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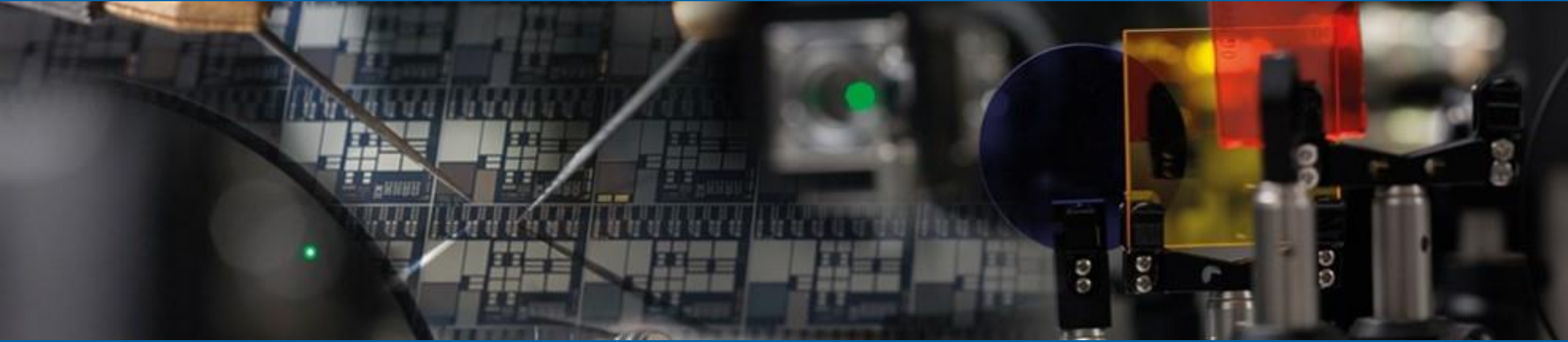
IAP

On-stage solar cell degradation process: DLTS and LT-PL-EL study



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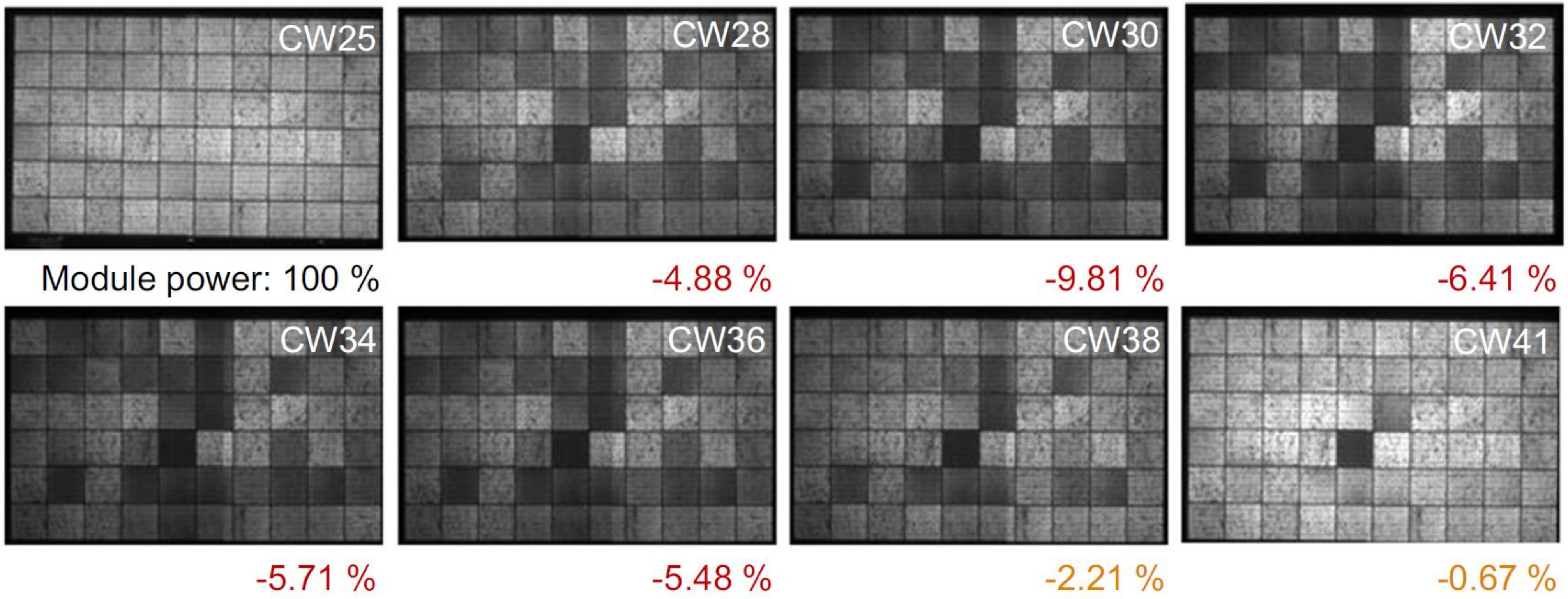
Light and elevated Temperature Induced Degradation[1, 2, 3] : (LeTID)[3]



[3]

EL and module power measurement (STC) sequence showing the degradation–regeneration cycle and the time-resolved contribution of single cells. "CW" is for a Calendar Week.

[1] K. Ramspeck, et al., **2012**
[2] F. Fertig, et al., **2015**
[3] F. Kersten, et al., **2015**

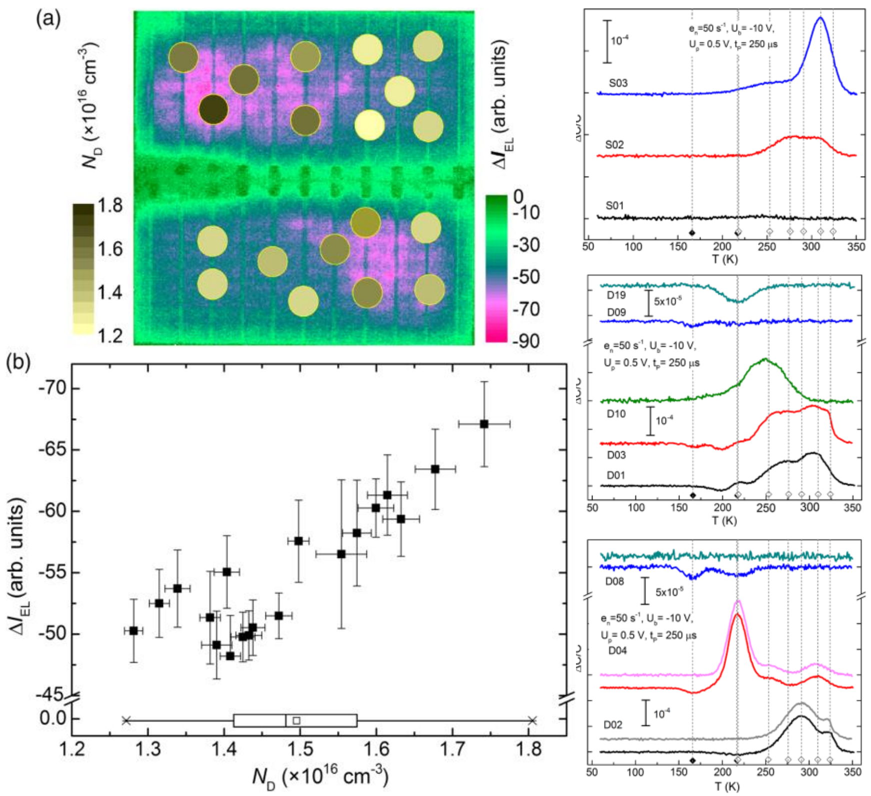
Light and elevated Temperature Induced Degradation (LeTID)

- Is LeTID still a problem for the PV industry? - Almost not[4,5].
- Has the role of hydrogen in LeTID been proven? - Almost yes [4].
- Do other defects/impurities, or layers play a role? - Maybe [5].
- Can dopant-hydrogen complexes be a cause of LetiD? - Maybe[6, 7].
- Is the LeTID mechanism understood? - Not [4,5,7].

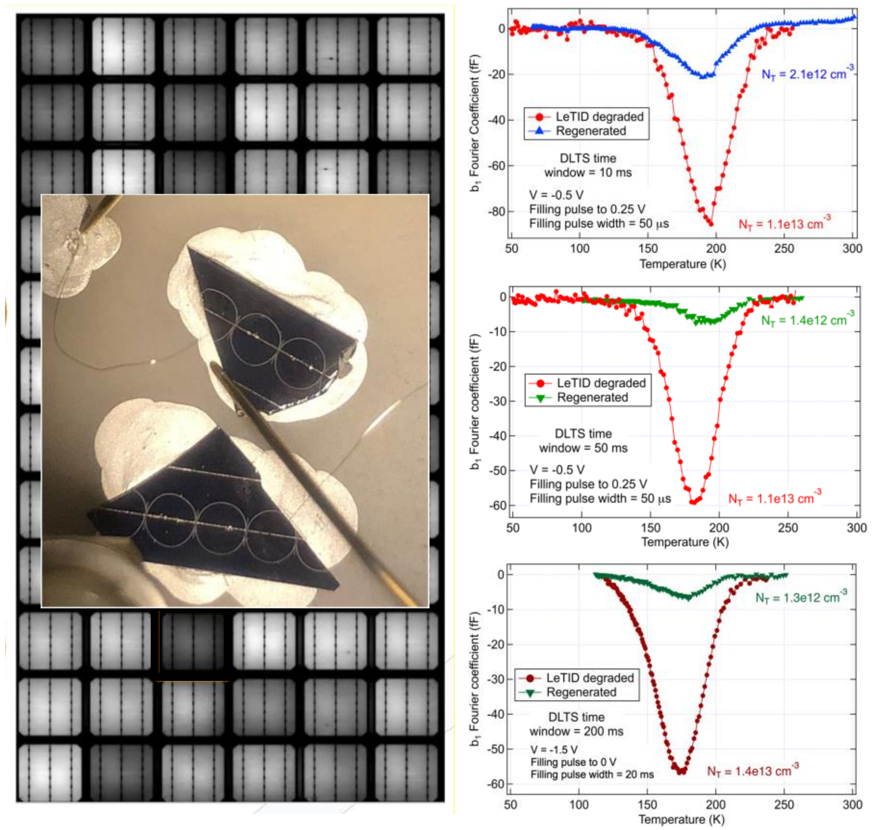
[4] D. Chen, et al., **2021**
[5] L. Ning, et al., **2022**
[6] T.O. Abdul Fattah, et al., **2023**
[7] J. Coutinho, et al., **2024**

Local PL and DLTS measurements on the cells

[8]



[9]



[8] T. Mchedlidze, et al., **2019**

[9] S. Johnston, et al., **2022**

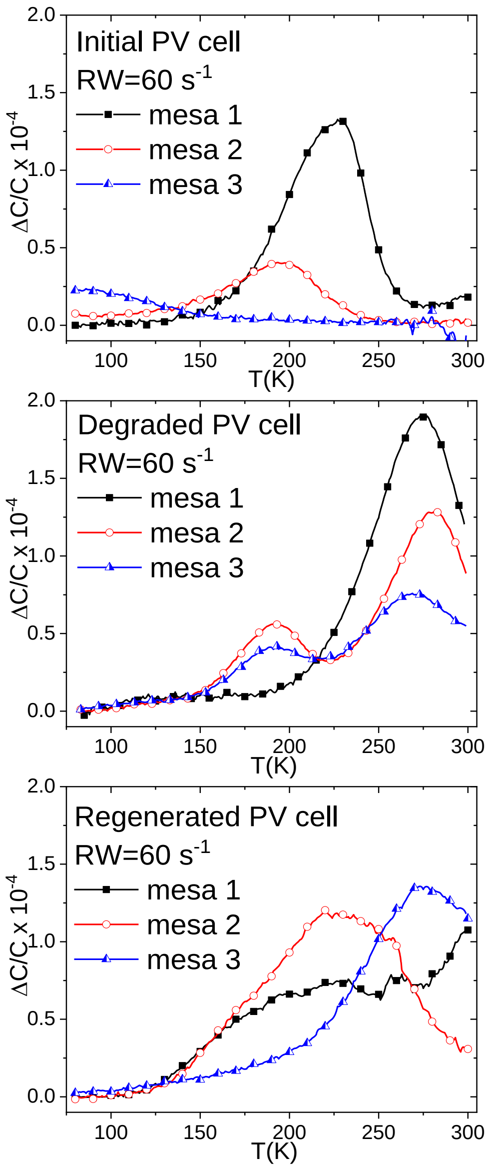
Experiments with “multisamples”

DLTS: similar locations cutout from „sister“ wafers of PV-cell in:

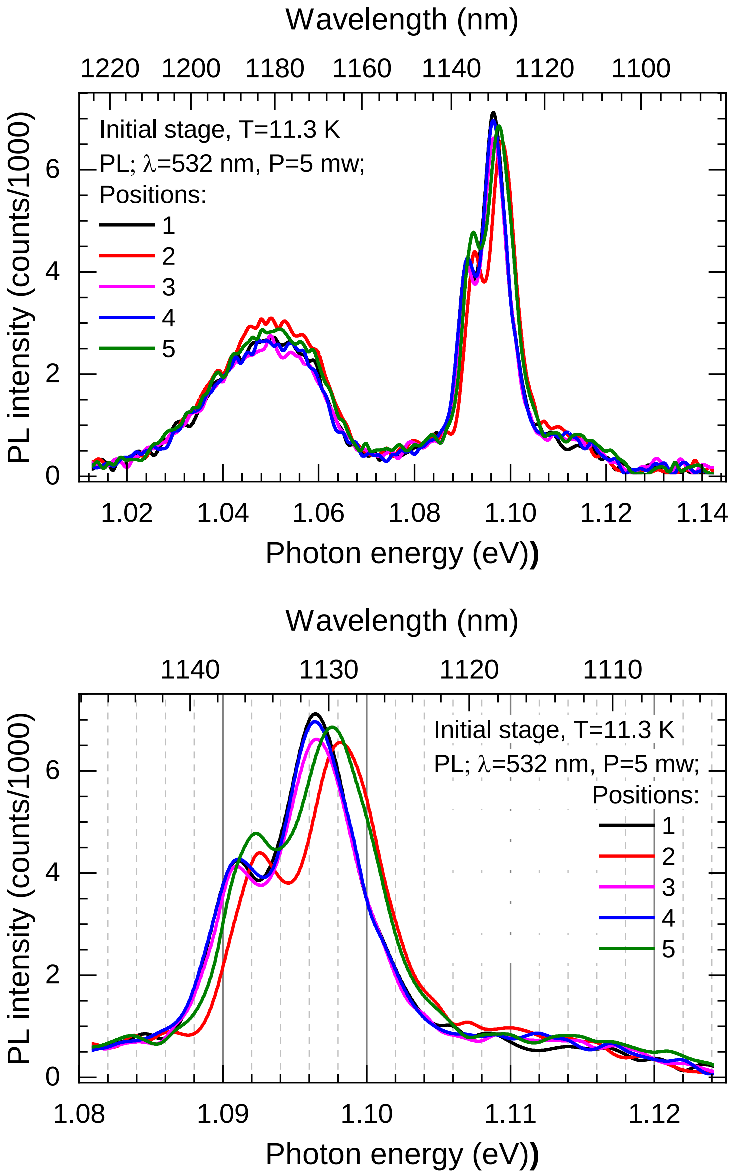
Initial state:

