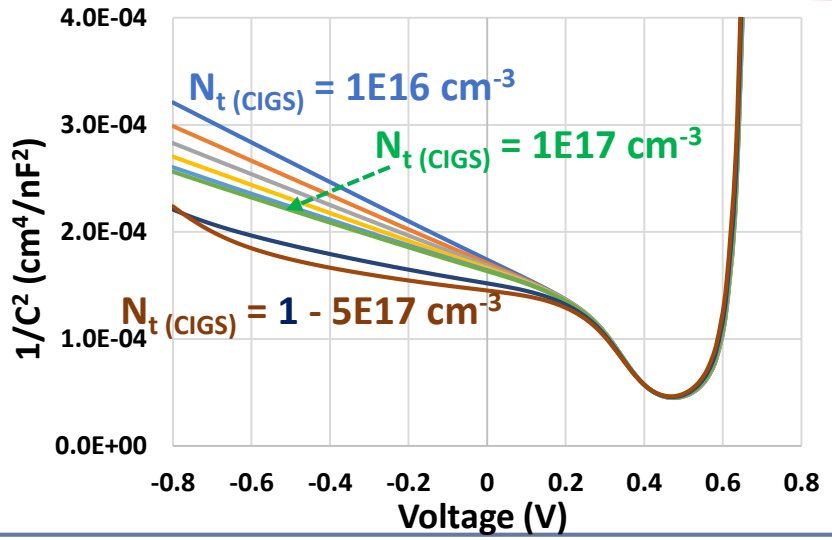


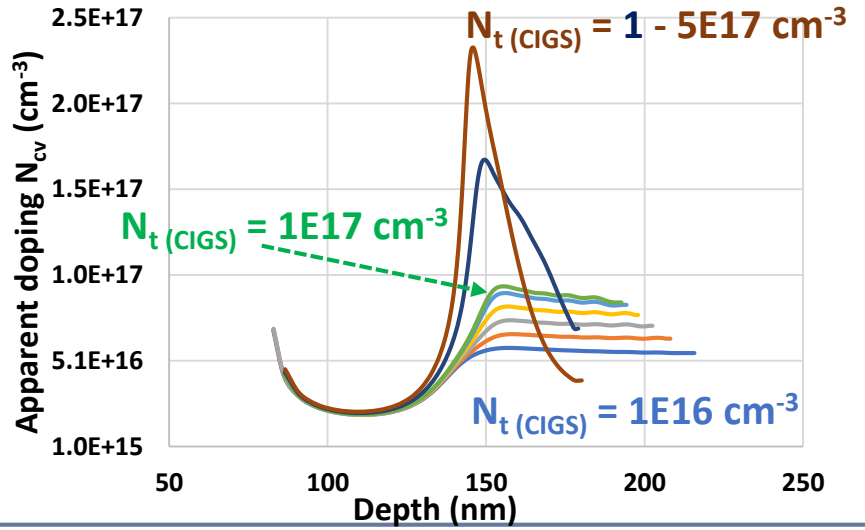


Modification of the Mott Schottky plot

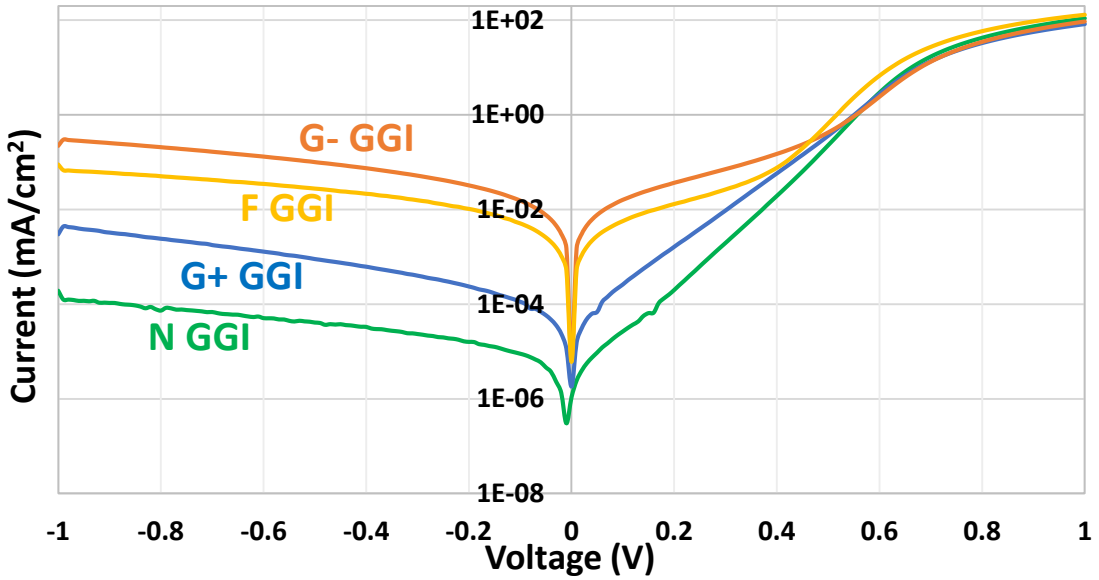
Non ideal P/N junction

