Workshop on Radiation Effects on Optoelectronics detectors and Photonics Technologies

RADOPT

Impact of 63 MeV proton irradiation on the dark current of Ga-free T2SL XBn barrier infrared detector

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[2]: Airbus Defence & Space, Toulouse, France

[3]: CNES, Toulouse, France

[4]: Lynred, Veurey-Voroize, France

29th of November 2023

CONTEXT : INFRARED DETECTORS FOR SPACE APPLICATIONS

- **InfraRed (IR) detector :** essential device for the observation of the Earth and Space
- **Allows complementary observations**
  - 2 images of space (visible and infrared)

Credit : Eagle Nebula, NASA

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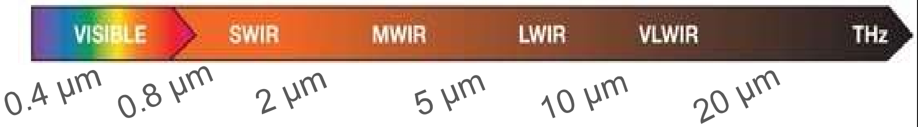

Infrared detectors for imaging

MCT	**InSb**	**InGaAs**	**QWIP**	**Si : As**

Well established infrared technologies

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- **Investigation of a new technology :**

T2SL material

➔ Covering the SWIR, MWIR and LWIR domains
➔ Broad band detection
➔ Good homogeneity
➔ Potentiality for high operating temperature

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➔Covering the SWIR, MWIR and LWIR domains
➔Broad band detection
➔Good homogeneity
➔Potentiality for high operating temperature

- **But** for space missions ?

What about their tolerance in this harsh environment ?

- This work investigates proton-induced performances degradation of T2SL : $\mathbf{J_{dark}}$

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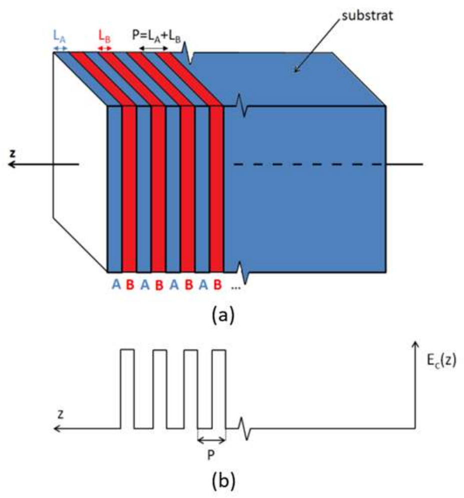
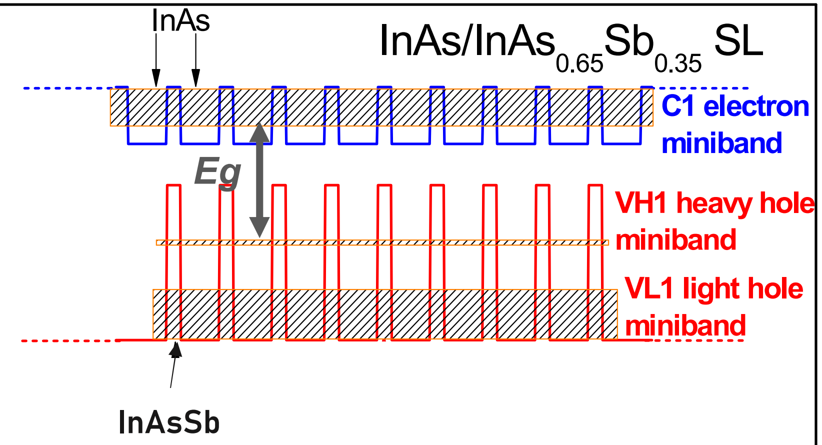
CONTEXT : SUPERLATTICE STRUCTURE

RADOPT

- **Superlattice :** structure with a repeating sequence of thin layers of different materials



Period : L_A+L_B



Band diagram of a « Ga-free » InAs/InAsSb T2SL

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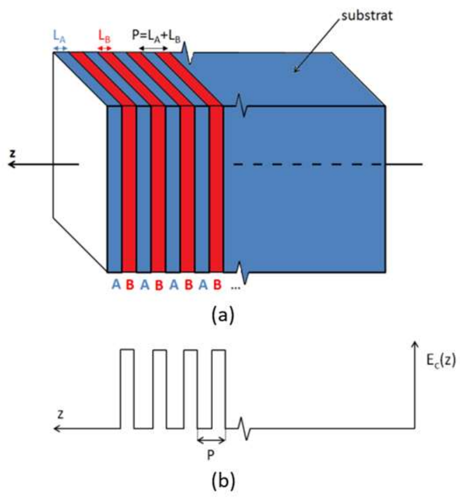

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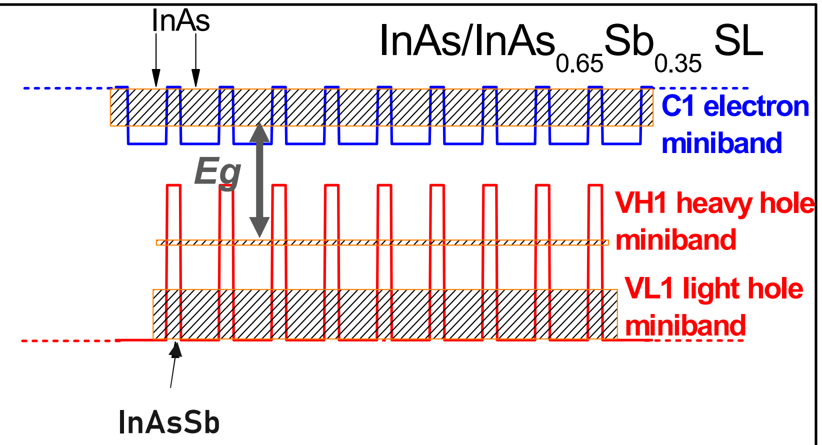

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Coupled Multiple Quantum Wells

Creation of **energy minibands**

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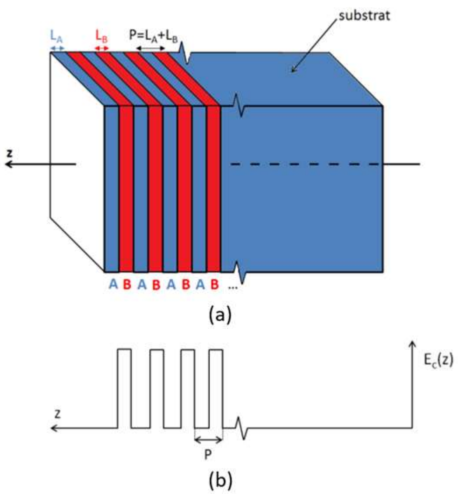

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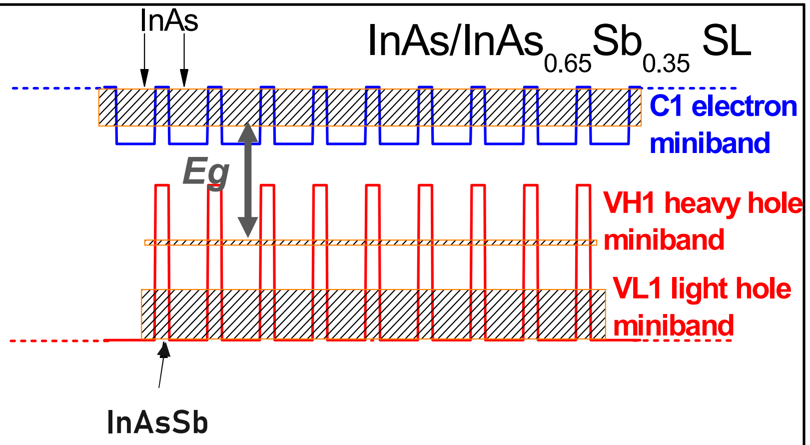

Band diagram of a « Ga-free » InAs/InAsSb T2SL

Coupled Multiple Quantum Wells

Creation of **energy minibands**

➔ Creation of semiconductor with a tunable bandgap (E_g)
➔ E_g depends on the antimonide (Sb) concentration and superlattice period

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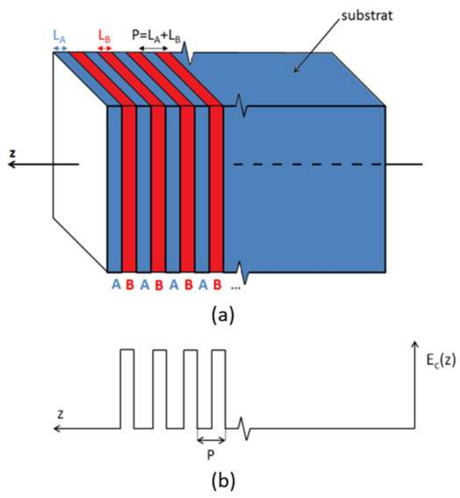

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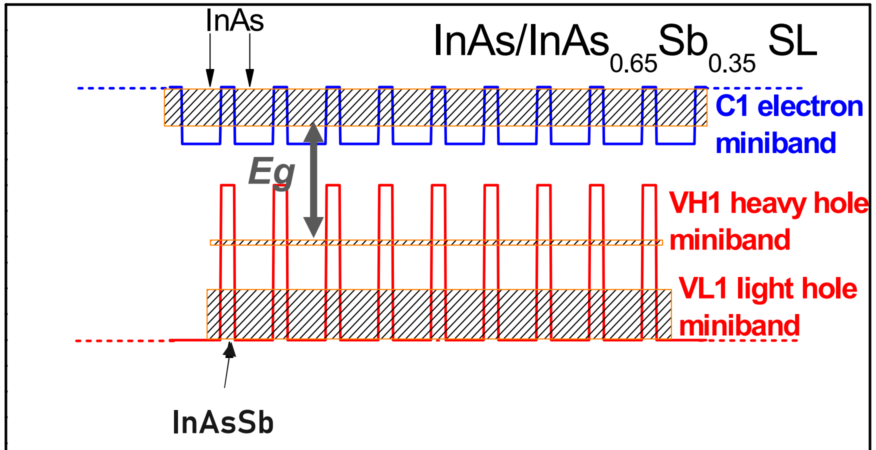

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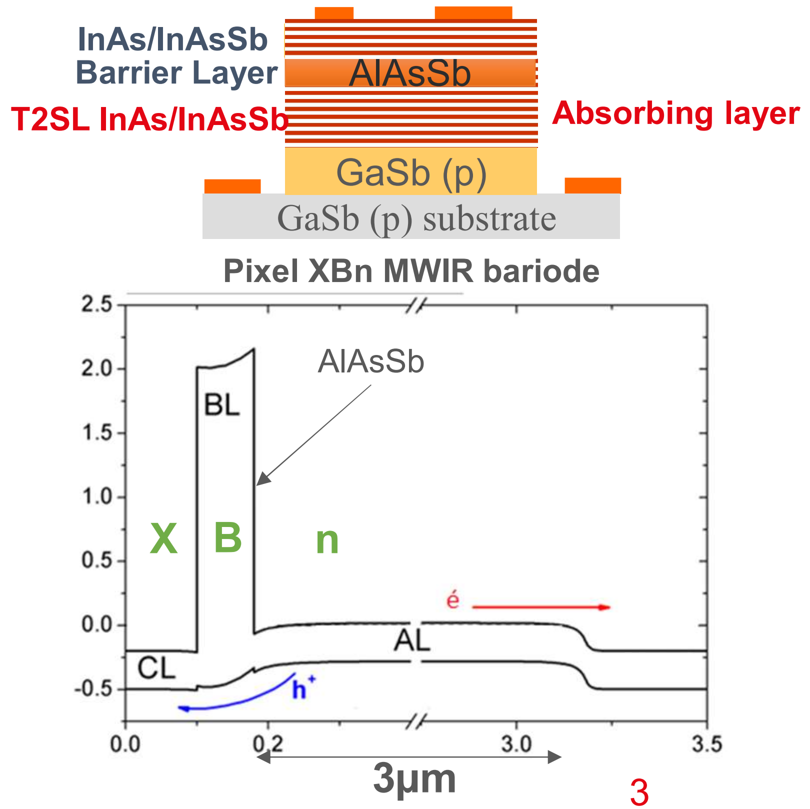
T2SL absorbing layer of bariode detector