Degraded state:

Regenerated state:



PL: different locations on the same PV-cell in **initial** state:



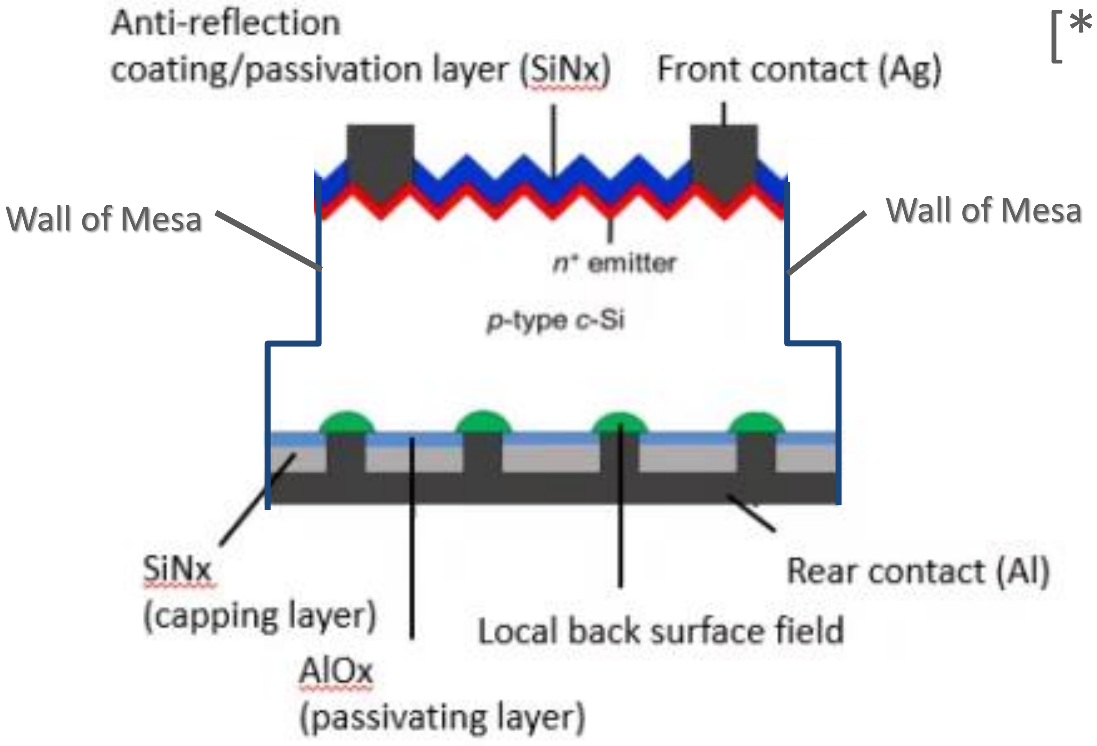
Near BG spectra

Details near BE, FE

Mesa samples from solar cells[*]

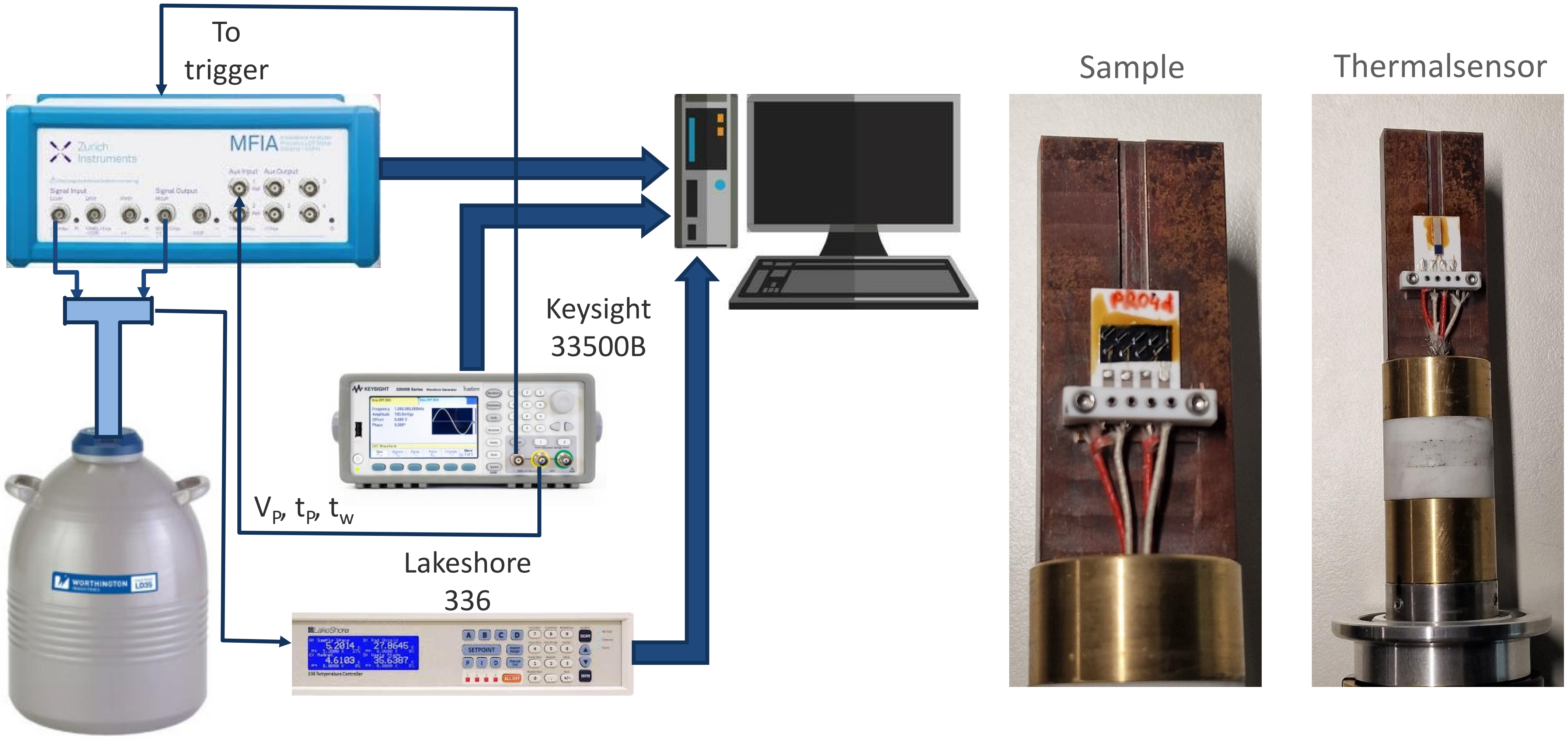
- PERC solar cells, Cz-Si, standard PERC fabrication procedure [2], B-doped, $N_B = 1.1 \cdot 10^{16}$ cm^{-3};
- Mesa-diodes prepared from the PERC cells using chemical etching process;
- Three LeTID states: initial (I), degraded (D), regenerated (R);
- “Multisamples”: mesa diodes on samples cutout from similar locations of sister wafers for I, D, and R states; D and R were processed on complete solar cells by CID procedure;
- “Monosample”: the same sample (mesa diode) for I, D, and R stages obtained by on-stage CVID procedure, degradation (50 min) and regeneration (6 h).

[**]



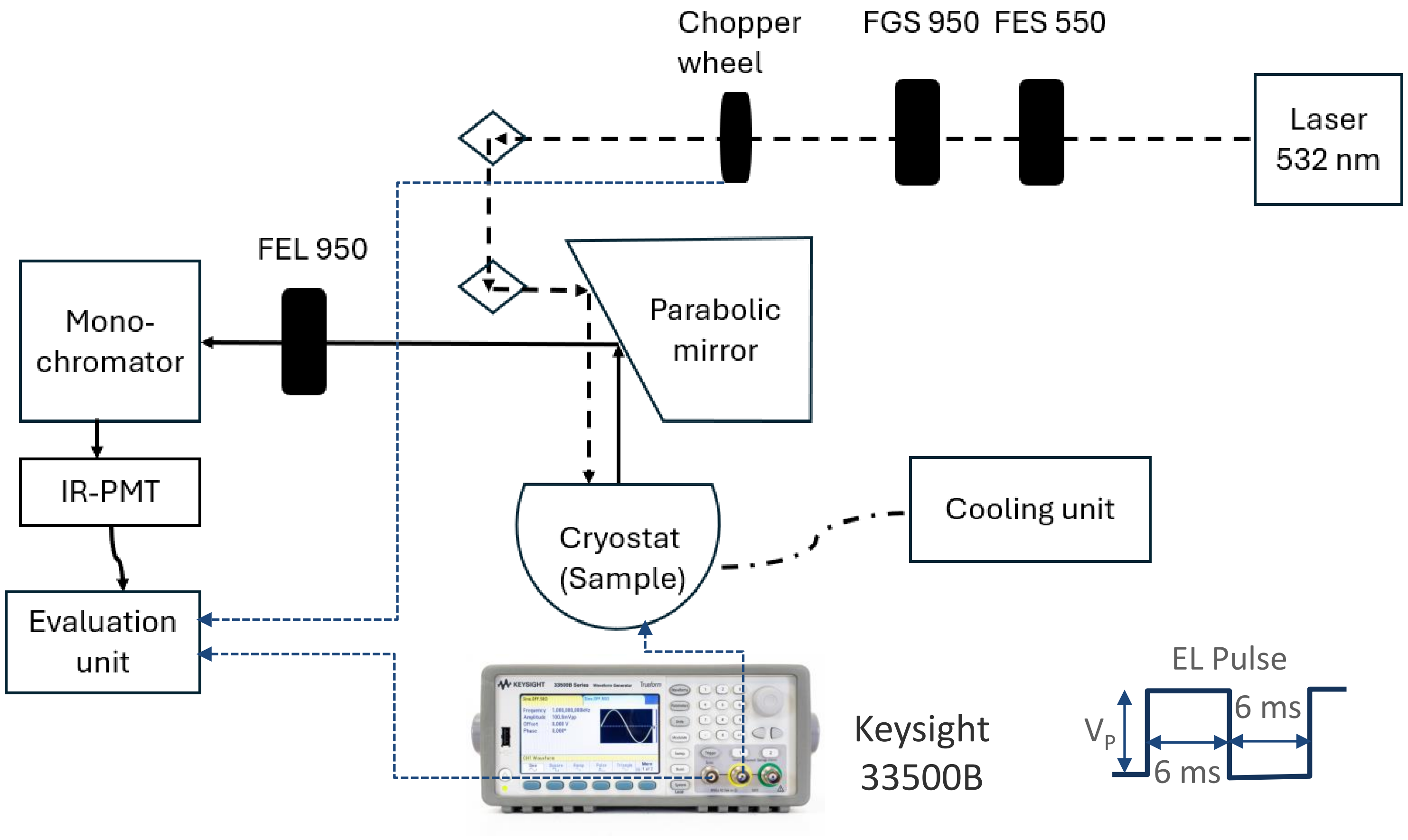
[*] Samples were fabricated in the frame of the “ZORRO” project (contract no. 03EE1051D).
[**] https://hjtpv.com/perc-technology-and-solar-panels/

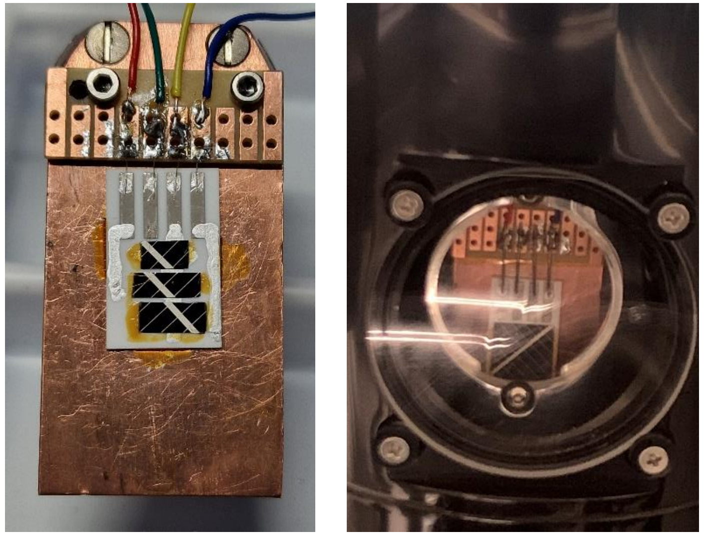
DLTS setup[10]