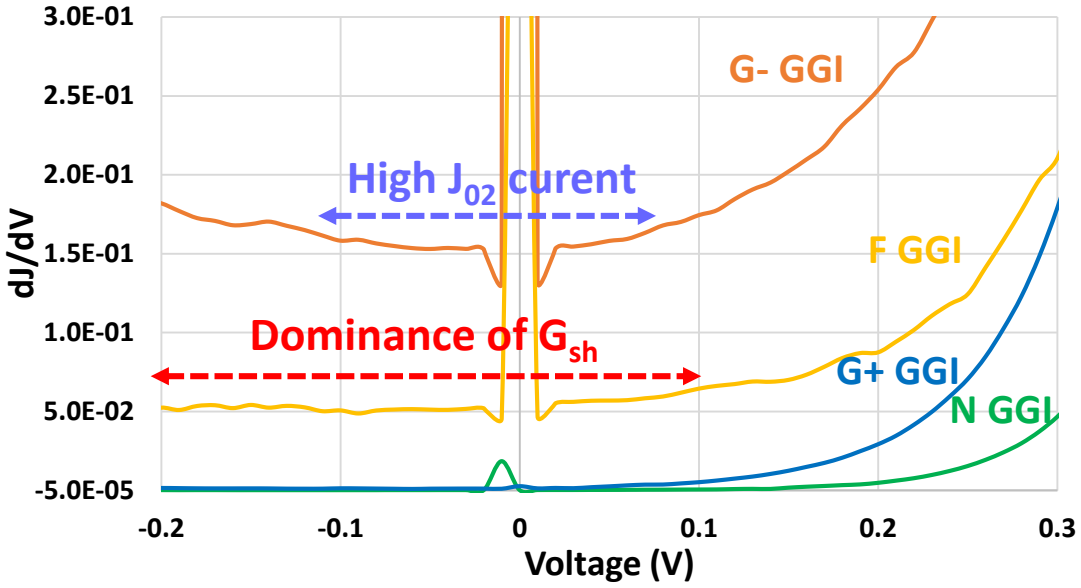
When Nt > Na Napp ~ Nt





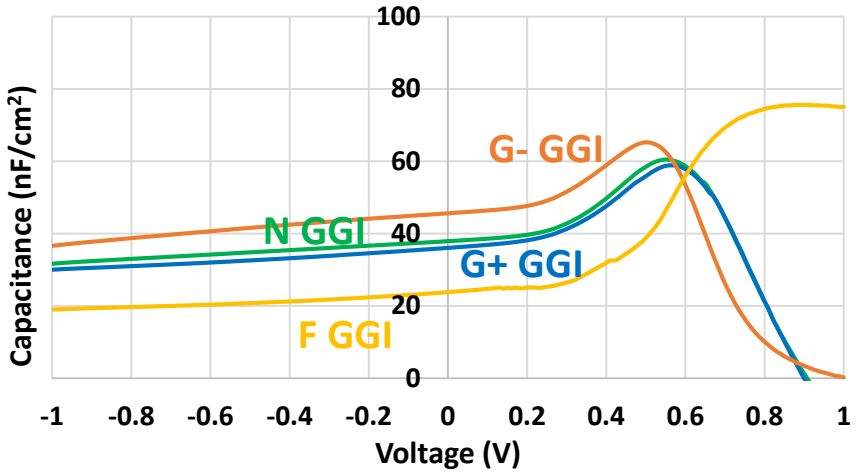
➢ Characterization results : current - voltage (*J-V*) Grading effects