EXPERIMENTAL DETAILS : DEVICES UNDER TEST

RADOPT

- XBn T2SL InAs/InAsSb monopixel bariode

MidWave InfraRed (MWIR, 3-5µm)

Homemade technological process

MWIR T2SL structure	Cut-off wavelength	V_{op}	AL thickness	Number of periods
Samples XBn	λc = 5 µm (150K)	- 1 V	3 µm	545

Different objectives :

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Dark current analytic calculations

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Dark current analytic calculations

Influence of the **detector's temperature during the irradiation** (150 K VS 300 K)

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EXPERIMENTAL DETAILS : SETUP DESCRIPTION

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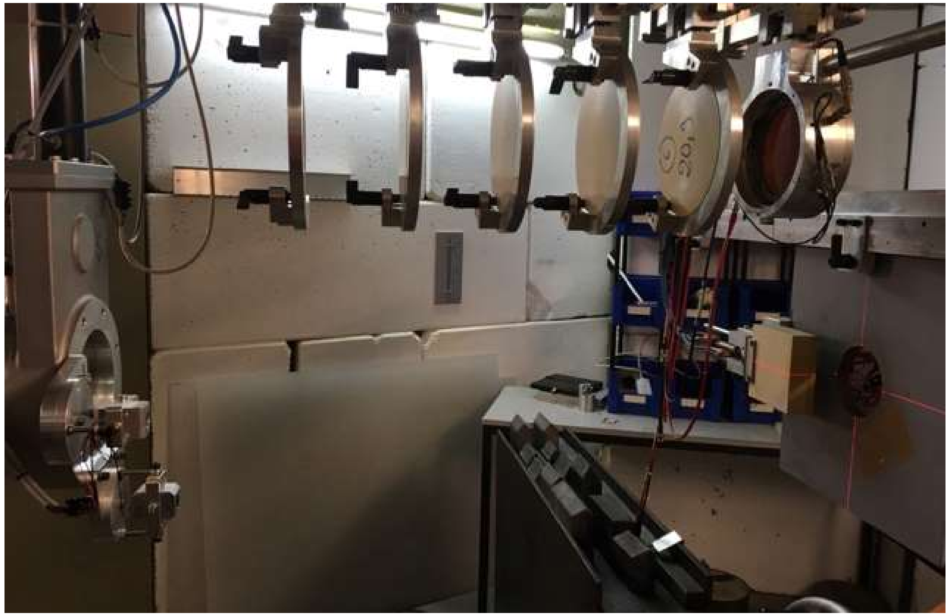
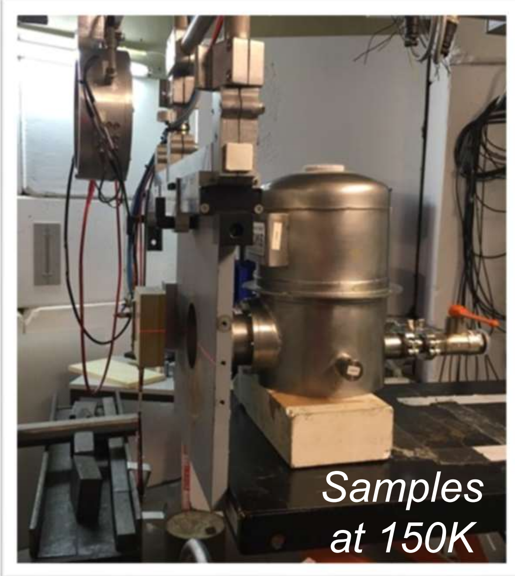
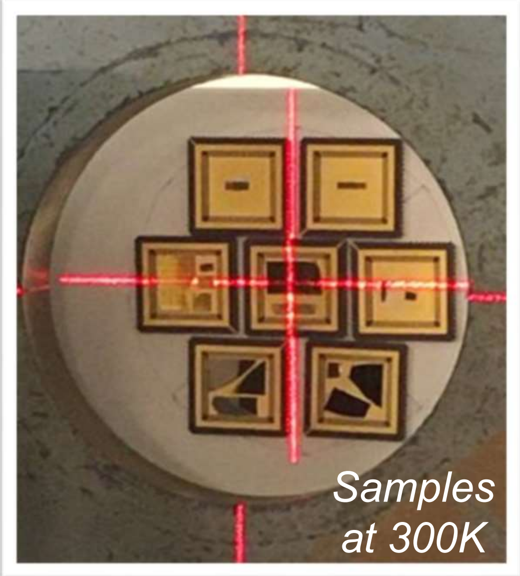
Proton irradiation

UCL Louvain (Université Catholique de Louvain), Belgium



63 MeV Protons,
fluence up to 8×10^{11} H^+/cm^2
Proton flux : 2×10^8 $H^+/cm^2/s$





Measurements performed after each irradiation step

Measurements performed after last irradiation step ~ few days @ RT

All measurements at T_{op} = 150 K

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1^{st} objective :

Evaluate the damage of dark current density under **proton fluence ($T_{irradiation}$ = 150 K)**

EXPERIMENTAL : EVOLUTION OF J_{DARK} UNDER PROTON FLUENCE STEPS

MWIR T2SL structure	Cut-off wavelength	AL thickness	Number of periods
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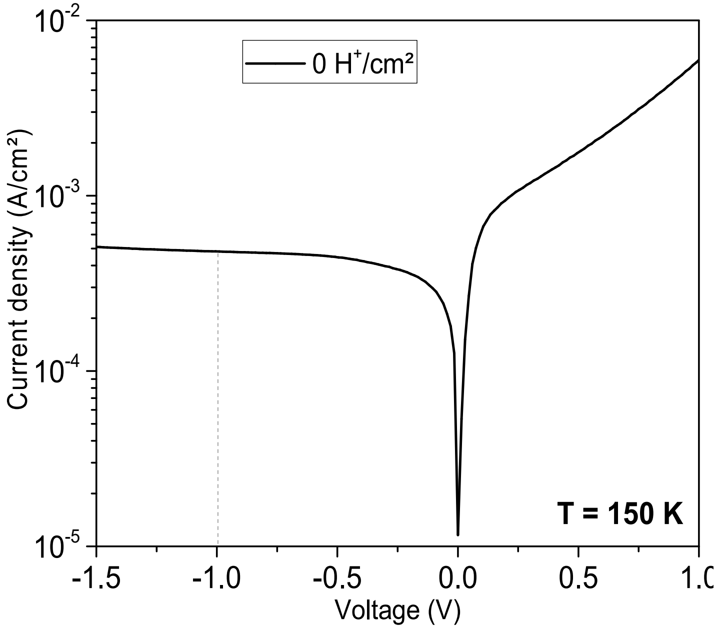
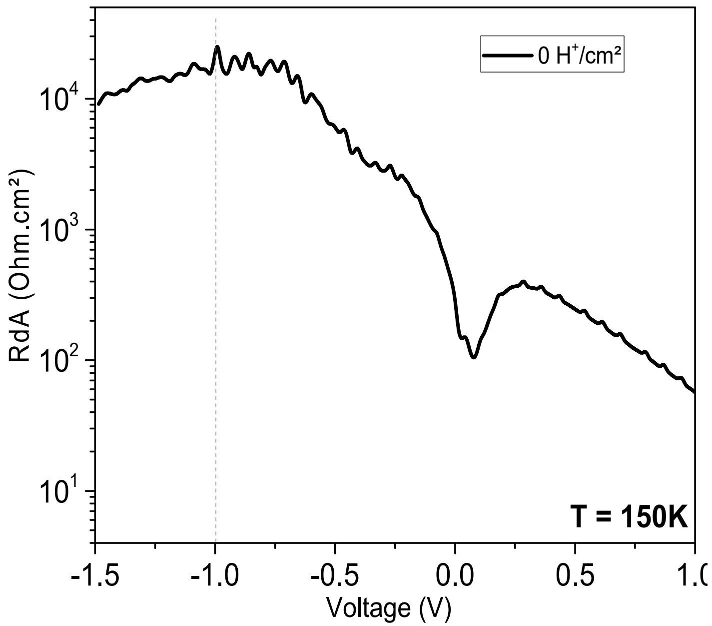


$$D^* = R_\lambda \sqrt{\frac{1}{2qJ_{dark} + \frac{4kT}{R_d A}}}$$

$$R_d A = \left(\frac{dJ}{dV}\right)^{-1}$$



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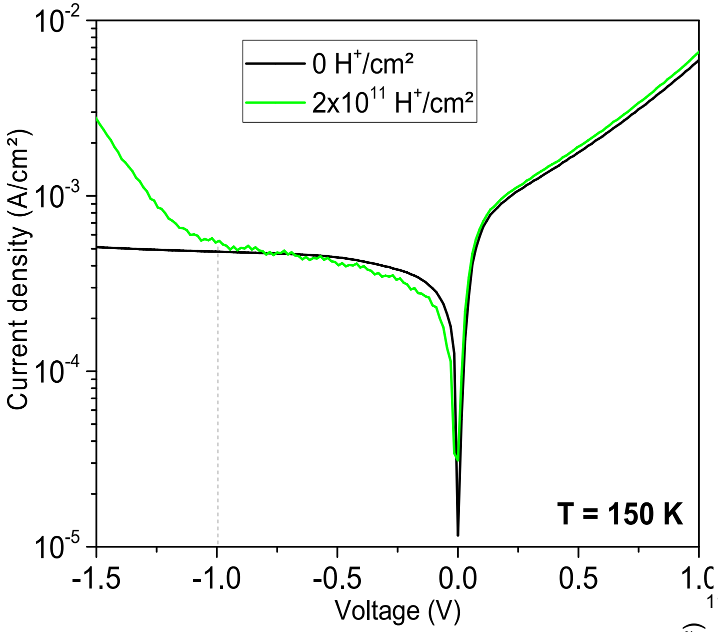

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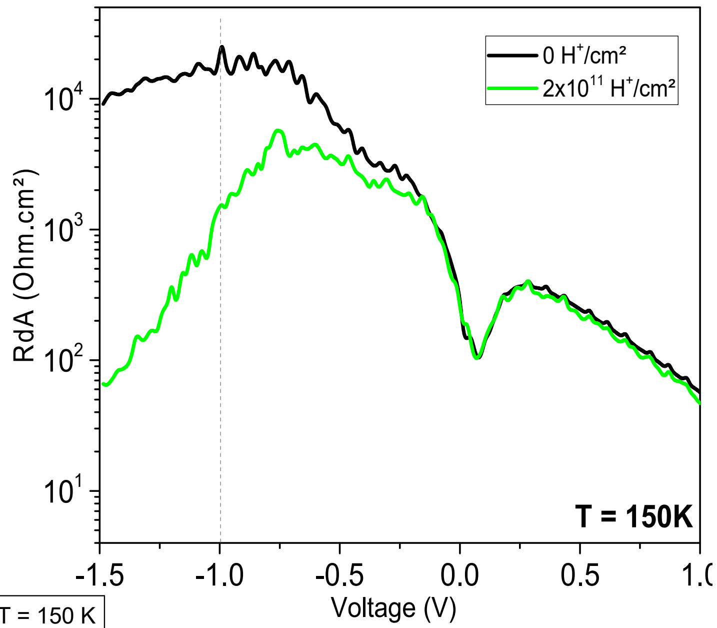