[10] T. Mchedlidze, **2023**

EL(········) and PL(- - - -) setup



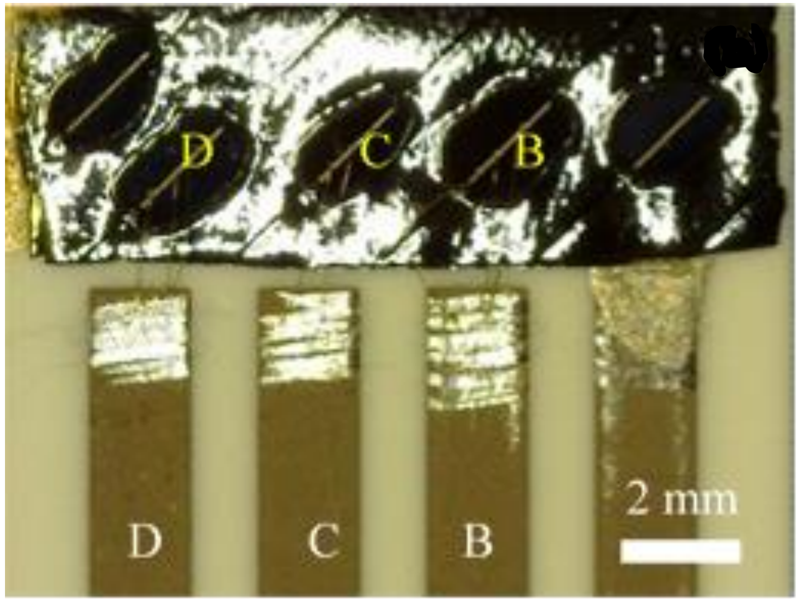


On-stage LeTID of mesa-diodes

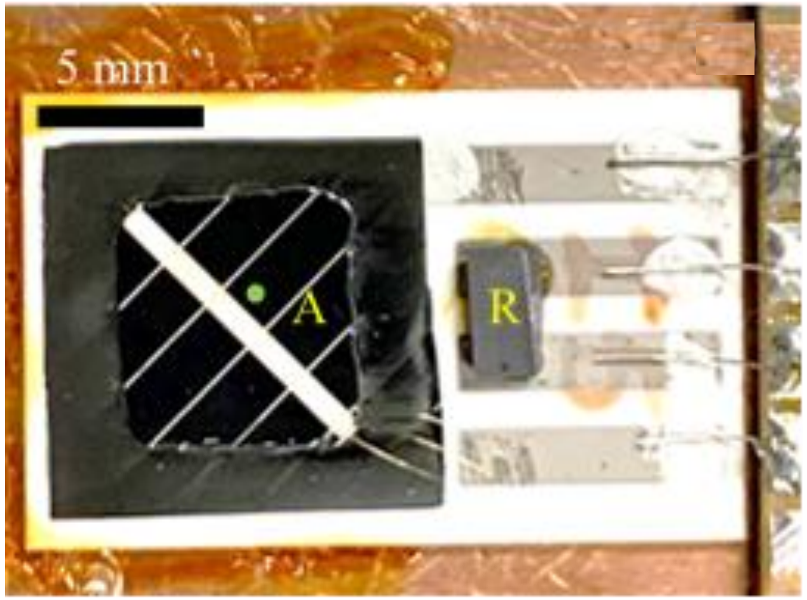
Can local methods for defect investigation be applied for LeTID investigations in the cells and, if “yes”, how?

Study of the same samples mounted on the measuring setup in initial, degraded and regenerated states.

For DLTS



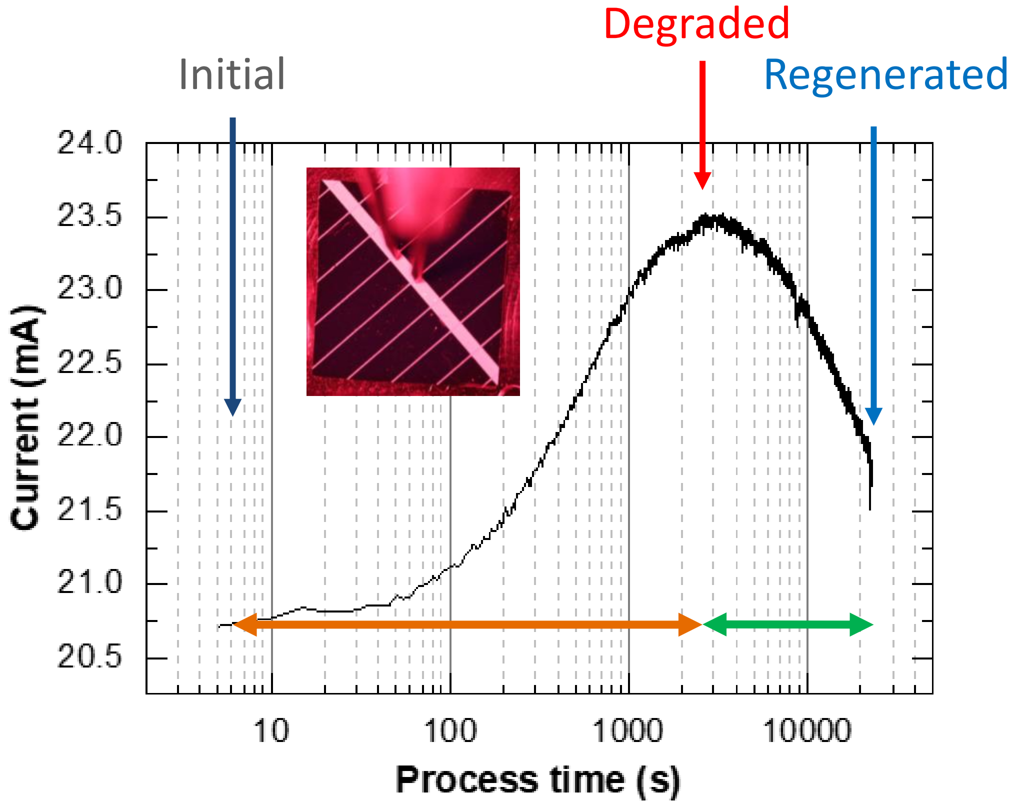
For LT-EL-PL



On-stage LeTID of mesa-diodes:

Degradation procedure

- Current induced degradation (CID) at elevated temperatures is frequently used to model LeTID[4].
- However, due to leakage current at the perimeter of mesa diodes, especially for small area mesas, it is preferable to use constant voltage induced degradation (CVID).
- CID ≈ CVID was confirmed.
- From the experimental LeTID curve:
  - ➢ t(degradation) = 50 min;
  - ➢ t(regeneration) = +6 hours.



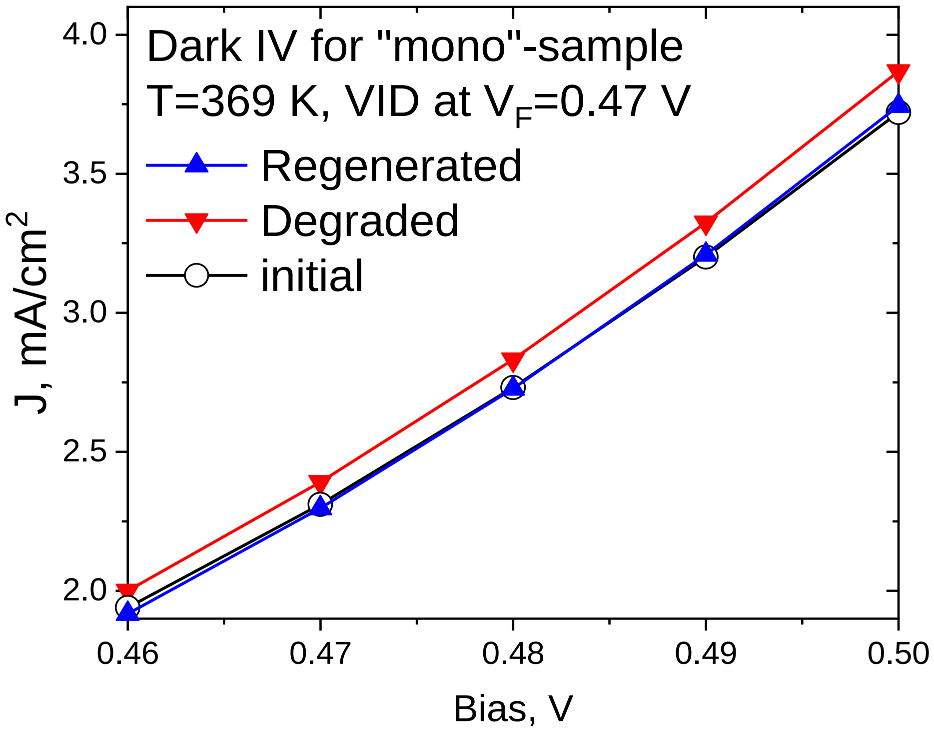
Area of cleaved out cell 1 cm^2

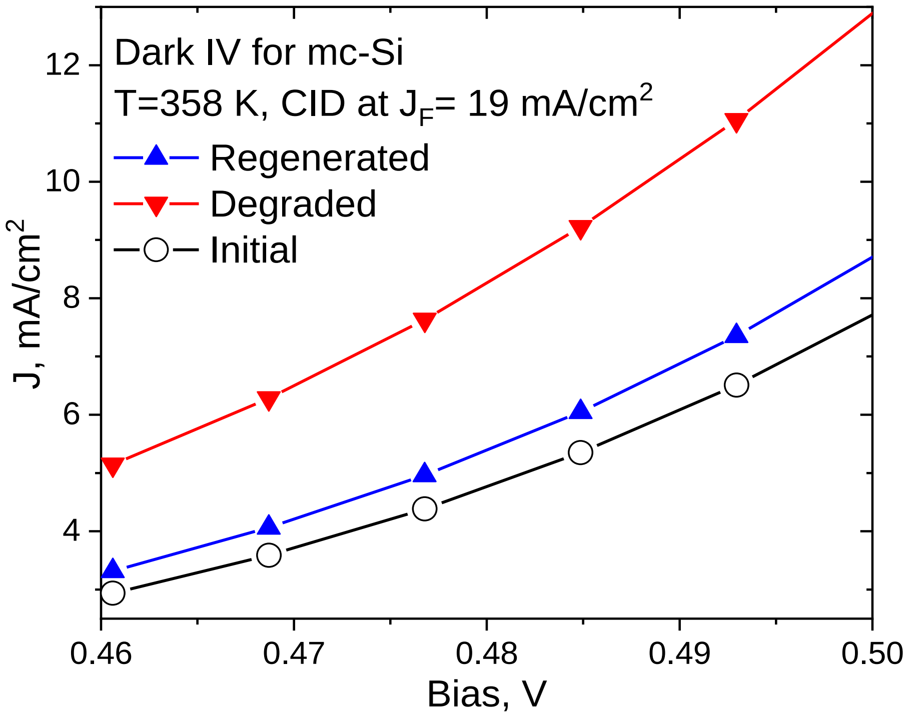
$V_{F,\ const}$ = 470 mV, T = 369 K

[4] D. Chen, et al., **2021**

On-stage LeTID of mesa-diodes:

dark IV

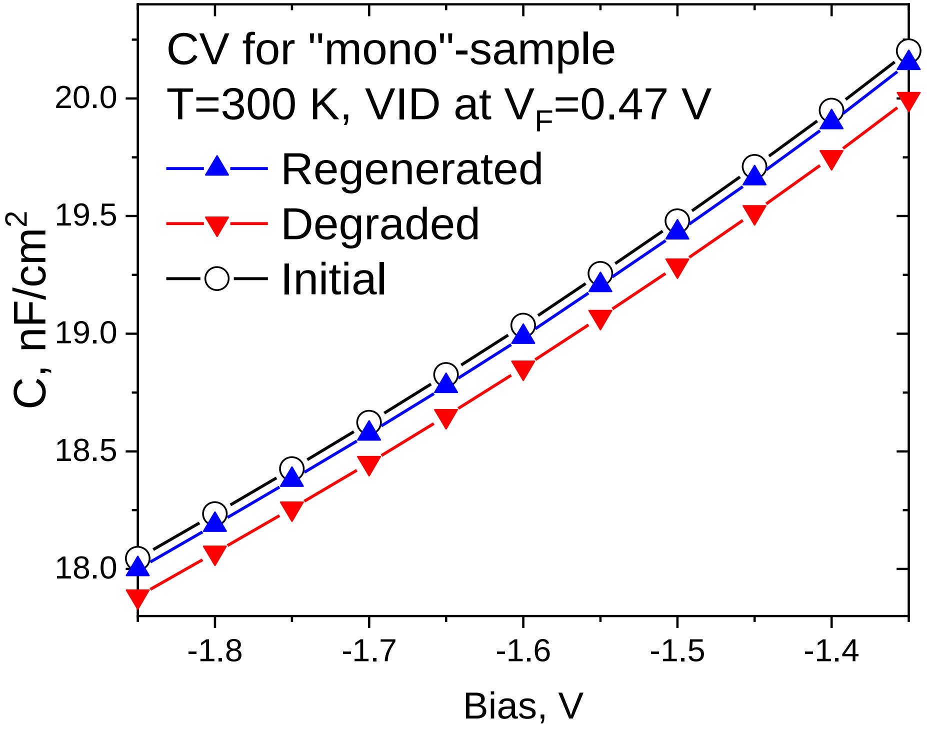


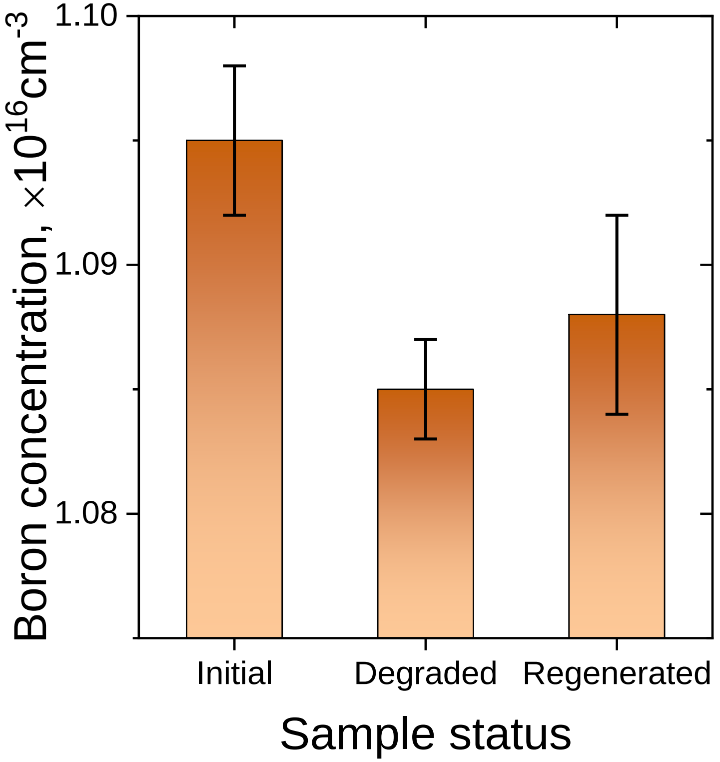


Similarities between CVID on mesa diode and CID on complete mc-Si solar cell.