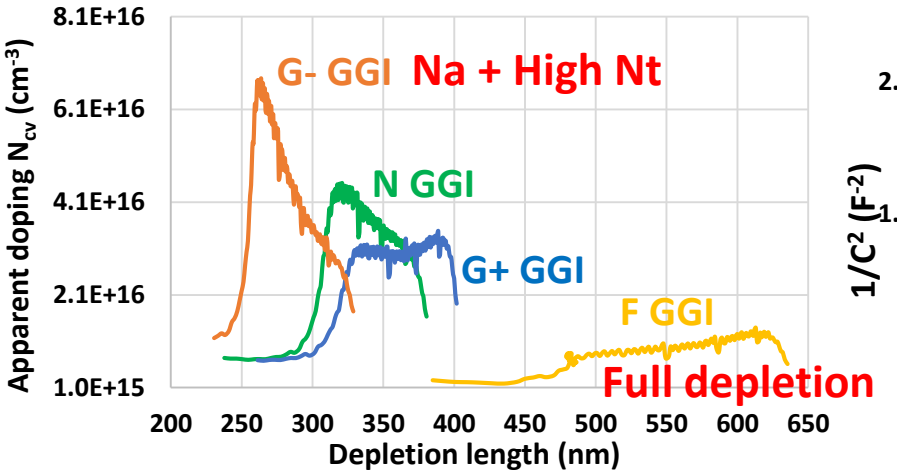


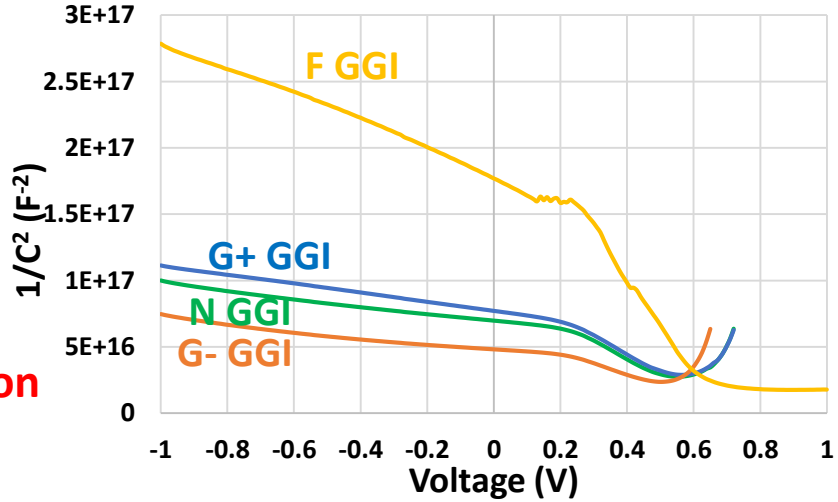


Current-Voltage parameters	Dark parameters						Parameters under illumination			
	J_{01} (mA/cm²)	J_{02} (mA/cm²)	n_1	n_2	R_s (Ω.cm²)	R_{sh} (Ω.cm²)	J_{sc} (mA/cm²)	V_{oc} (V)	FF (%)	Eff (%)
N GGI	3.20E-06	3.81E-06	1.69	2.00	2.45	6.21E+06	25.22	667	73.39	12.69
G^+ GGI	2.23E-05	2.28E-05	1.98	1.43	2.17	1.76E+05	25.86	663	70.83	12.14
G^- GGI	2.25E-05	6.80E-03	2.00	4.43	2.52	2.62E+03	24.78	674	71.70	11.98
F GGI	1.18E-05	2.65E-03	1.78	4.75	2.65	1.26E+04	23.51	592	53.71	7.48