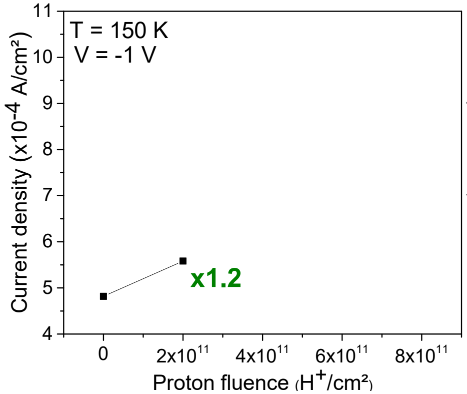

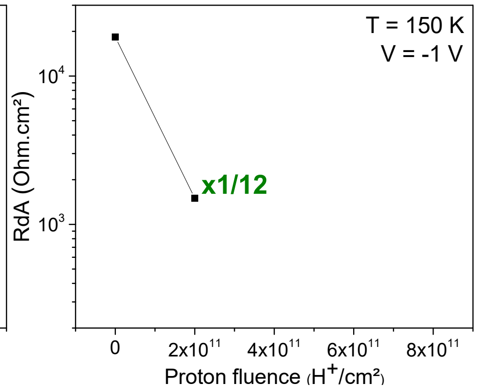

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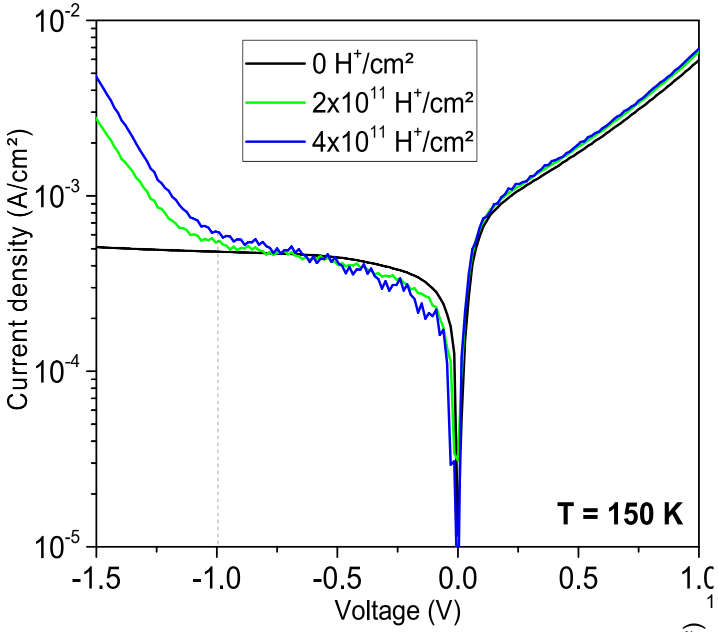

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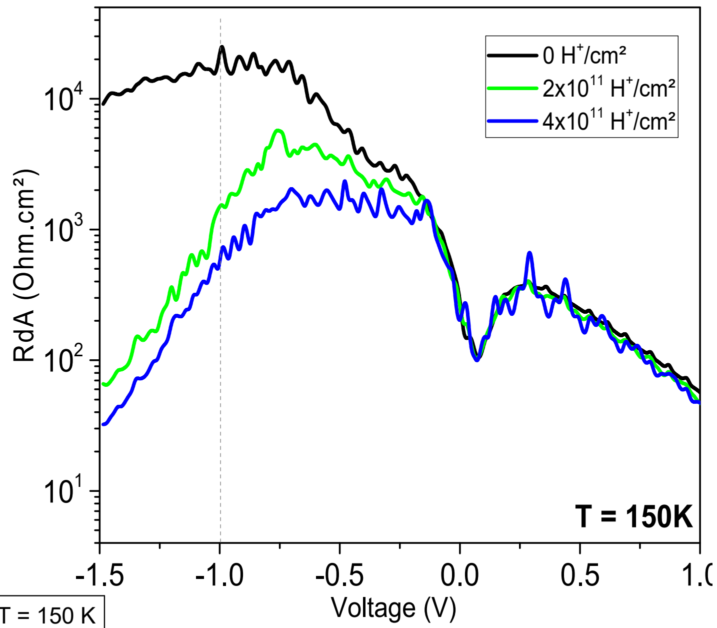

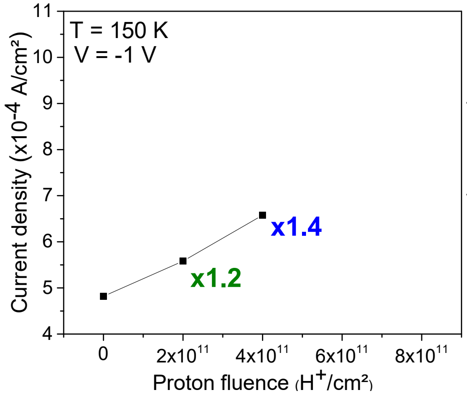

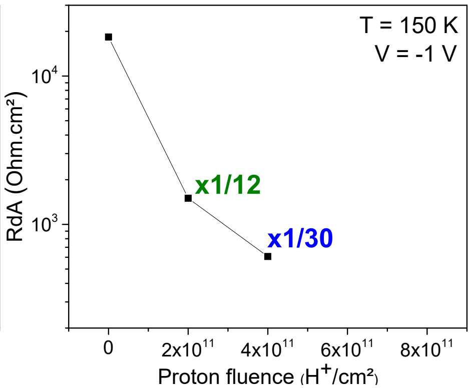

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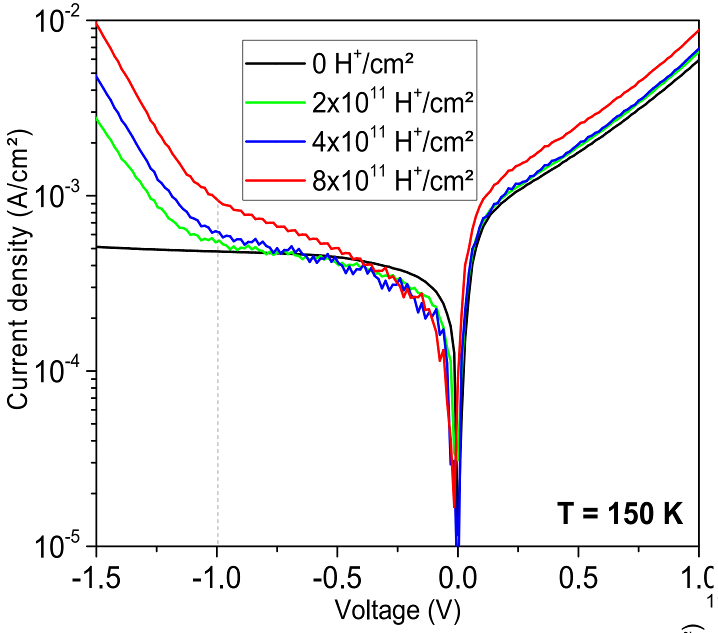

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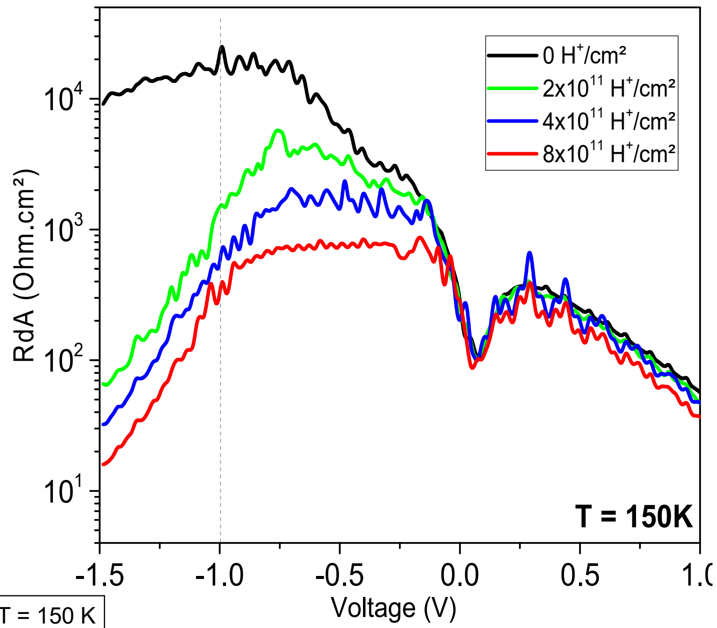

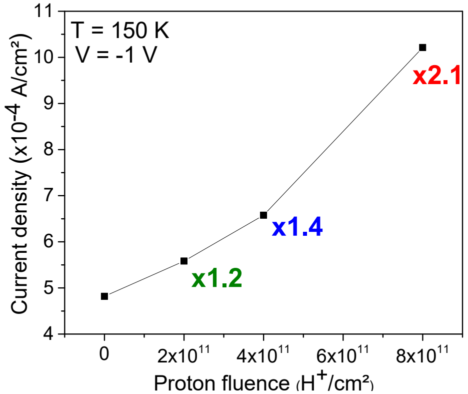

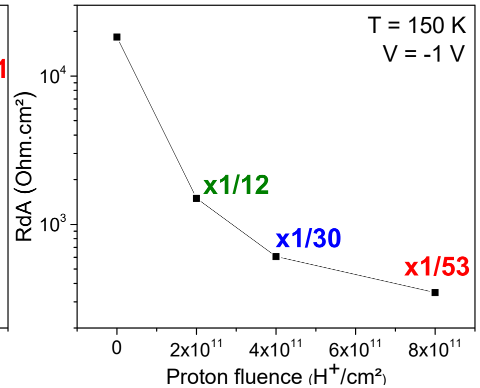

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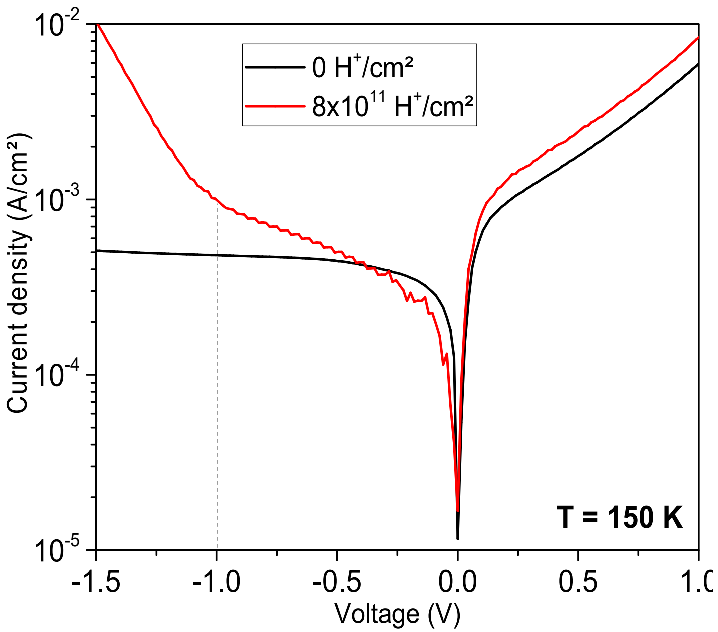
EXPERIMENTAL : INFLUENCE OF THERMAL CYCLE ON J_{DARK} EVOLUTION