On-stage LeTID of mesa-diodes:

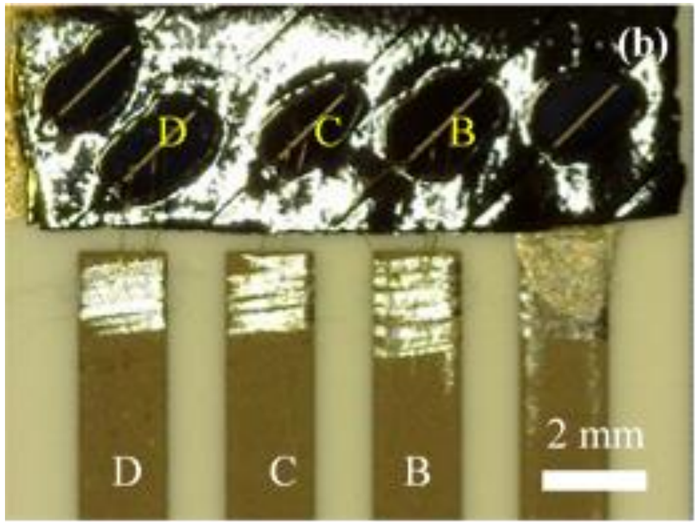
CV measurements

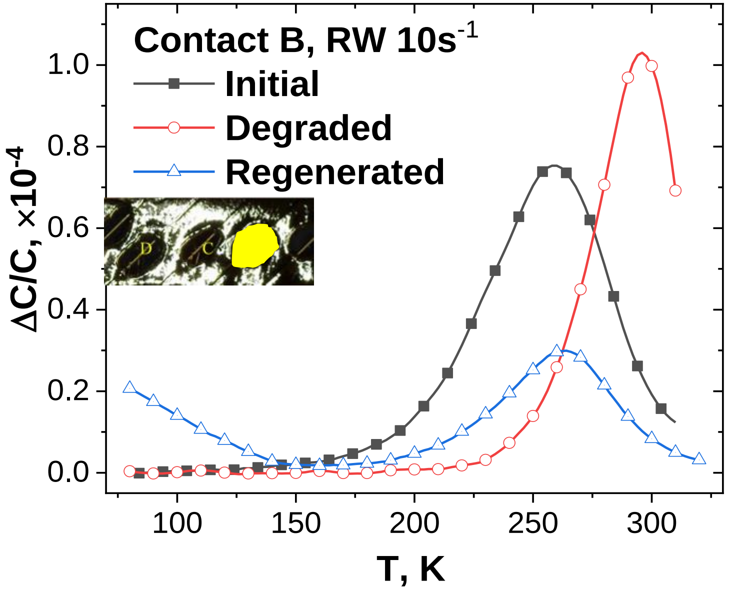


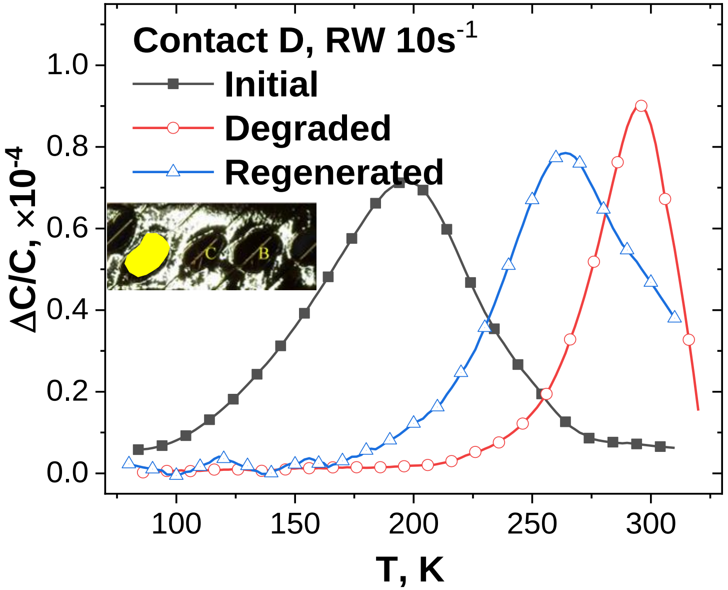


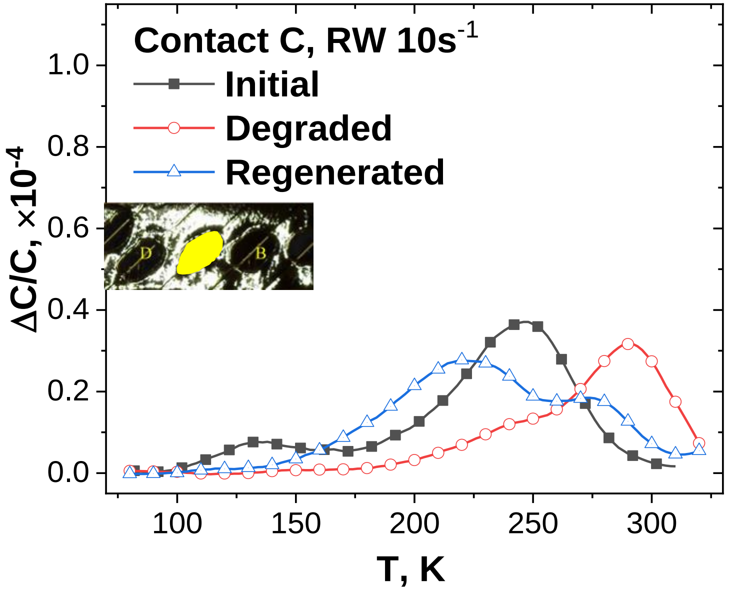
Changes in CV curves indicate on suppression of dopants in degraded state.