➢ Characterization results : capacitance - voltage *(C-V)* Grading effects



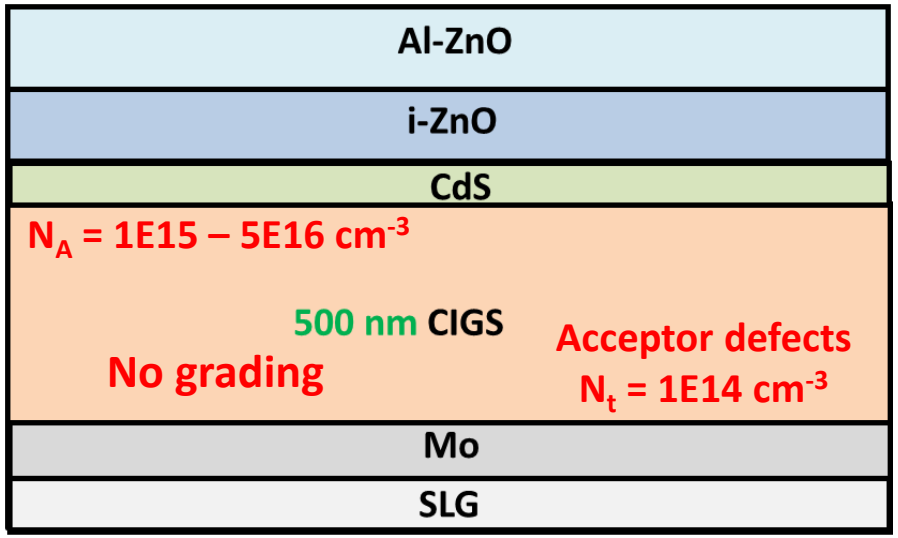




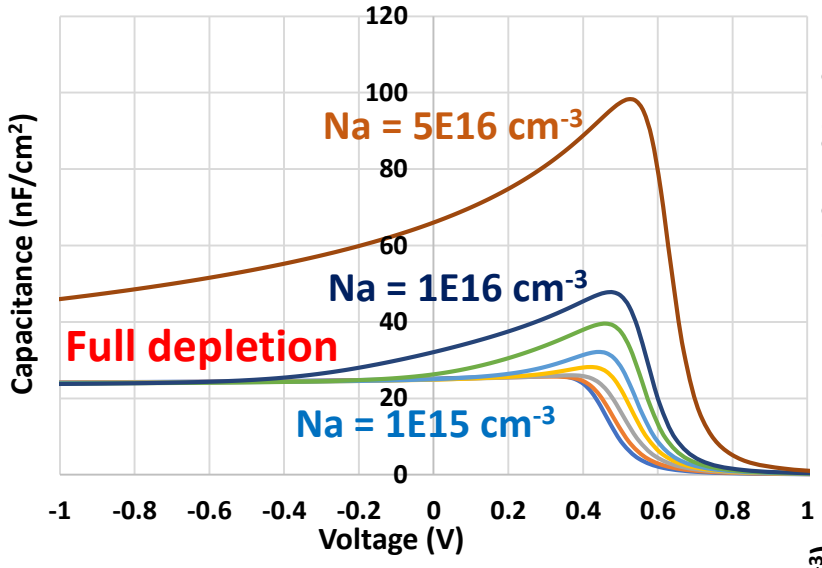
$$V_{oc} = \frac{nkT}{q} ln\left[\frac{(N_A + \Delta n)\Delta n}{n_i^2}\right]$$