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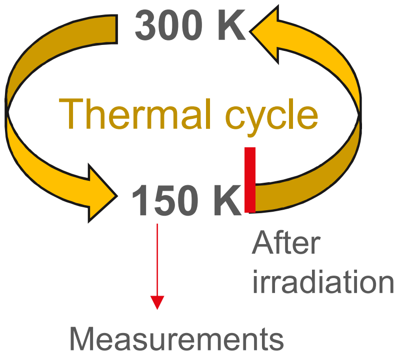

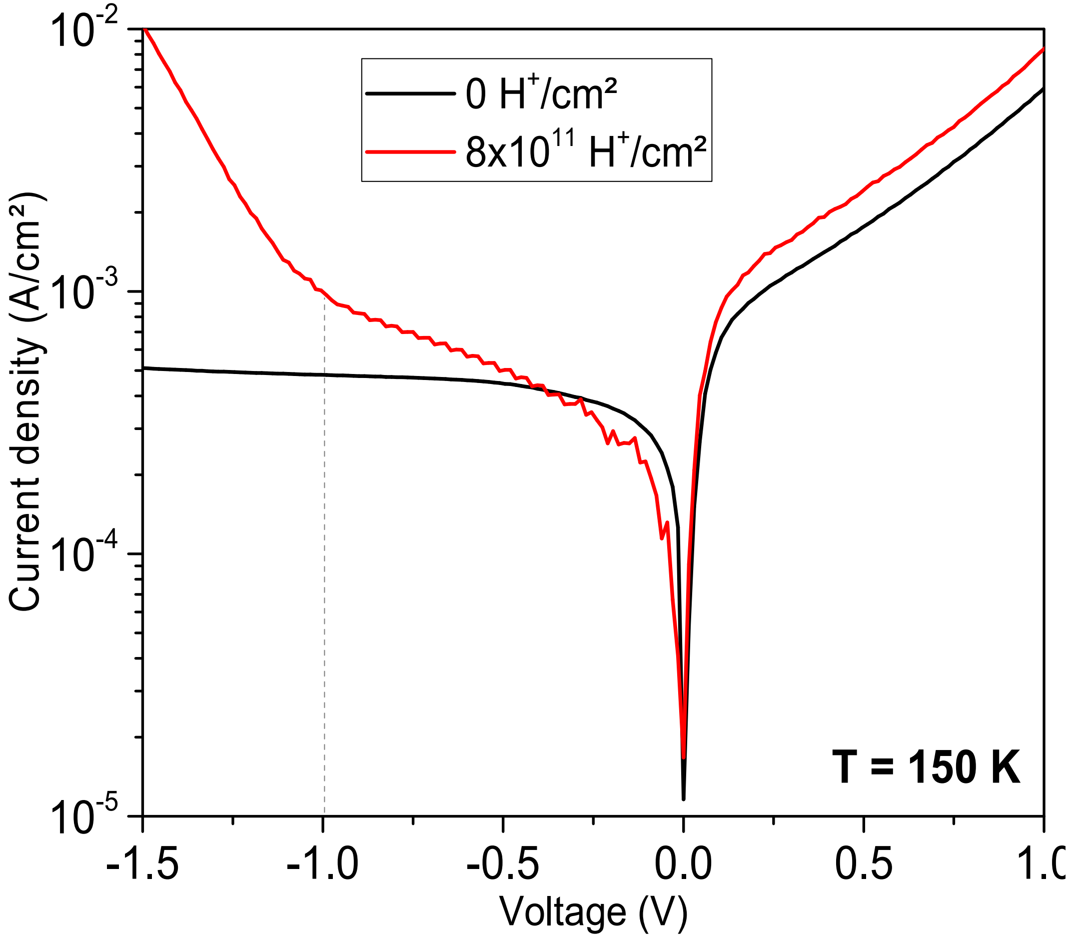

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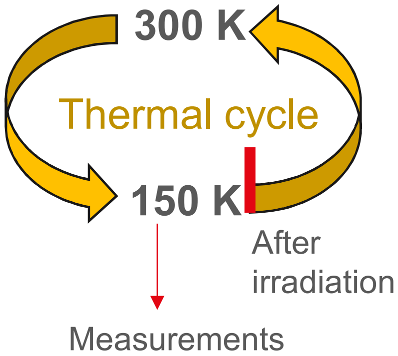

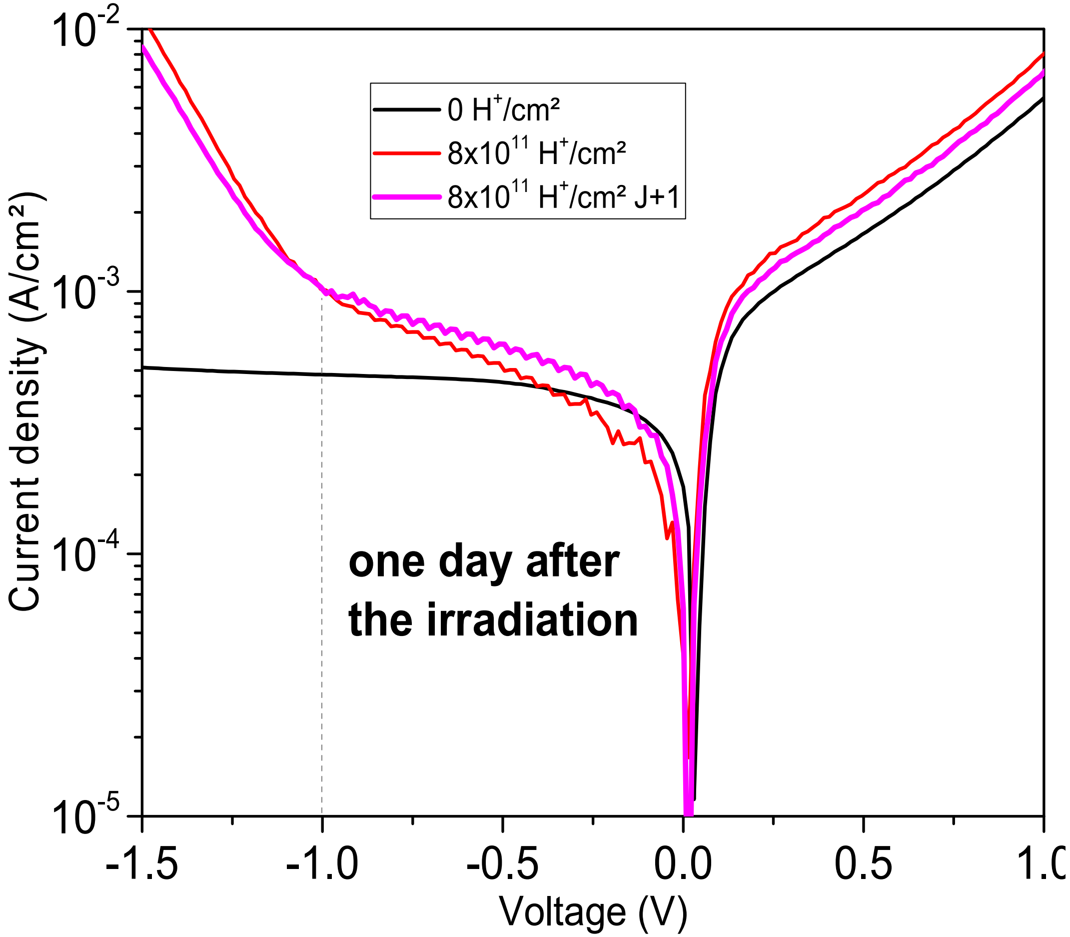

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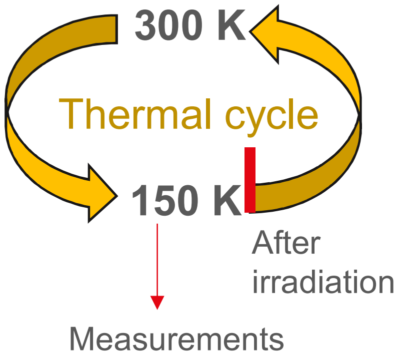

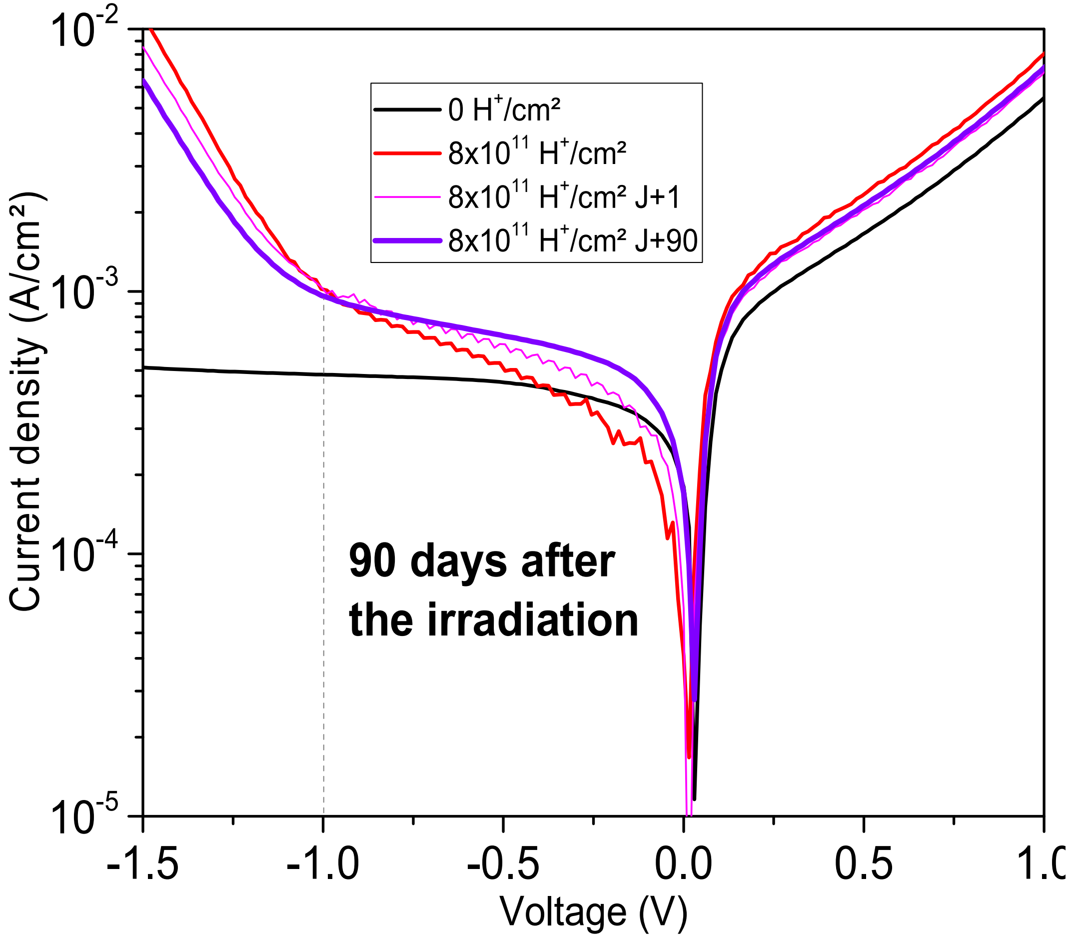

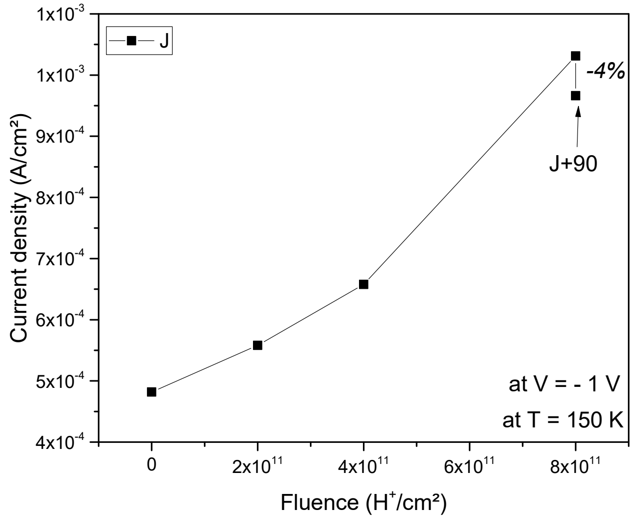

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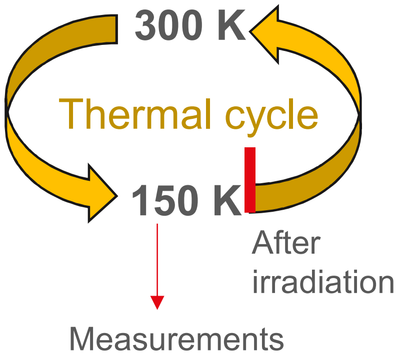