On-stage LeTID of mesa-diodes: DLTS

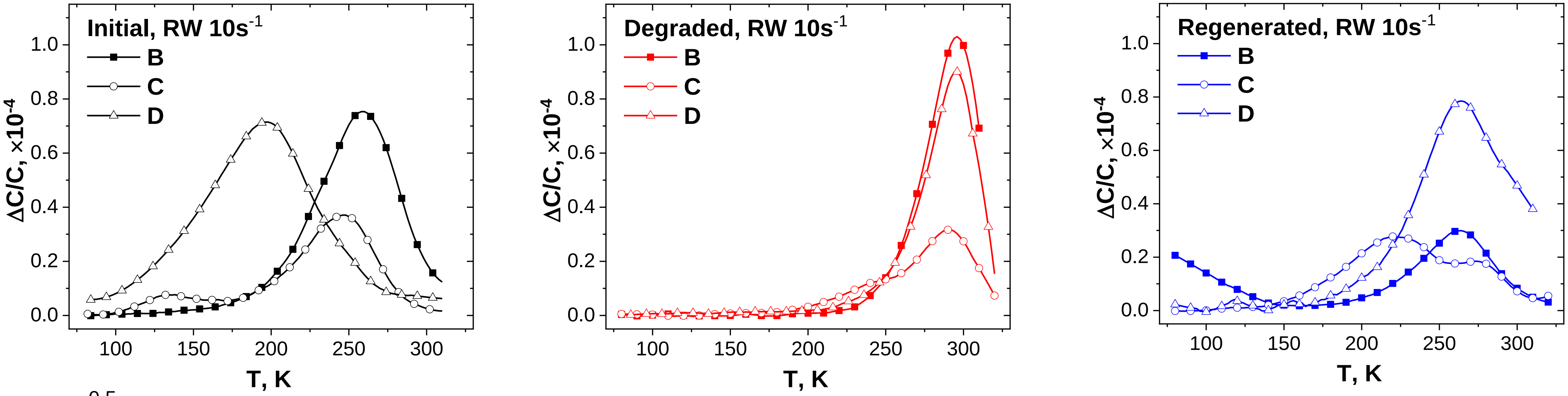


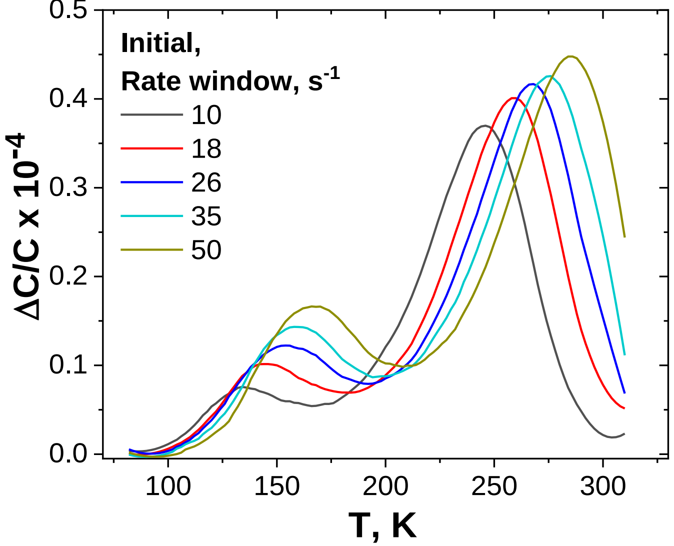


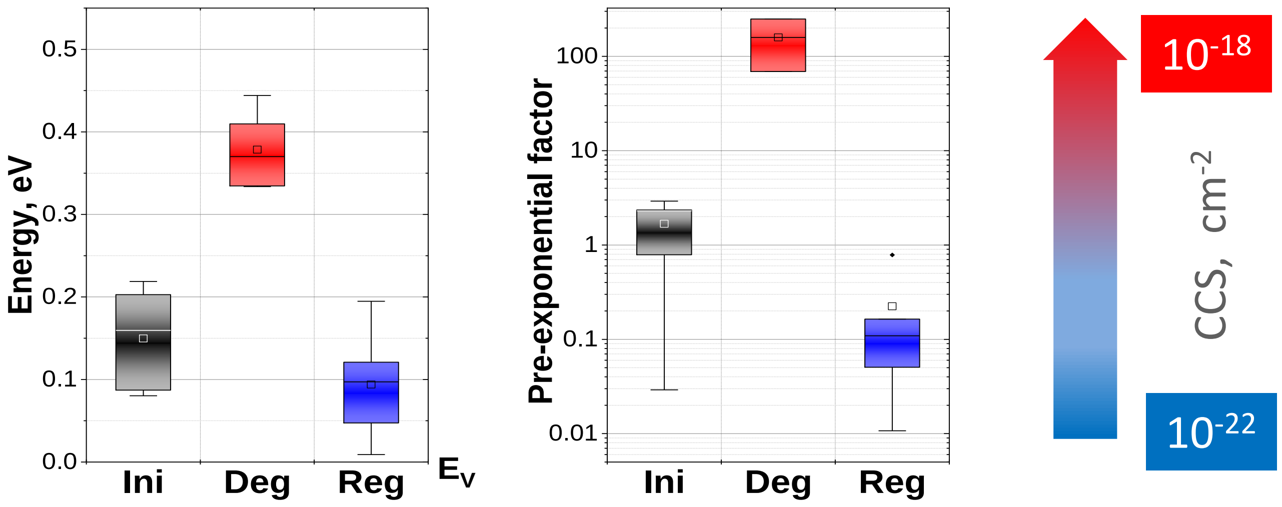




On-stage LeTID of mesa-diodes: DLTS

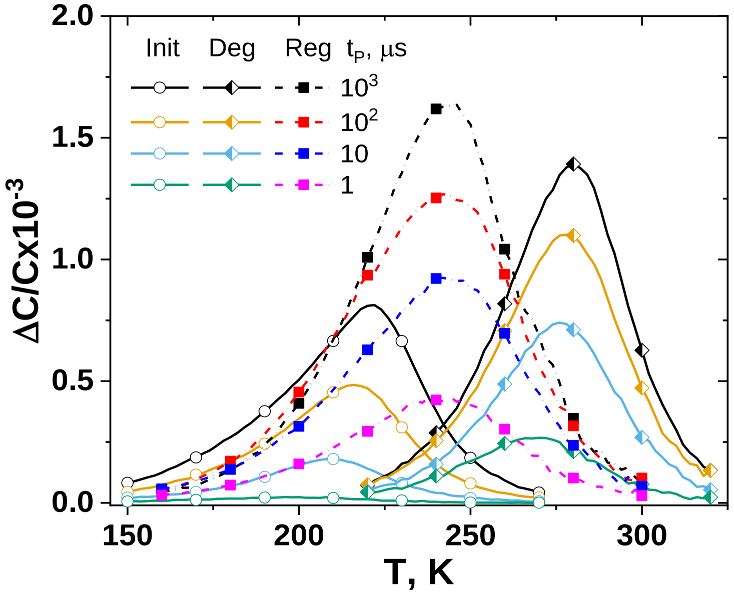


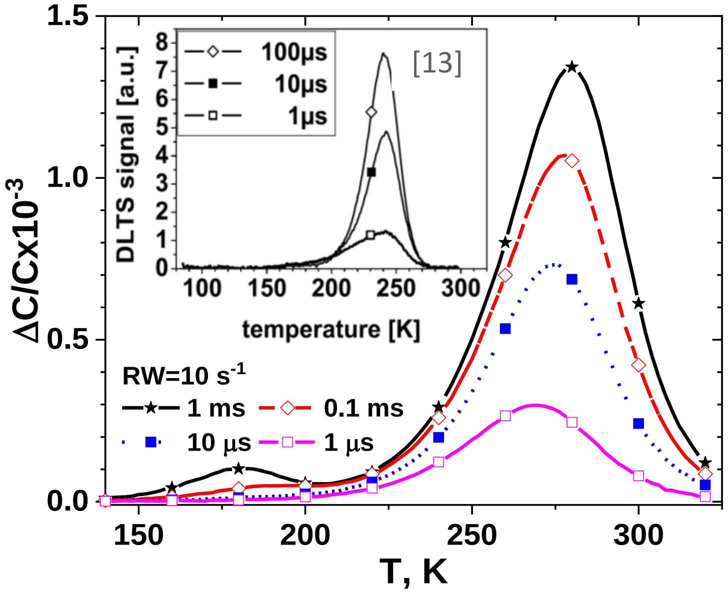


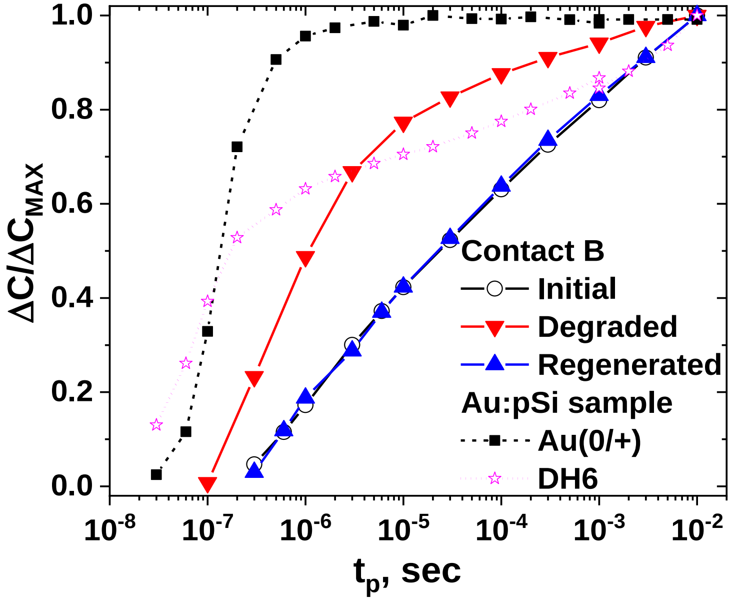


[11] M. K. Juhl, et al., **2023**
[12] J. T. Ryan, et al., **2015**

On-stage LeTID of mesa-diodes: DLTS





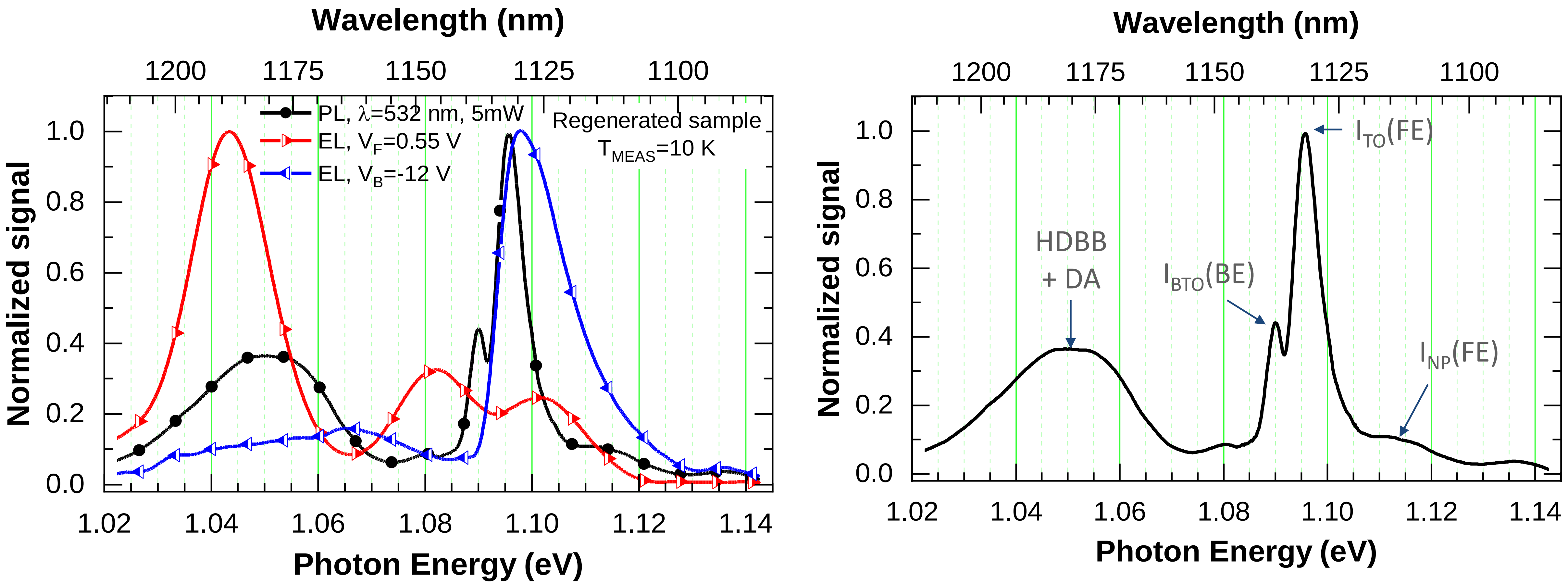


- Exact nature of the detected extended defects is not clear, however dislocations [14, 15] should be considered as candidates.
- Due to substantial leakage and overlap with majority carrier trap peaks we did not succeed detecting minority carriers in mesa diodes.

[13] M. Seibt, et al., **2009**
[14] L. Wang, et al., **2023**
[15] H.T. Nguen, et al., **2016**

On-stage LeTID of mesa-diodes: luminescence

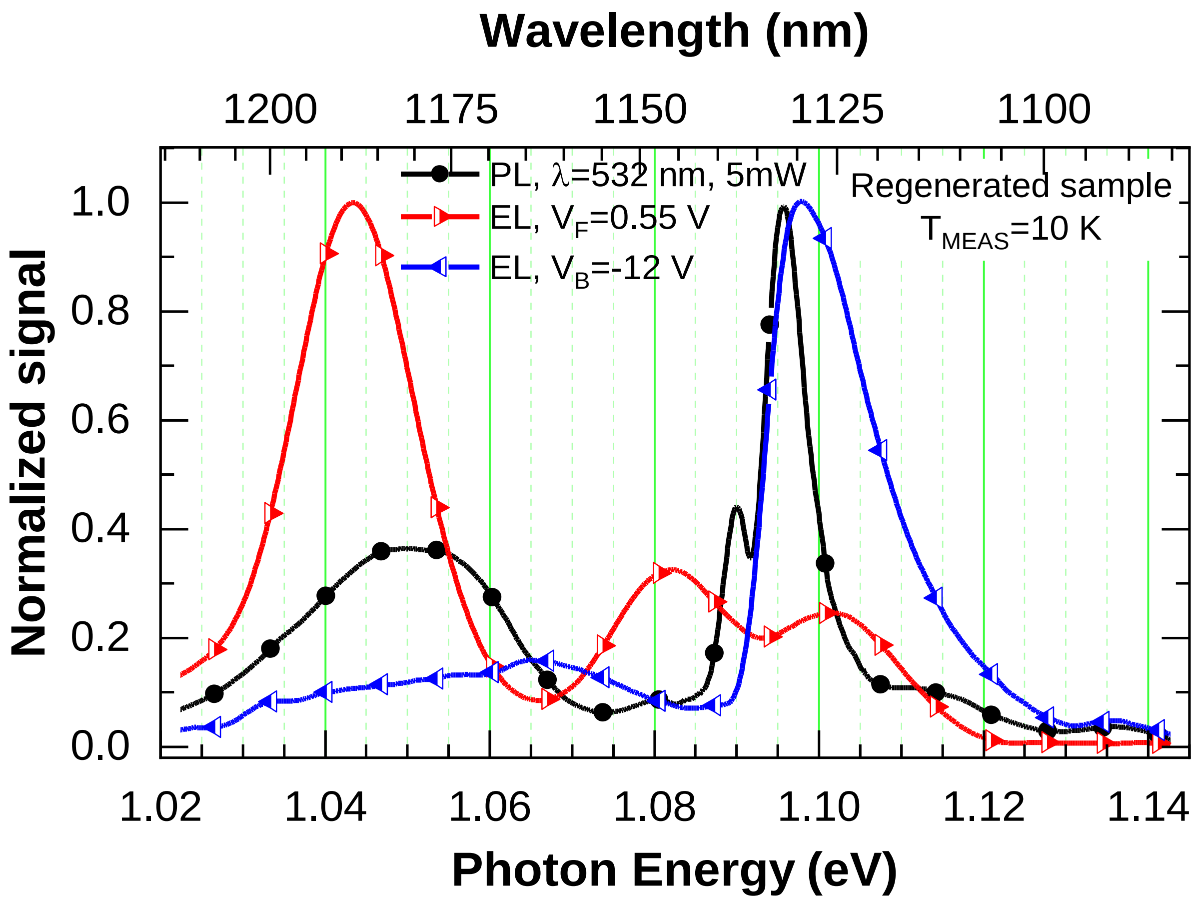
PL, λ_{EXC}=532 nm, P_{EXC}=5 mW, T_{MEAS}=10 K

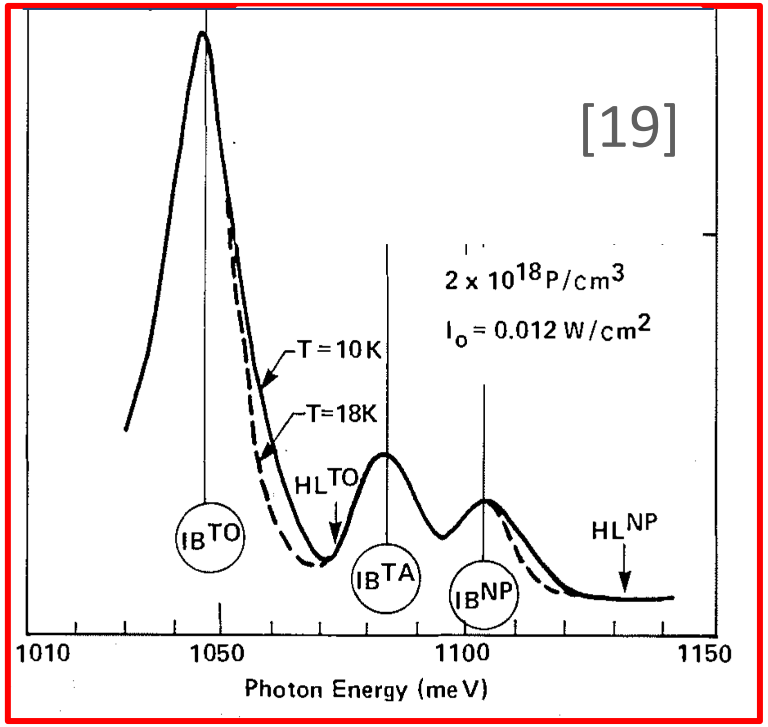


[16] M. Tajima, et al., **2011**
[17] H.T. Wu, et al., **2018**
[18] K. Peh, et al., **2023**