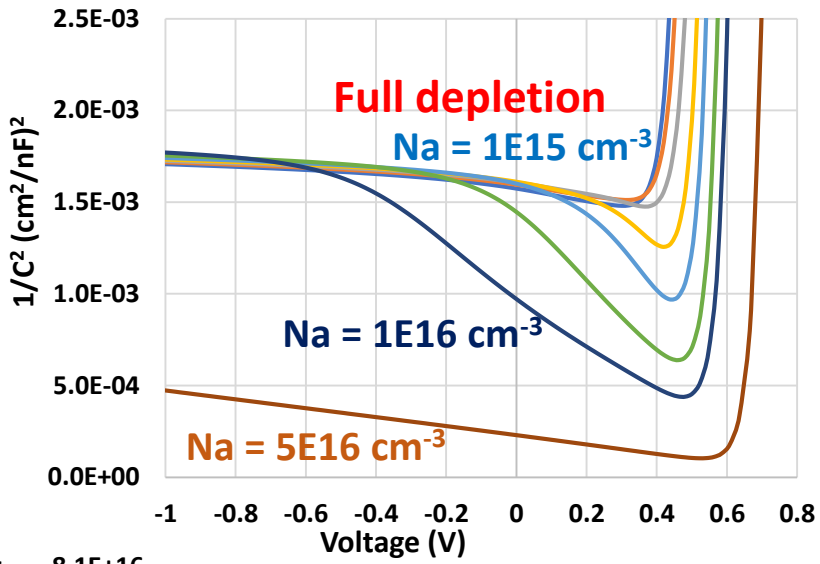
Capacitance-Voltage parameters	Dark parameters			Parameters under illumination			
	$N_{app(0\ V)}$ (cm^{-3})	X (nm)	V_{bi} (eV)	J_{sc} (mA/cm^2)	V_{oc} (V)	FF (%)	Eff (%)
N GGI	3.44E+16	318	1.94	25.22	667	73.39	12.69
G^+ GGI	3.05E+16	334	2.26	25.86	663	70.83	12.14
G^- GGI	5.23E+16	264	2.10	24.78	674	71.70	11.98
F GGI	7.30E+15	506	0.95	23.51	592	53.71	7.48

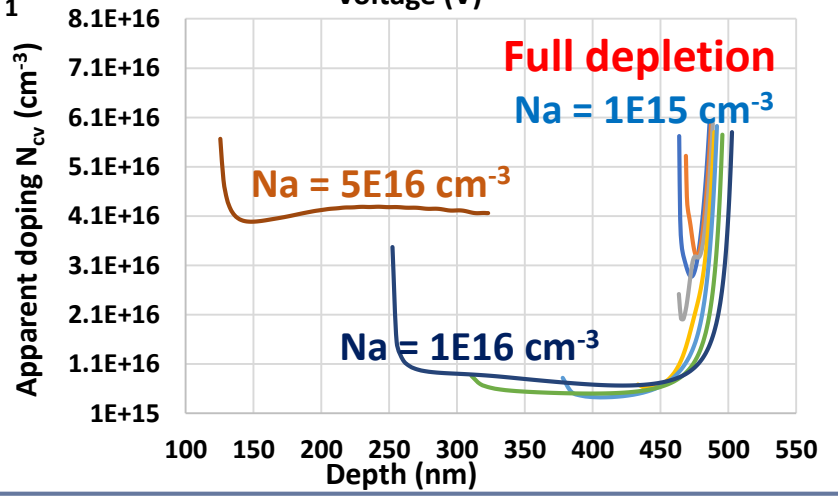
➢ SCAPS 1D Simulation: capacitance - voltage



Full depletion







Attention at the full depletion for very low doping especially for UT-CIGS

➢ **Summary:** characterization vs simulation (I-V, C-V) methodology toward optimization of UT-CIGS PV cells

Mechanism	Parameters in the dark	I-V	C-V	SIMU
		Higher performances under illumination		
Rear passivation	Lower of J_{01}, J_{02}, n_1, n_2	✓		✓
Rear contact patterning	Opening **W**, pitch **P**			✓
Grading CIGS	Lower J_{02}, n_2, Increase of N_a	✓	✓	
		Lower performances under illumination		
Steel substrate	Defects due to substrate N_t	✓	✓	
Bulk absorber defects	Trap defects N_t	✓	✓	✓
Series/shunt resistance	High R_s, Low R_{sh}	✓		
Full depletion	High J_{01}, Low doping N_a		✓	✓

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