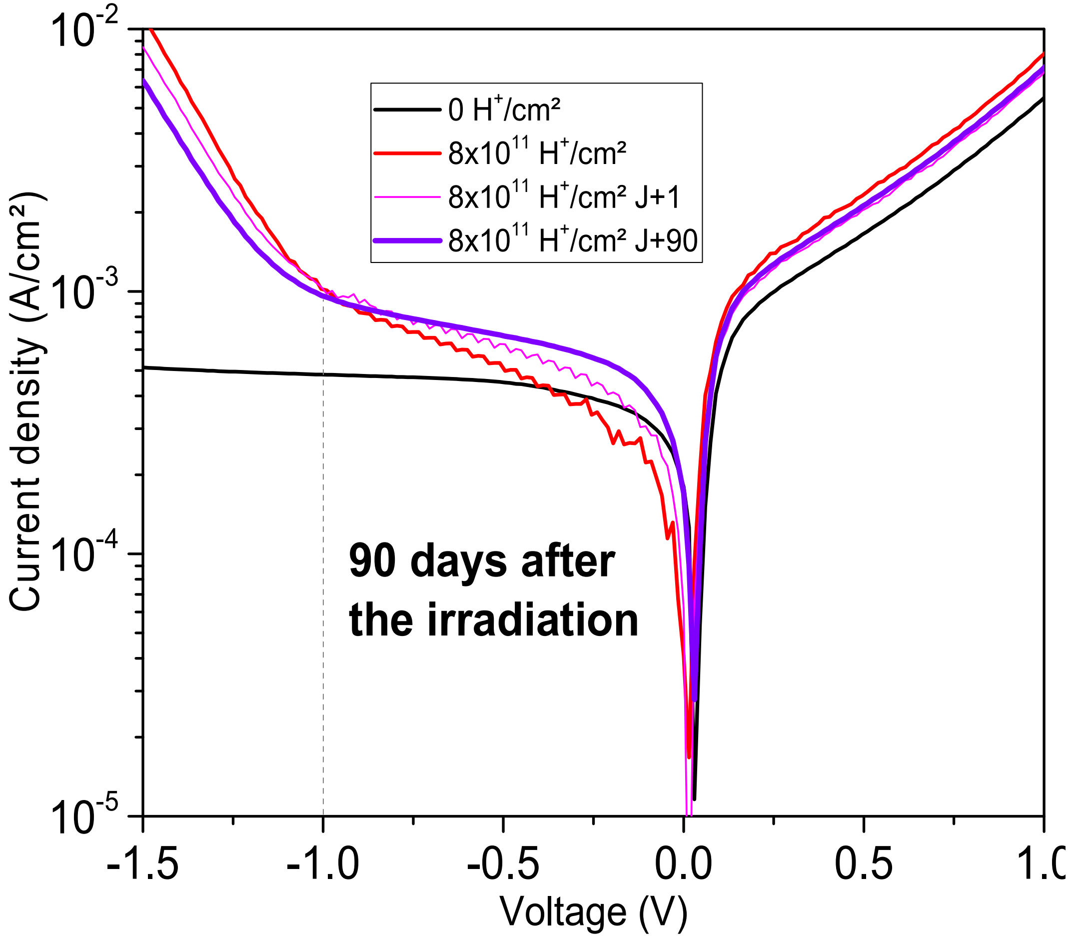

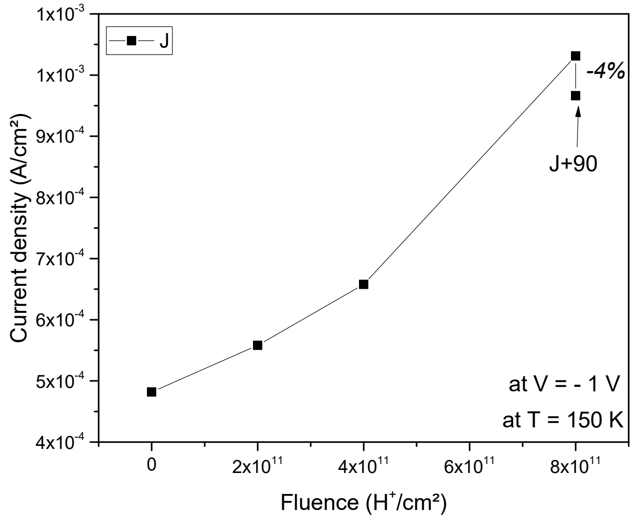

Thermal cycle can not restore the initial dark current

EXPERIMENTAL : INFLUENCE OF BIAS APPLIED VOLTAGE ON BARIODE

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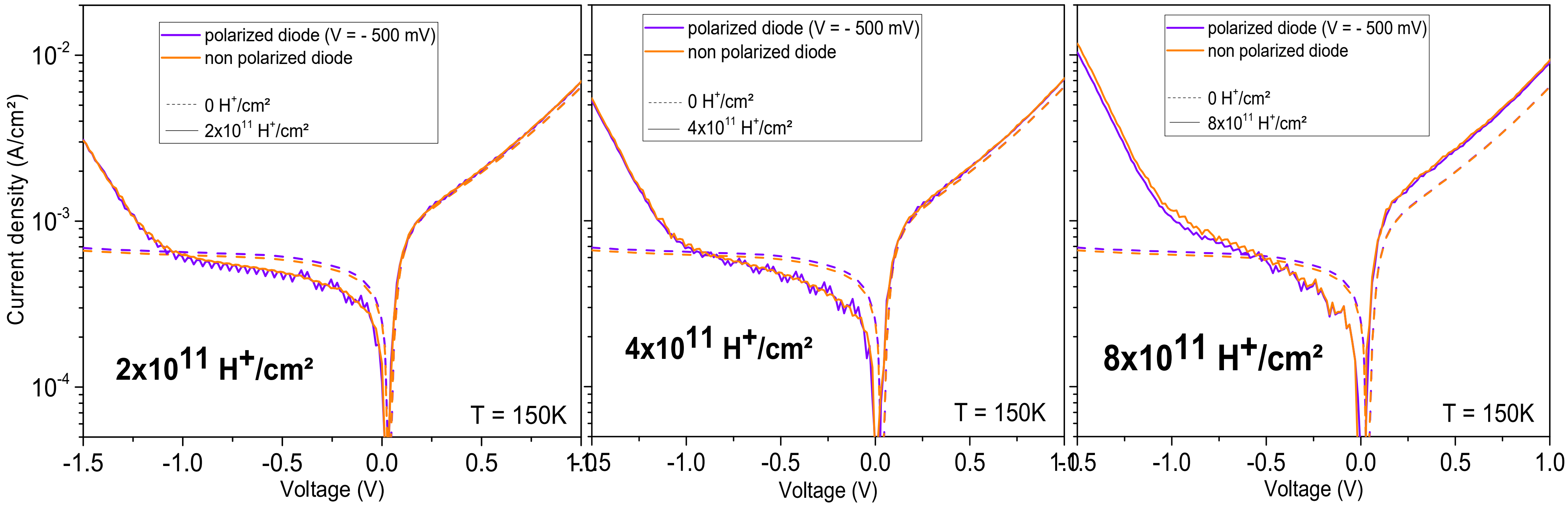

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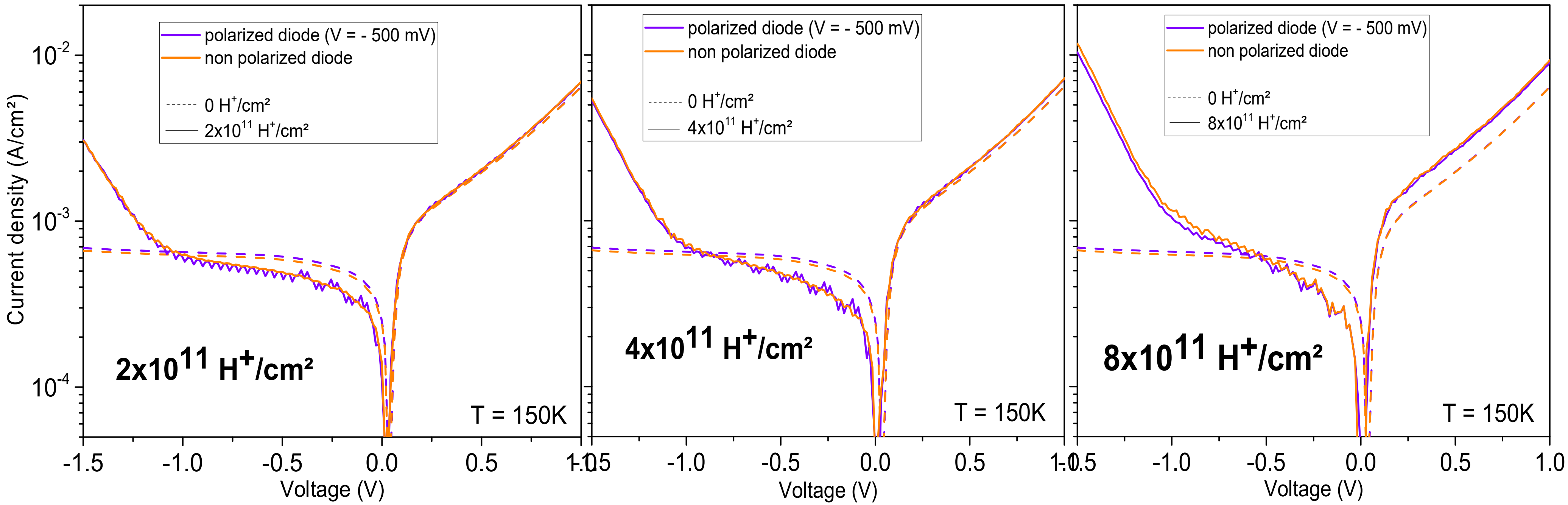