On-stage LeTID of mesa-diodes: luminescence

EL, Forward bias, V_{PULSE}=0.55 V, T_{MEAS}=10 K

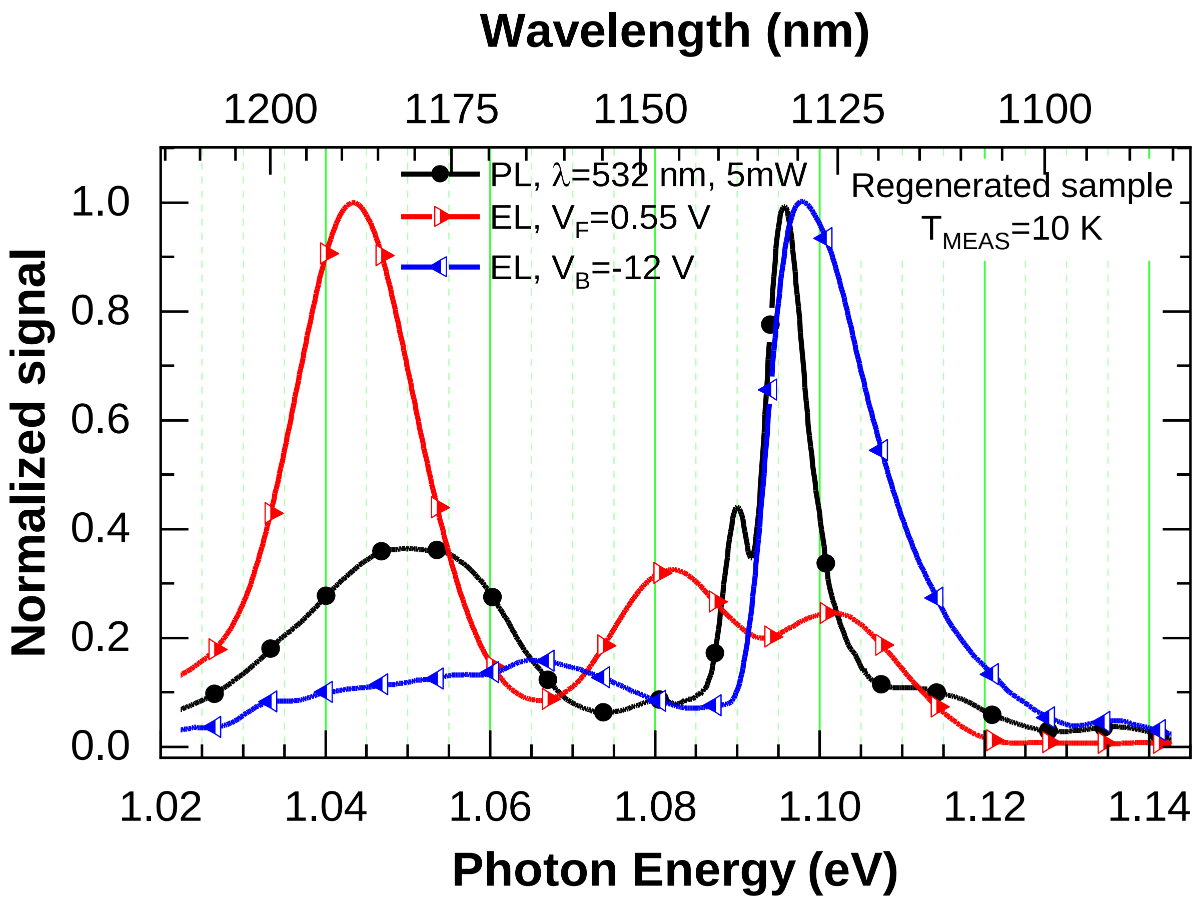


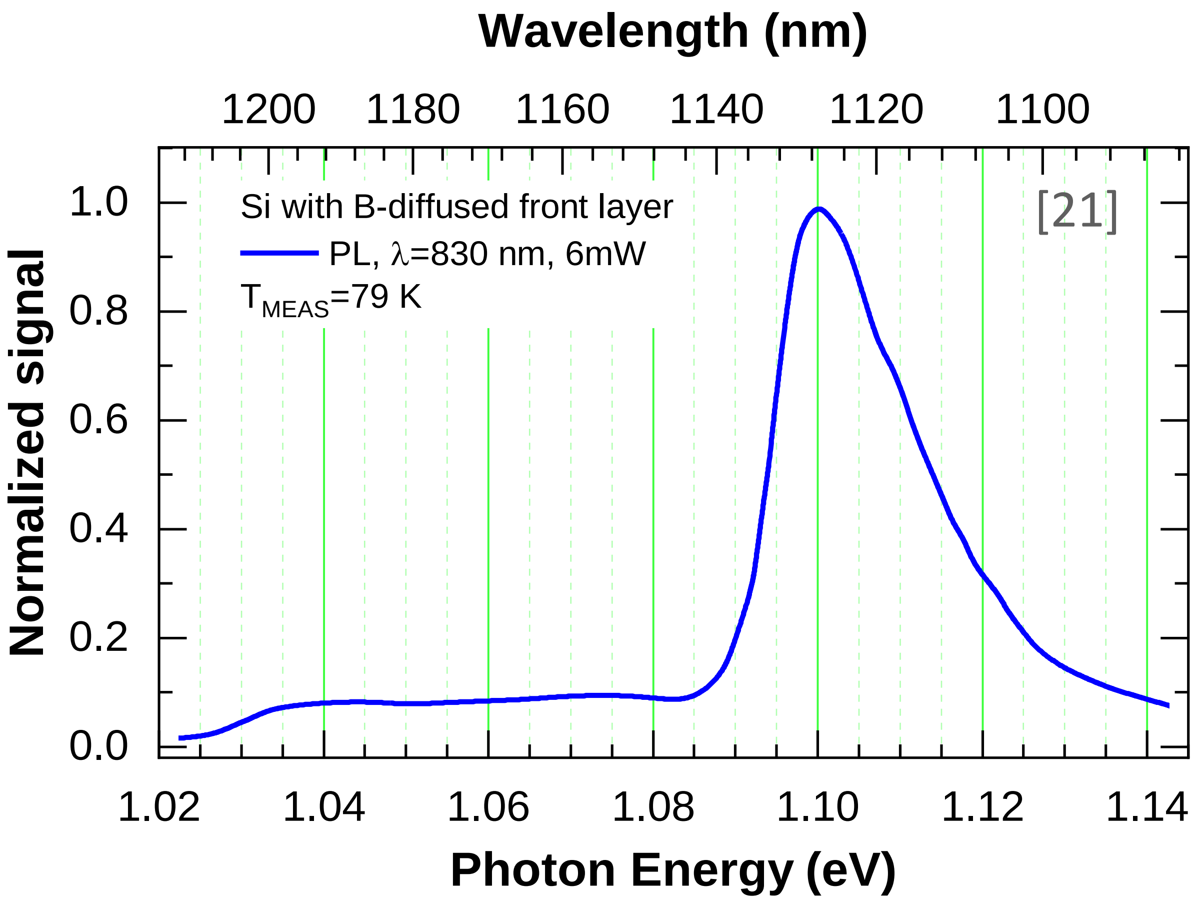


[19] R.R. Parsons, **1978**
[20] J. Wagner, **1984**
[16] M. Tajima, et al., **2011**

On-stage LeTID of mesa-diodes: luminescence

EL, Reverse bias, V_{PULSE}=-12 V, T_{MEAS}=10 K

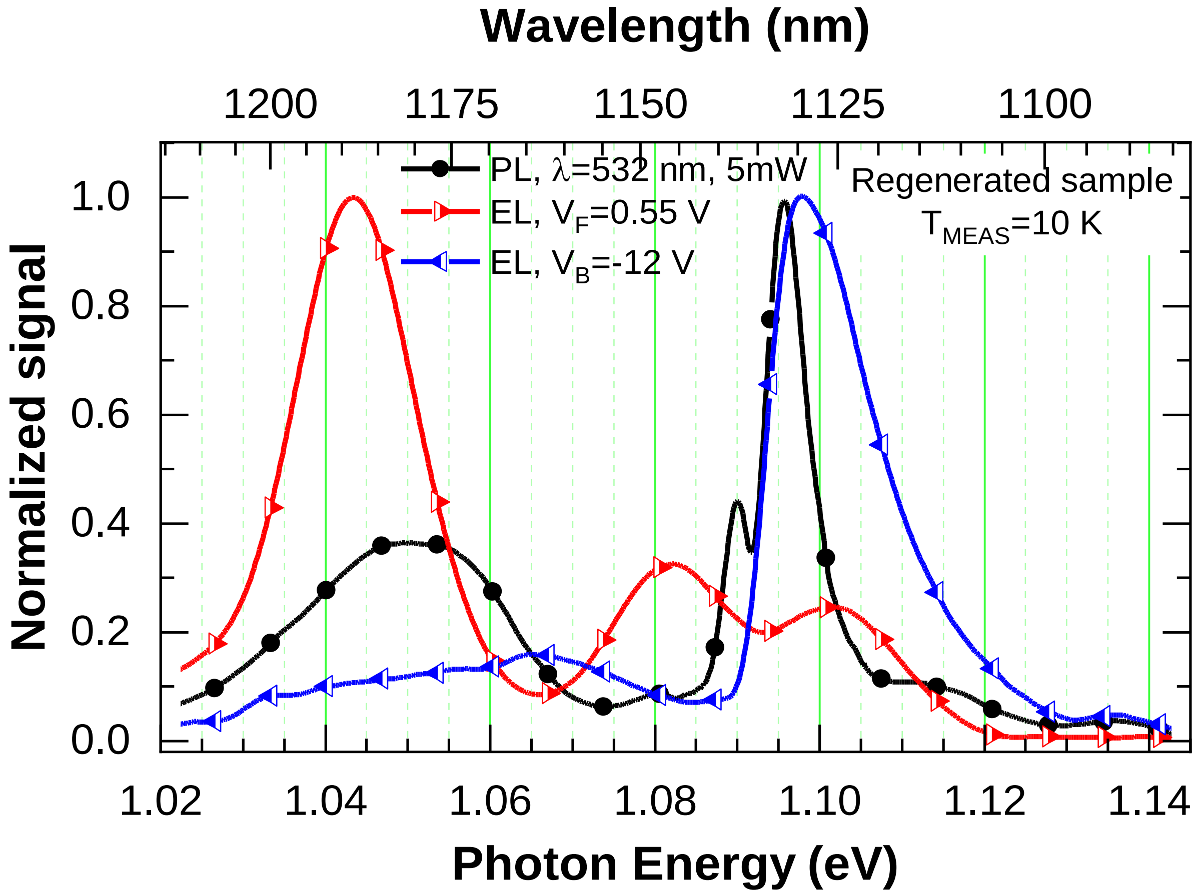




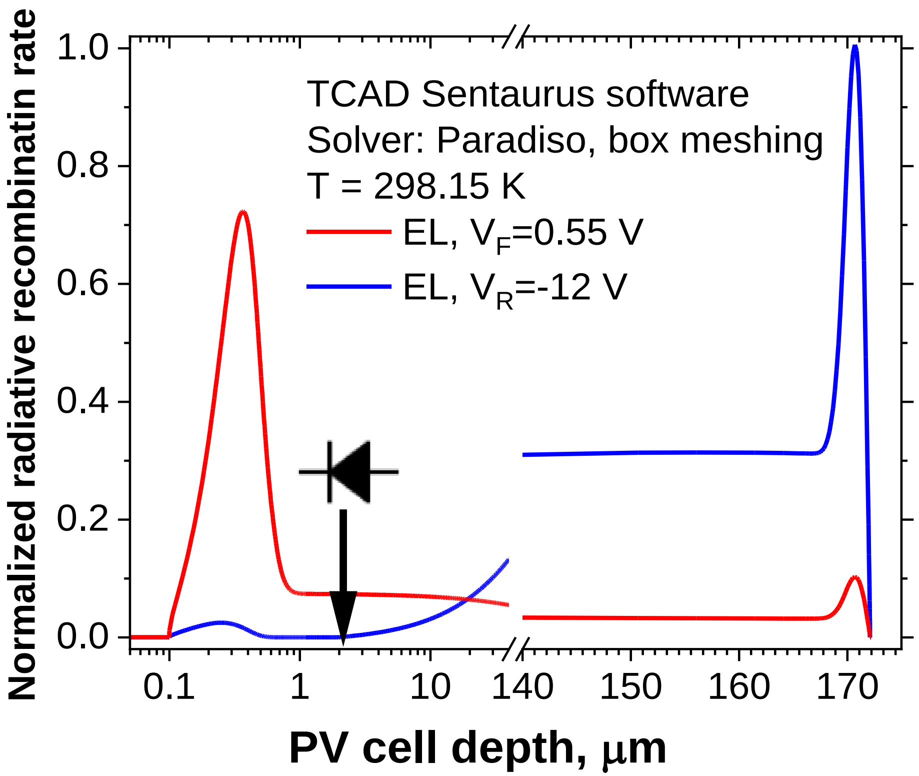
[21] H.T. Nguyen, et al., **2015**

On-stage LeTID of mesa-diodes: luminescence

Electroluminescence, TCAD modeling

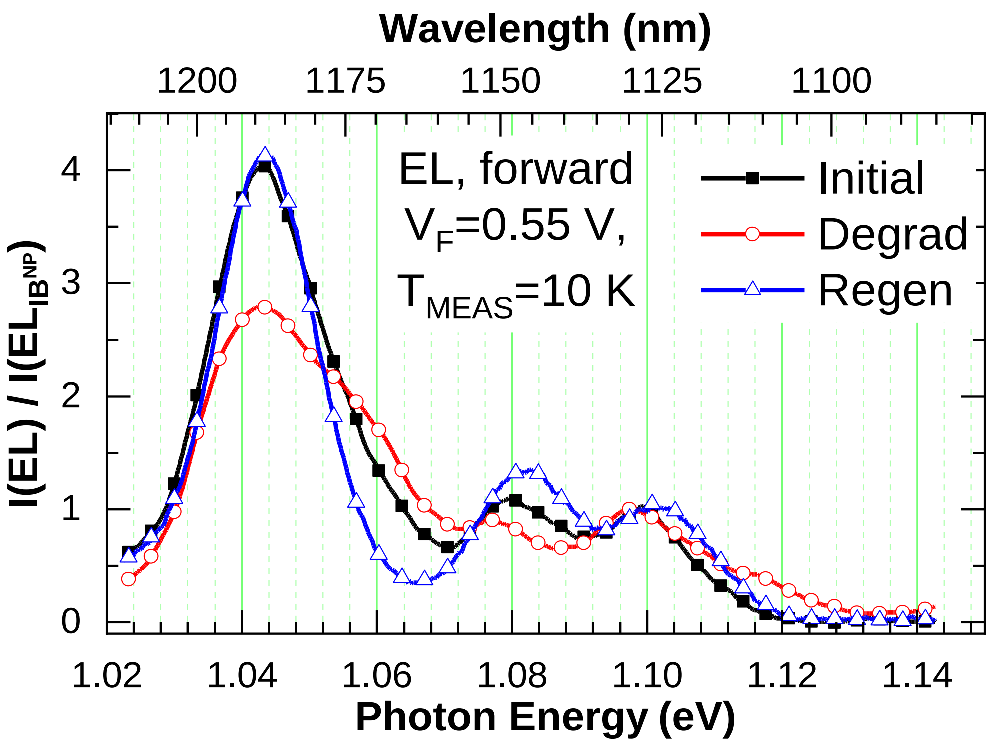


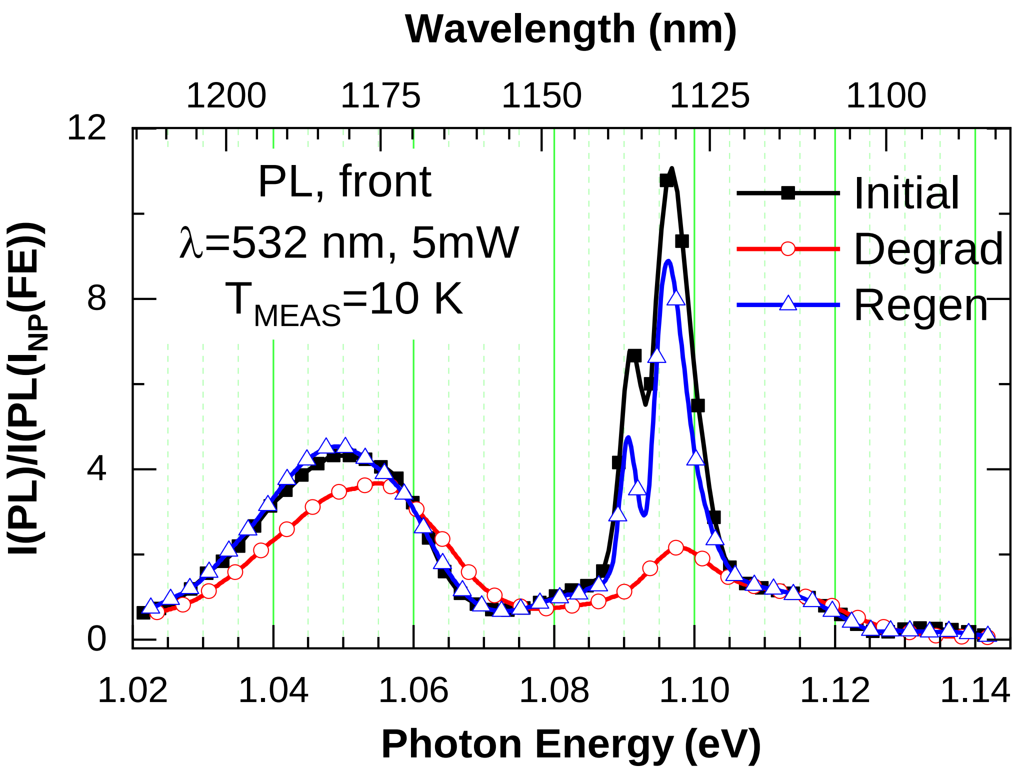
TCAD modeling



On-stage LeTID of mesa-diodes: luminescence

Results





- Similar EL, PL spectra for the initial and regenerated samples. Decrease of overall intensity for the degraded sample.