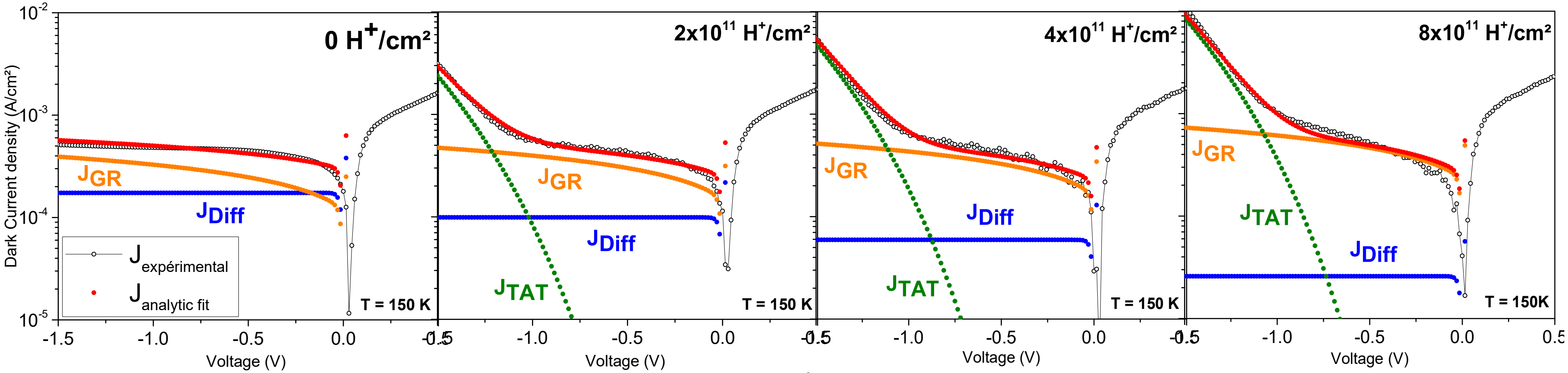
Degradation independent of the bias voltage applied (V = – 500 mV) on bariode during the irradiation

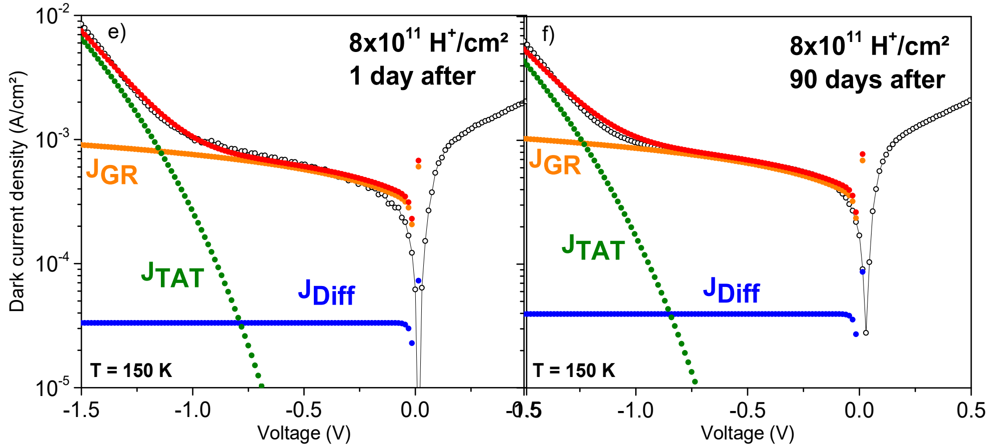
2^{nd} objective :

Understand the **evolution of dark current in T2SL** for a bariode irradiated at $\mathbf{T_{op} = 150\ K}$, at different **steps of fluence**

ANALYSIS : EVOLUTION OF J_{DARK} UNDER PROTON FLUENCE STEPS

$$I_{dark} = I_{diff} + I_{GR} + I_{TAT}$$





GR current :

- Increases with proton fluence

➔ Damage remains 90 days after irradiation

TAT current :

- Appears from the first step of fluence

➔ Weak reduction of damage is visible 90 days after irradiation

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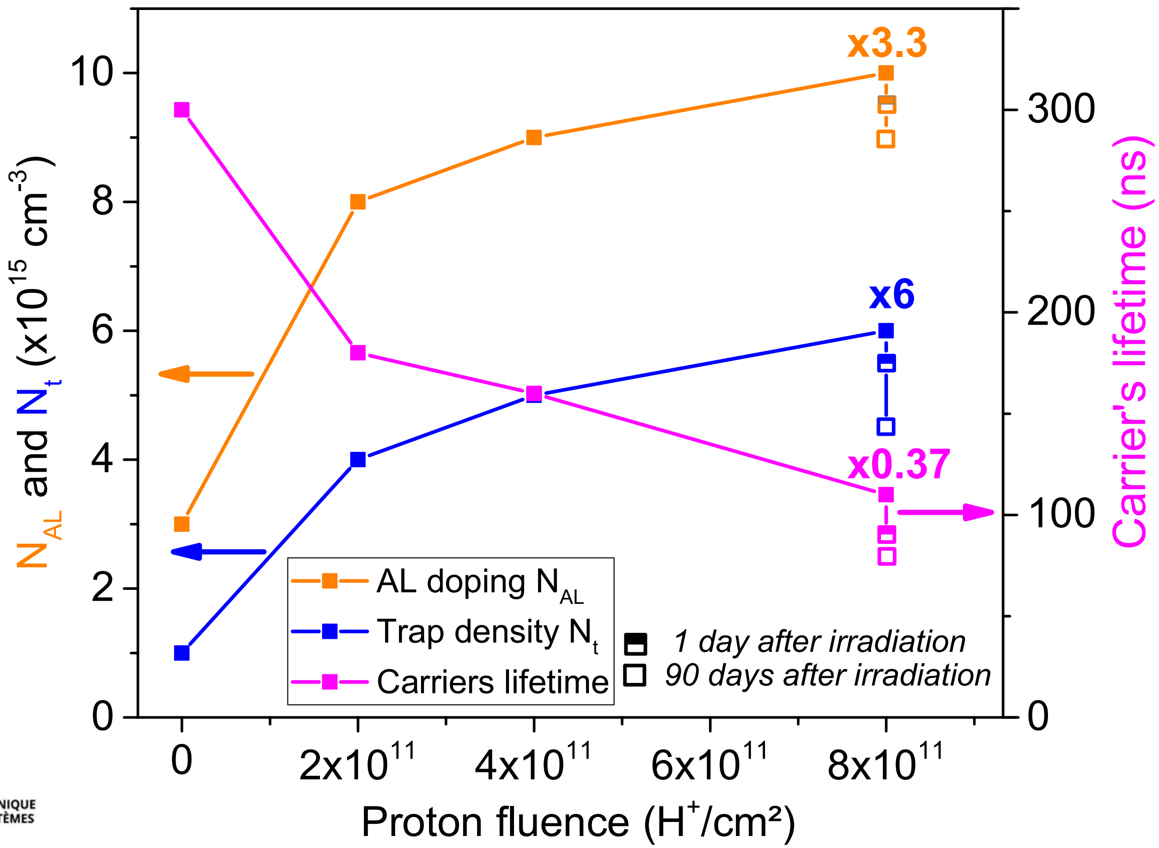
ANALYSIS : EVOLUTION OF J_{DARK} UNDER PROTON FLUENCE STEPS

$$I_{dark} = I_{diff} + I_{GR} + I_{TAT}$$

$$J_{diff} \propto q \frac{L_{diff}}{\tau \times N_{AL}} n_i^2 \qquad J_{GR} \propto q \frac{W(V)}{2 \times \tau} n_i \qquad J_{TAT} \propto q^2 \frac{V m_t M^2 N_t}{8\pi\hbar^3 (E_g - E_t)}$$



- Carrier lifetime τ decreases
- AL doping N_{AL} increases
- Trap density N_t increases (E_t cste)

Damage coefficients consistent with :
L. Höglund *et al., Appl. Phys. Let.*, **108**, 263-504, 2016

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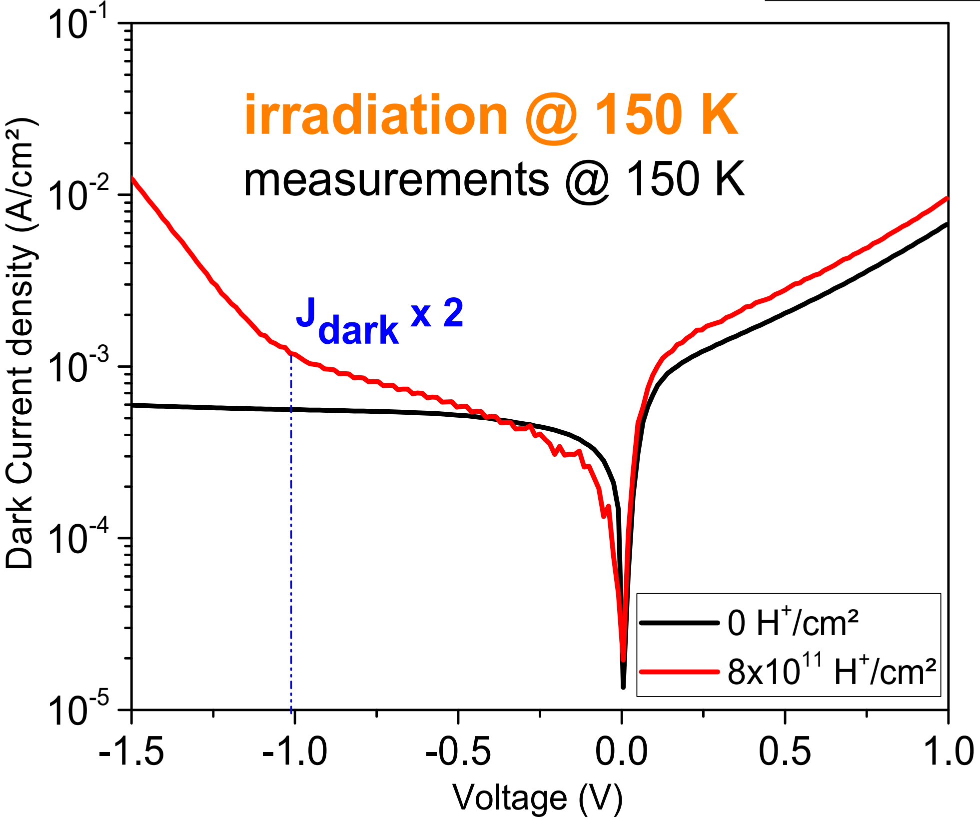
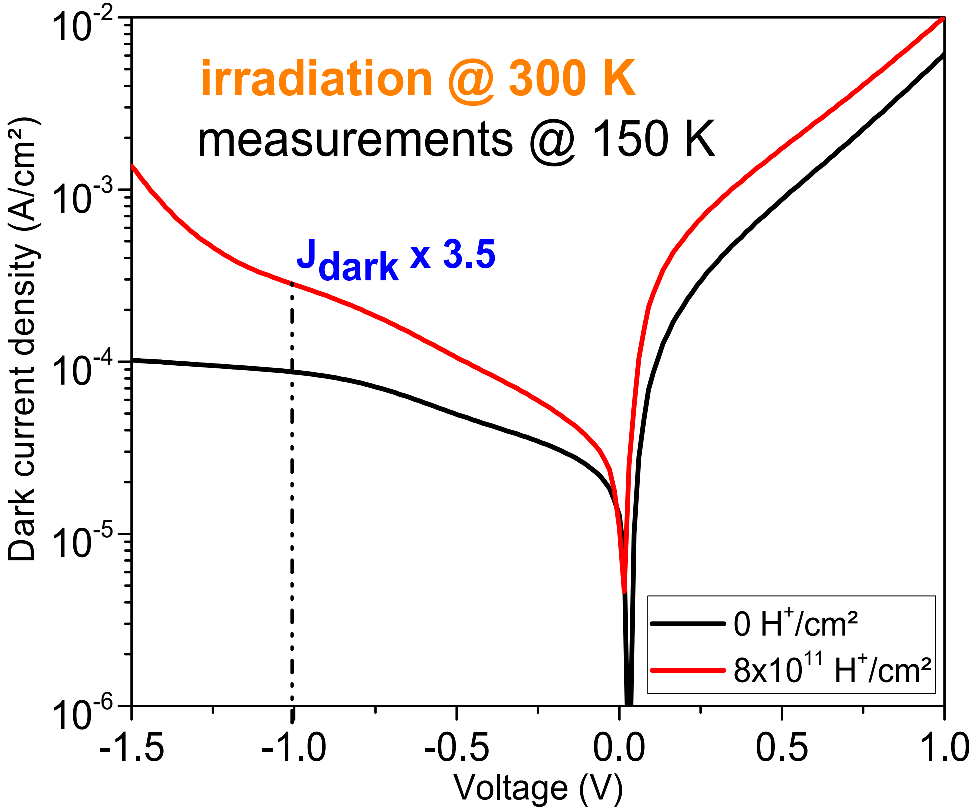
3rd objective :

Influence of the **detector's temperature during the irradiation** (150K / 300K)

INFLUENCE OF THE DETECTOR'S TEMPERATURE DURING IRRADIATION

Proton fluence : $8x10^{11}$ H^+/cm^2





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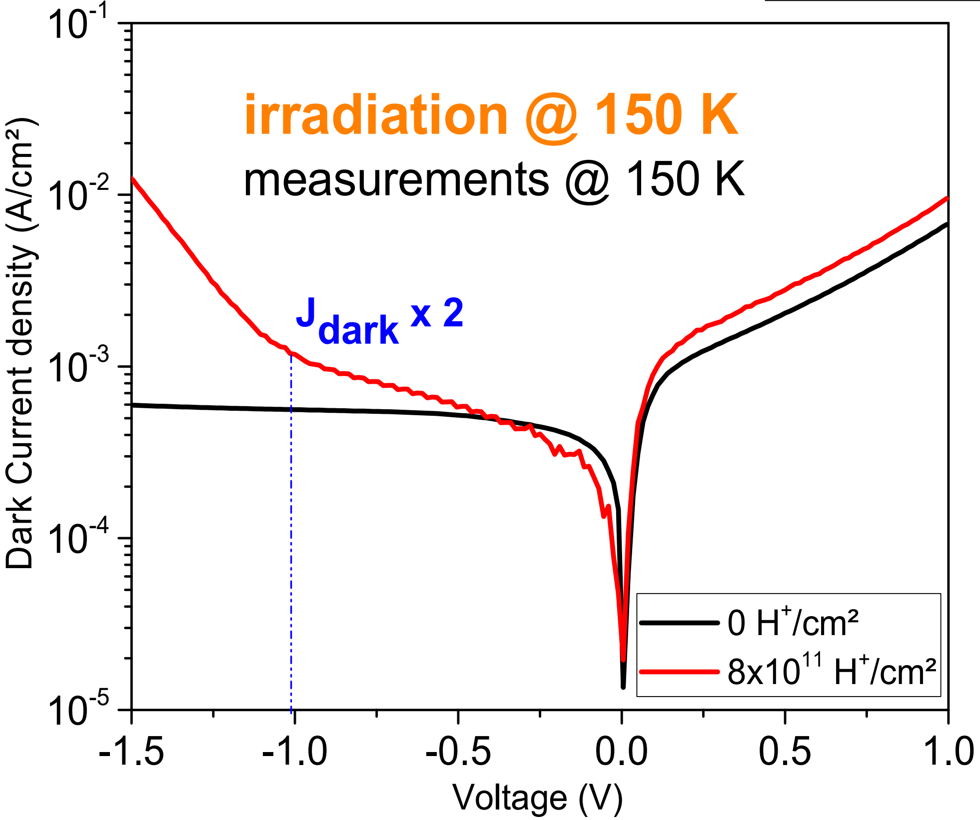

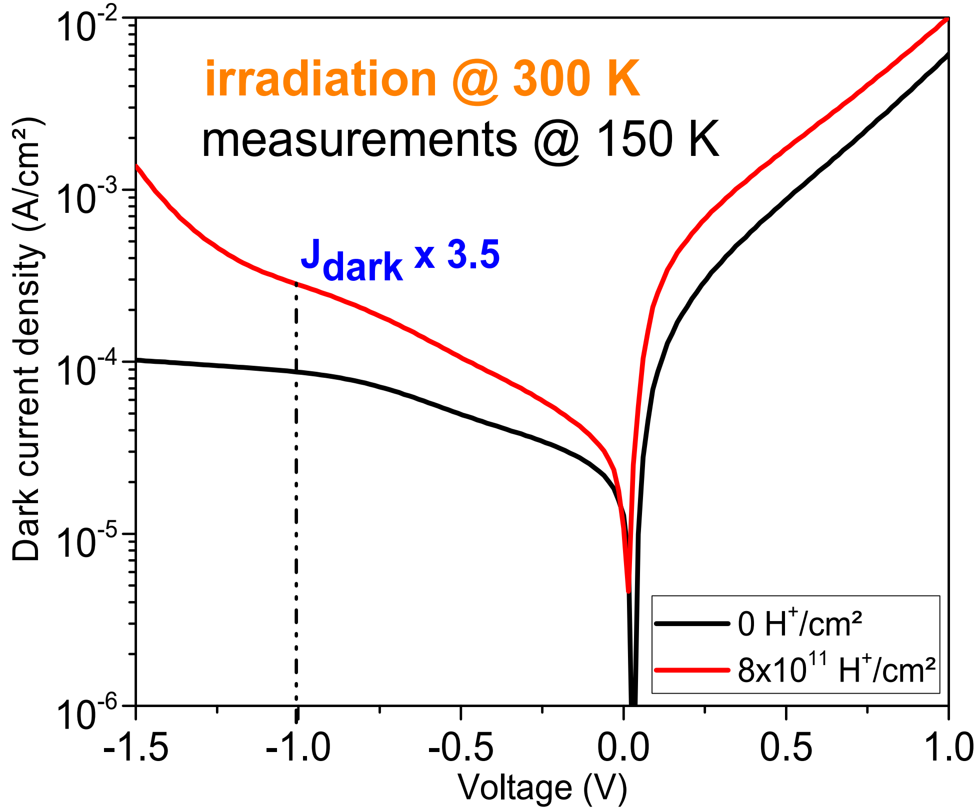

Degradation depends on the detector's temperature during the irradiation

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CONCLUSION

- ❑ **XBn InAs/InAsSb MWIR T2SL** detectors were irradiated by **proton at fluences up to $8x10^{11}$ H^+/cm^2**

CONCLUSION

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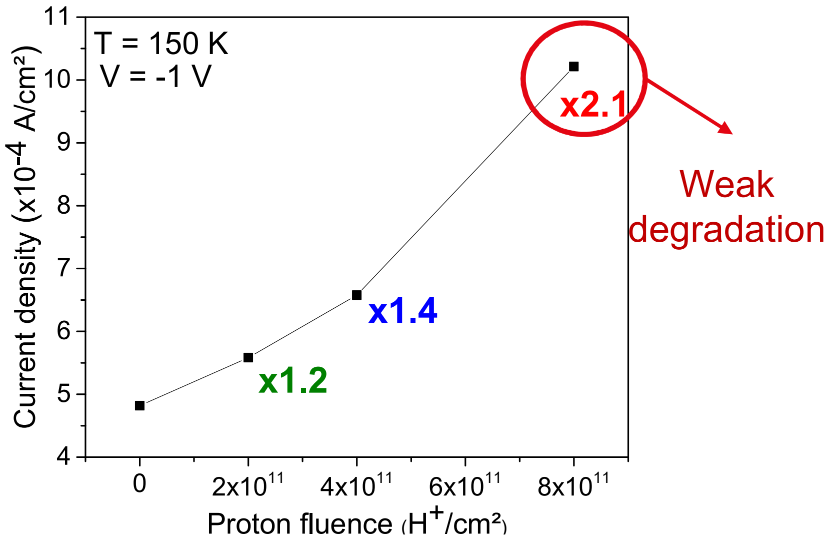
✓ **Weak degradation of dark current** under proton fluence
  - Increase of **GR current**
  - Apparition of **TAT current**

✓ **No effect of bias voltage applied** (V = - 500 mV) during irradiation

✓ Influence of **detector's temperature during irradiation :**
  - 150 K : J_{dark} **x2**
  - 300 K : J_{dark} **x3.5**

✓ **Thermal cycle** can not restore the initial dark current density



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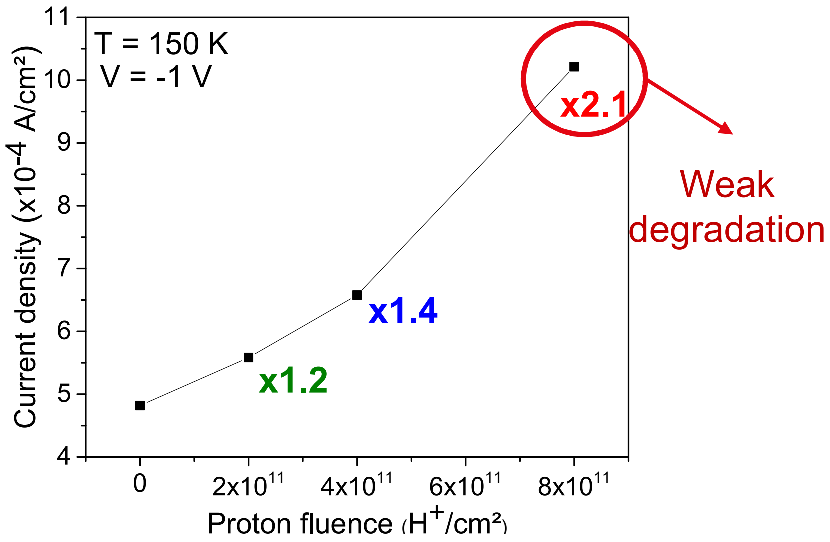

⇨ XBn T2SL : **WEAK DEGRADATION** of dark current but **WEAK RECOVERY** with thermal cycle
  - Further investigations by isochronous / isothermal annealing

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CONCLUSION

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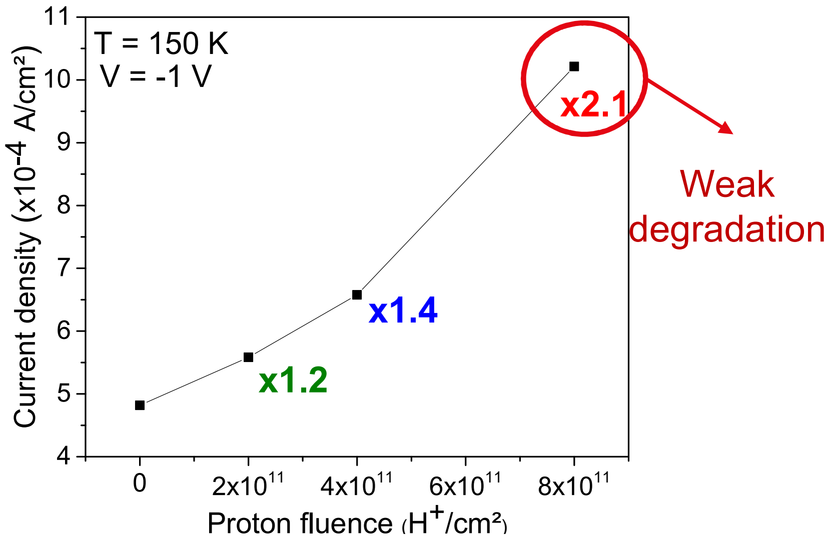