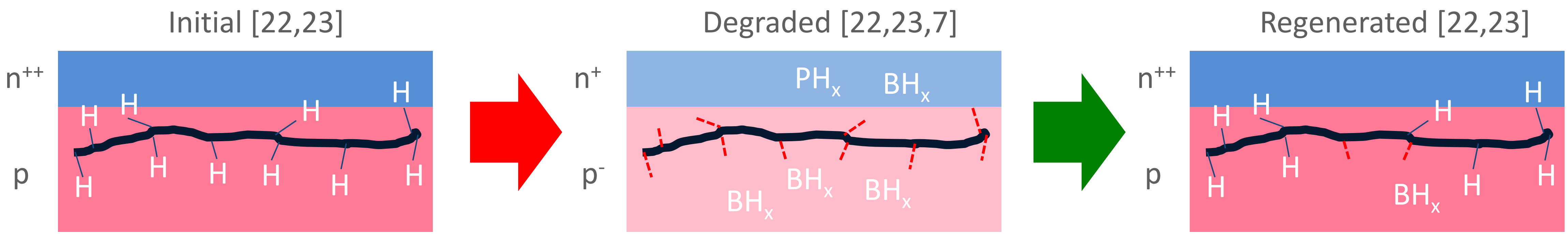
- For the degraded sample:
  - ➢ Changes in recombination in emitter caused by B (and P?) passivation.
  - ➢ Decrease of BE intensity in the bulk.

Discussion

Short summary of observations:

Method	Detected properties	Initial & Regenerated	Degraded	Probable reason
DLTS	Electrical activity of extended defects	Low	High	Hydrogen
CV	Concentration of active boron near to the junction	Higher	Lower	BH_2
PL & EL	Overal intensity	Higher	Lower	Ext. defects
	Intensity of boron related peaks	High	Low	BH_2

Possible (additional?) mechanism of LeTID:



[22] M. Matsubara, et al., **2010**
[23] J. Pankove, **1991**
[7] J. Coutinho, et al., **2024**

Summary

New methods proposed/used for LeTID study:

- On-stage degradation and regeneration of mesa PV cells for PL, EL and DLTS study.
- Low temperature (10 K) EL study under forward and reverse bias.
- Enhanced detection/characterization of extended defects by DLTS using MFIA-DLTS setup.

New results:

- We observed significant and reversible changes in local luminescence and electrical properties of PV cell during on-stage LeTID process.
- The changes can be attributed to interaction between extended defects, dopants and hydrogen and can imply a mechanism (additional?) of LeTID.

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Thanks are also due to Jan Bayer, Amy Albrecht, and Kuei-Shen Hsu (Bergakademie Freiberg) for their assistance with PL measurements and Steffi Güldner for help with sample preparations.

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[3] F. Kersten, P. Engelhart, H-C Ploigt, et al. Degradation of multicrystalline silicon solar cells and modules after illumination at elevated temperature. Sol Energy Mater sol Cells. **2015**; 142: 83; DOI: 10.1016/j.solmat.2015.06.015

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[7] J. Coutinho, D. Gomes, V.J.B. Torres, T.O. Abdul Fattah, V.P. Markevich, and A.R. Peaker, Hydrogen Reactions with Dopants and Impurities in Solar Silicon from First Principles; Sol. RRL **2024**, 8: 2300639, DOI: 10.1002/solr.202300639

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[10] T. Mchedlidze, “How to avoid distortions of trap probing due to instrumental recovery time during Deep-Level Transient Spectroscopy measurements", How to avoid distortions of trap probing due to instrumental recovery time during Deep-Level Transient Spectroscopy measurements", Preprint, **2023**; DOI: 10.13140/RG.2.2.24131.78884

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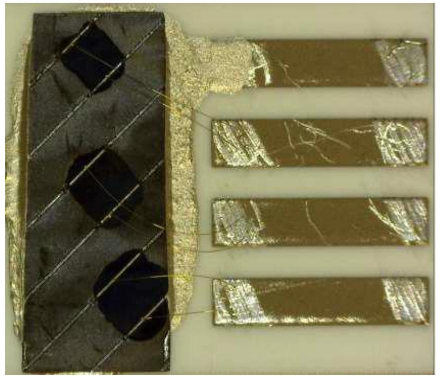
Appendix 1: TCAD modelling

Software	TCAD Sentaurus O-2018.06-SP2
Materials	Silicon, Oxides and Aluminum
Domain	Smallest symmetrical element
Meshing	• "Box" method volume $[\mu m^2] \longrightarrow$ PERC: $1.192 \cdot 10^5$ MESA: $1.193 \cdot 10^5$ • Total number of elements $\longrightarrow$ PERC: 46,399 MESA: 71,986
Generation & V-range	$1.5 \cdot 10^{19} \left[\frac{1}{cm^3 \cdot s}\right]$ & V [mV] $\in$ [0; 690]
Surface recombination	On all intermediate areas, not on edge surfaces
Physical models	• Intrinsic carrier density model: Schenk bandgap narrowing model and calculation by Altermatt et al. [2;3] • Charge carrier density mobility: Klaassen model [4;5]
Solver	Pardiso: Gaussian elimination for systems of equations

Appendix 1: TCAD modelling

Excess Charge carrier density



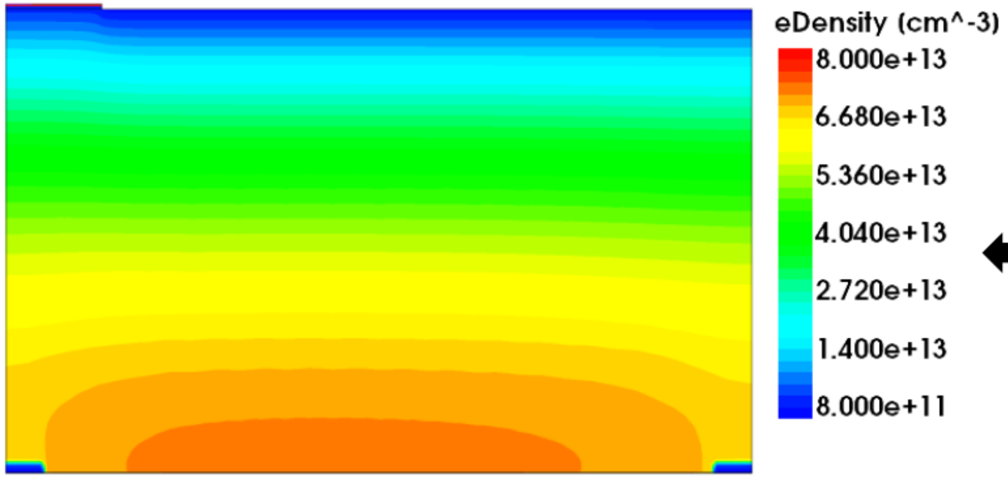
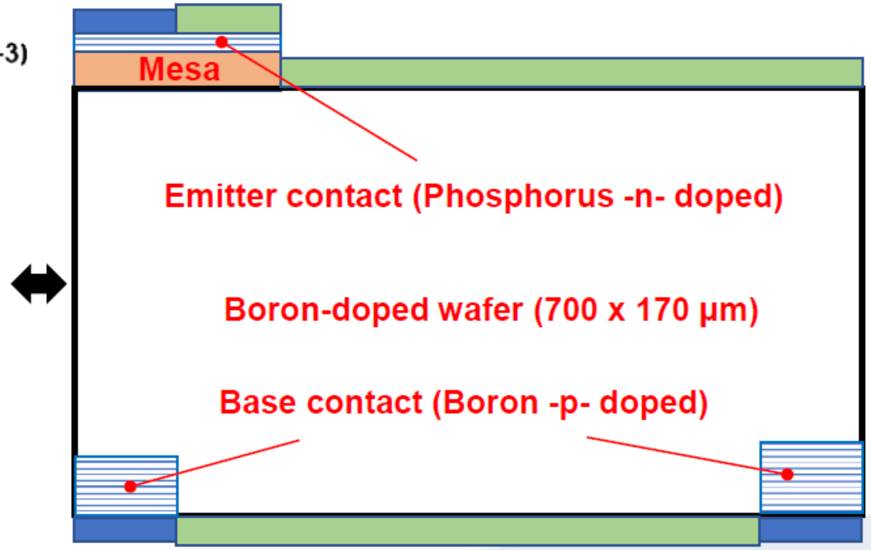


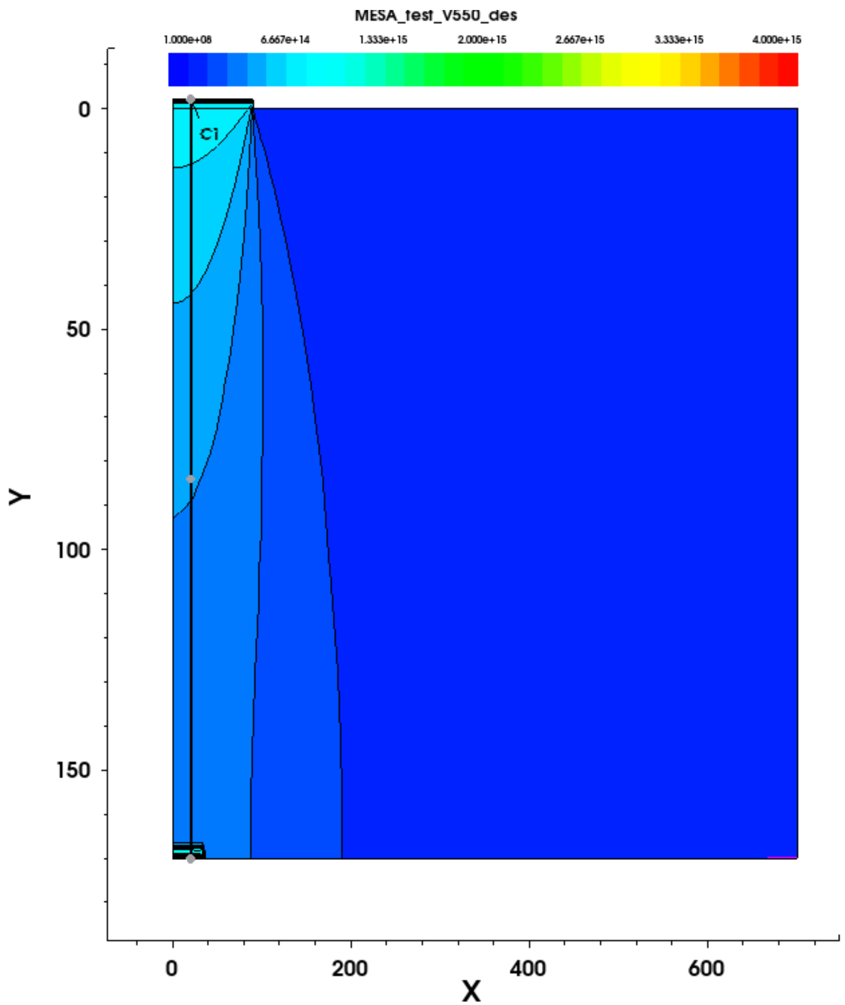
Fig. 3.4 Excess charge carrier density within MESA cell for $S_p = 2580 \left[\frac{cm}{s}\right]$ and $V_{MPP} = 488\ [mV]$



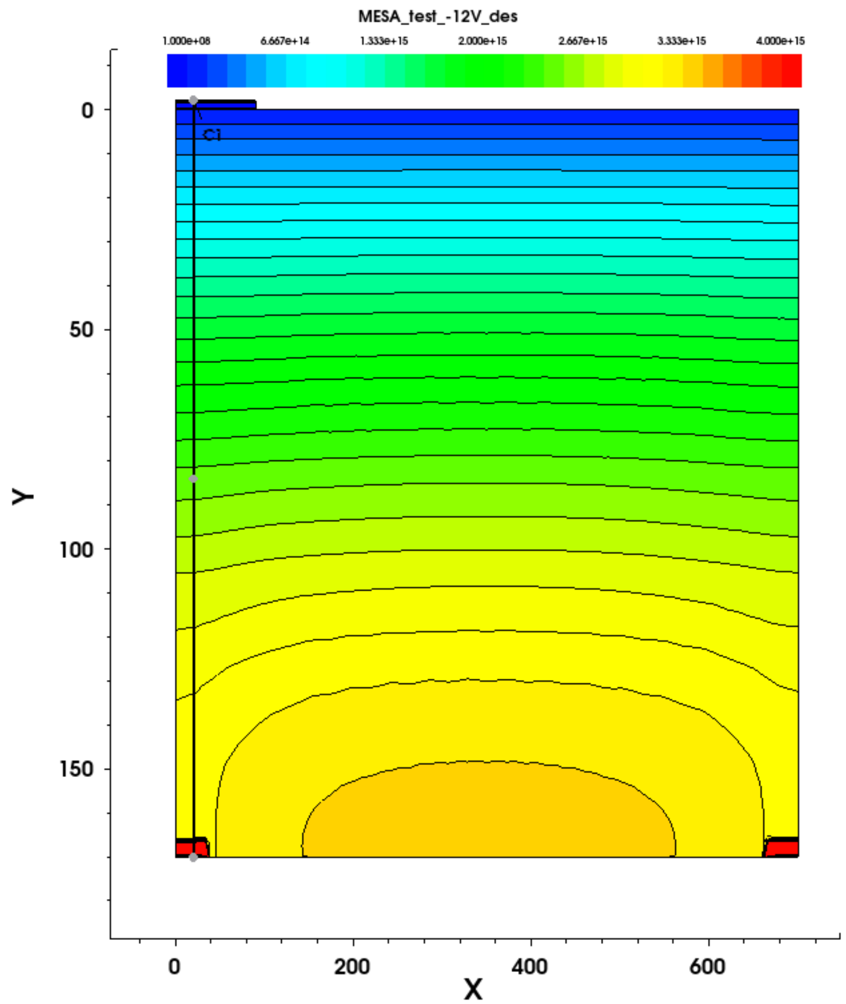
Appendix 1: TCAD modelling

Solving of equations	Poisson, Electron, Hole
Solver	Pardiso
T [K]	298.15
wafer	Boron doped
p_0 [1/cm3]	9.74E+15
Phosphoros concentration at emitter described by Gauss -> peak value [cm-3]	1.65E+20
wafer resistance [Ohm*cm] at 300 K	1.5
Surface recombination velocity of 1. holes and 2. electrons (fcont1ox?)	1E7; 1E7
Meshing with..	Box Method

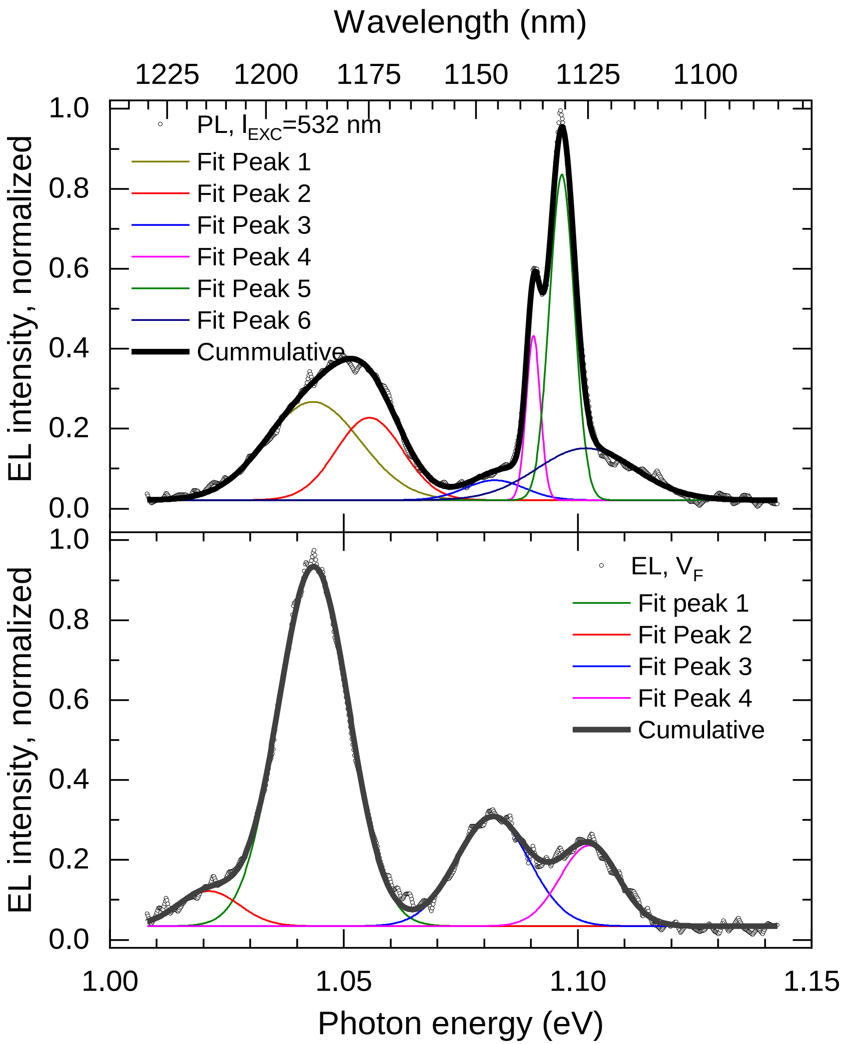
Forward bias: 0->690 mV
Operating: 550 mV

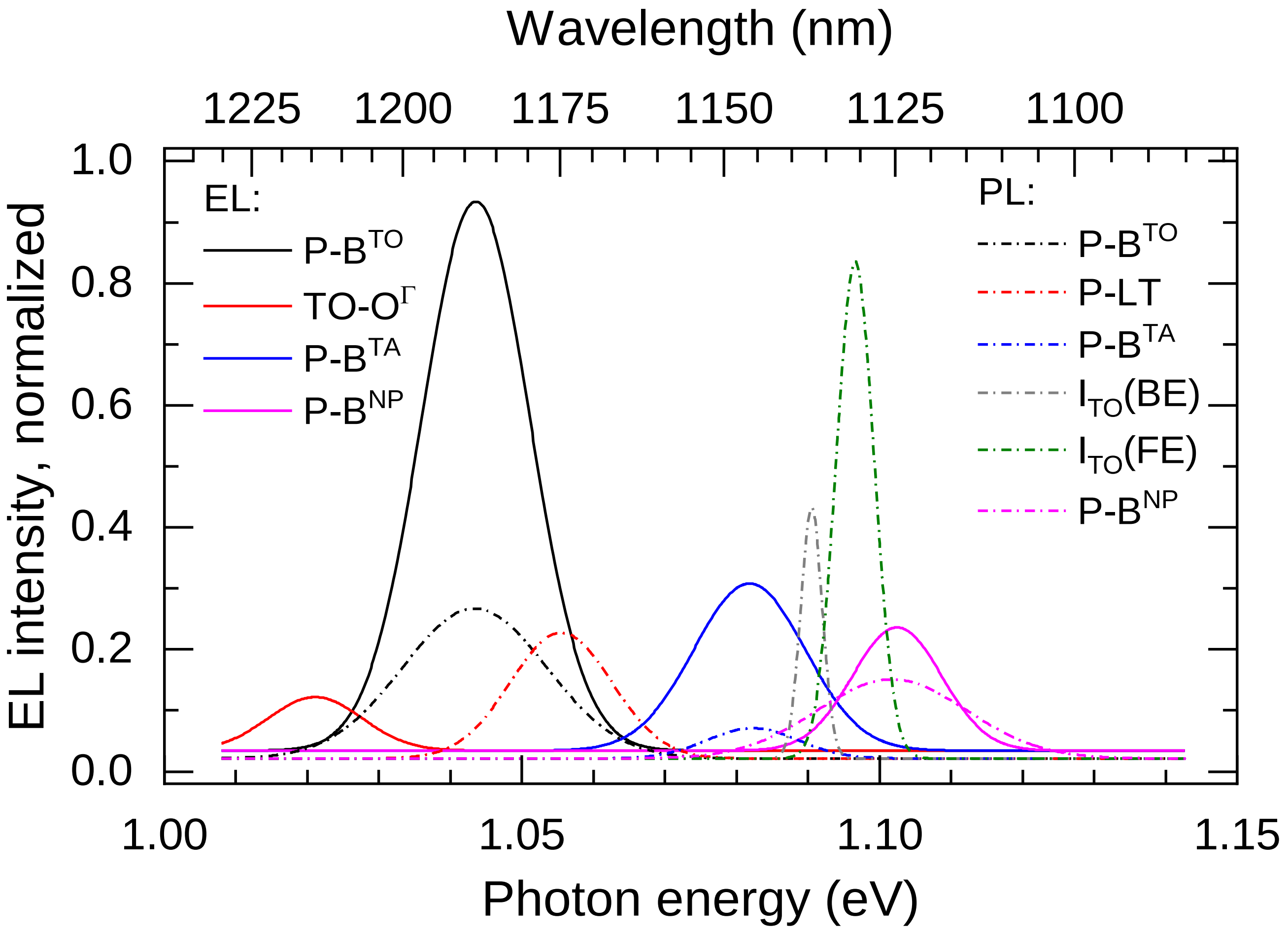


Reverse bias: 0-> -12 V
Operating: -12 V

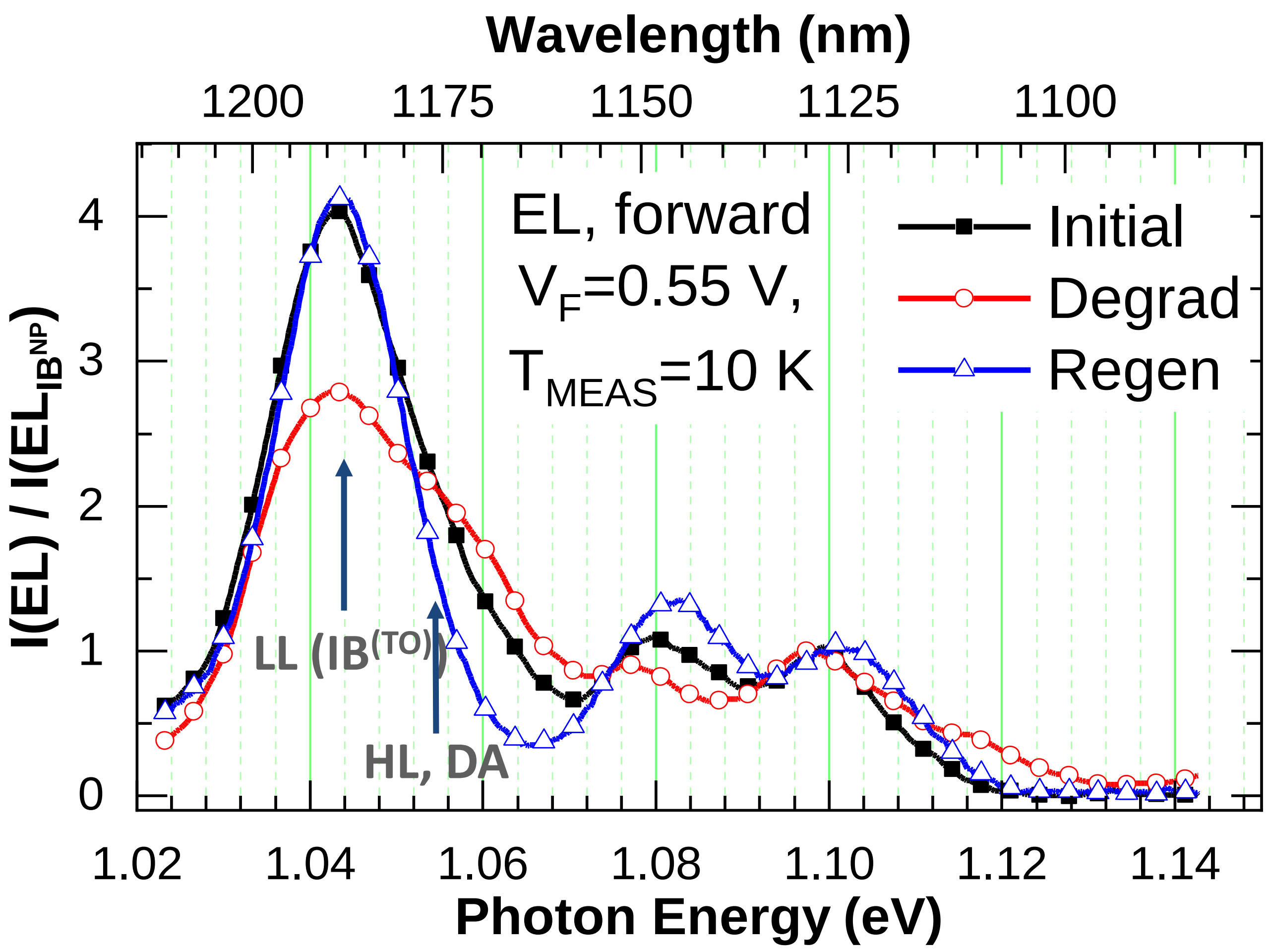


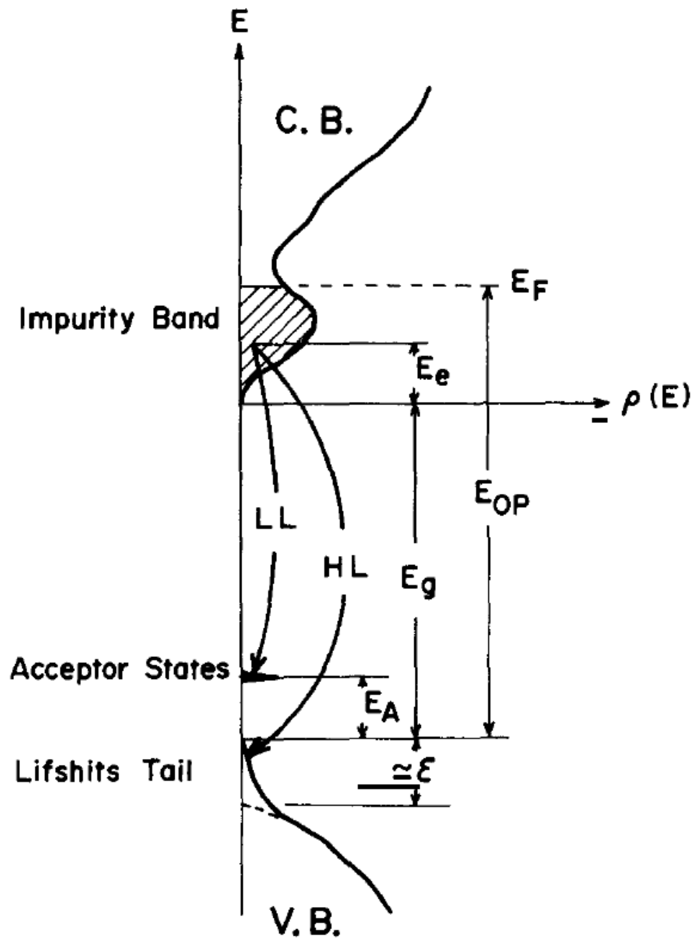
Appendix 2: Luminescence, fitting





Appendix 3: Change in DA recombination in Emitter





[19] R.R. Parsons, **1979**

Appendix 4: Luminescence, power dependence