➡ XBn T2SL : **WEAK DEGRADATION** of dark current but **WEAK RECOVERY** with thermal cycle
- ○ Further investigations by isochronous / isothermal annealing

THANK YOU FOR YOUR ATTENTION

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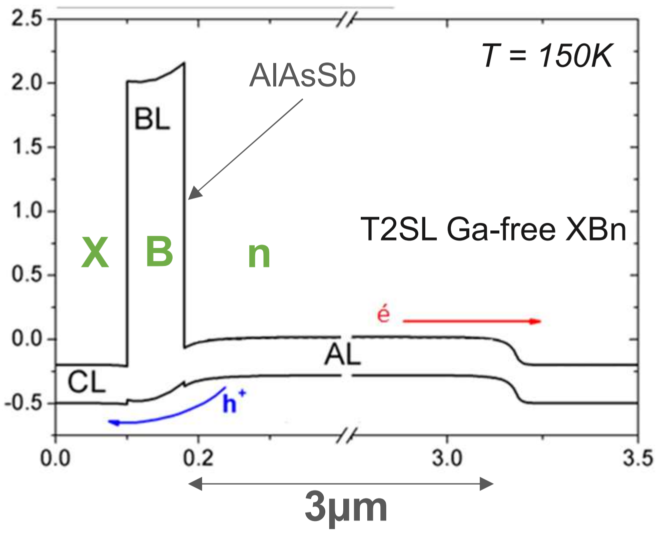
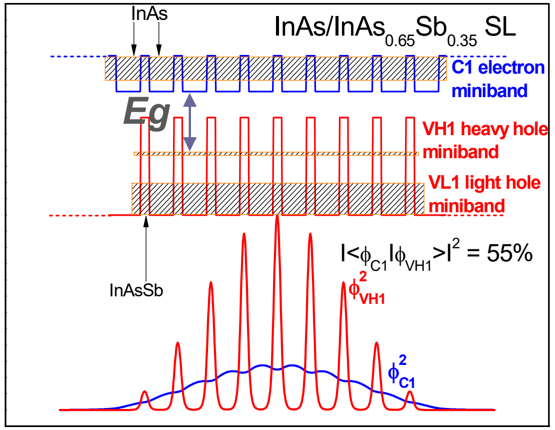
APPENDICES

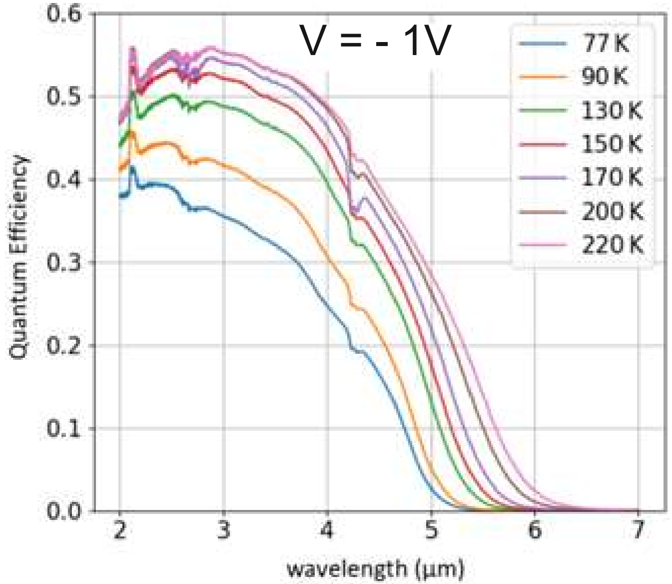
MWIR InAs/InAsSb T2SL DETECTORS

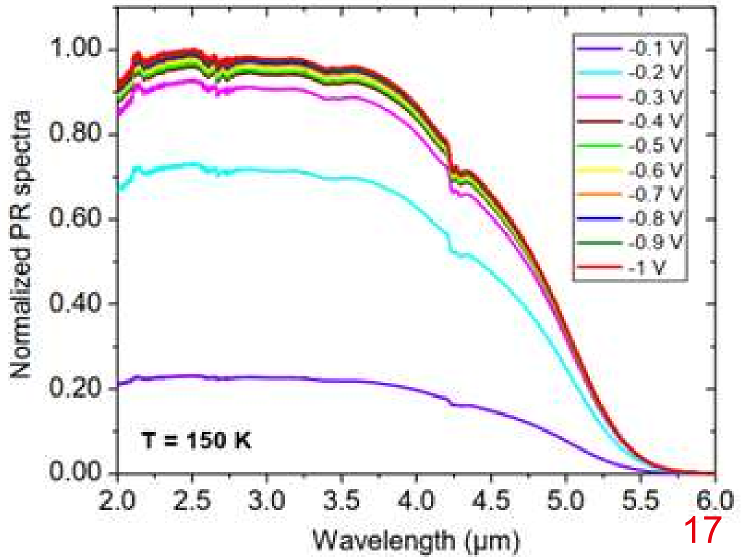


E_g(T=150 K) = 241 meV

InAs/InAsSb period = 5.5 nm
In absorbing layer : 545 périods



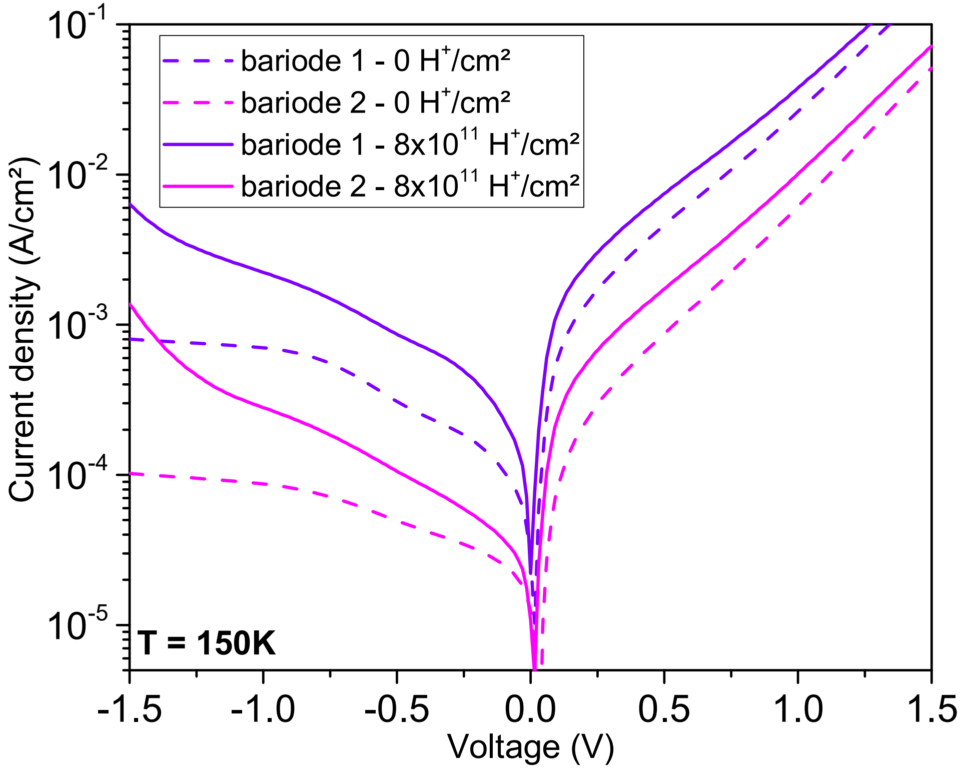




INFLUENCE OF THE INITIAL DARK CURRENT LEVEL

RADOPT

Temperature of detector during irradiation = 300 K



Area of bariodes : 130 µm

J / J_0	Photodiode 1	Photodiode 2
V = -0.75 V	x 2.7	x 2.6
V = -1 V	x 3.1	x 3.2
V = -1,25 V	x 4.4	x 4.6

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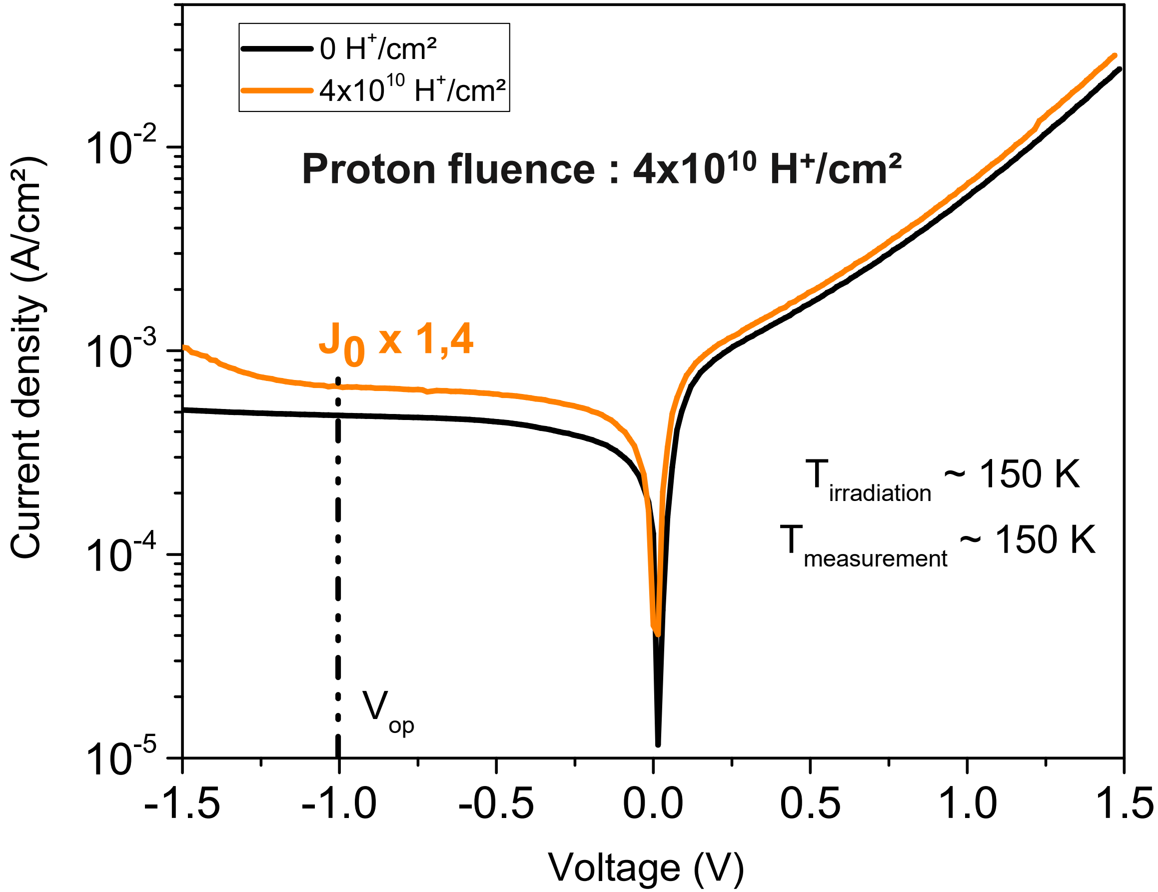
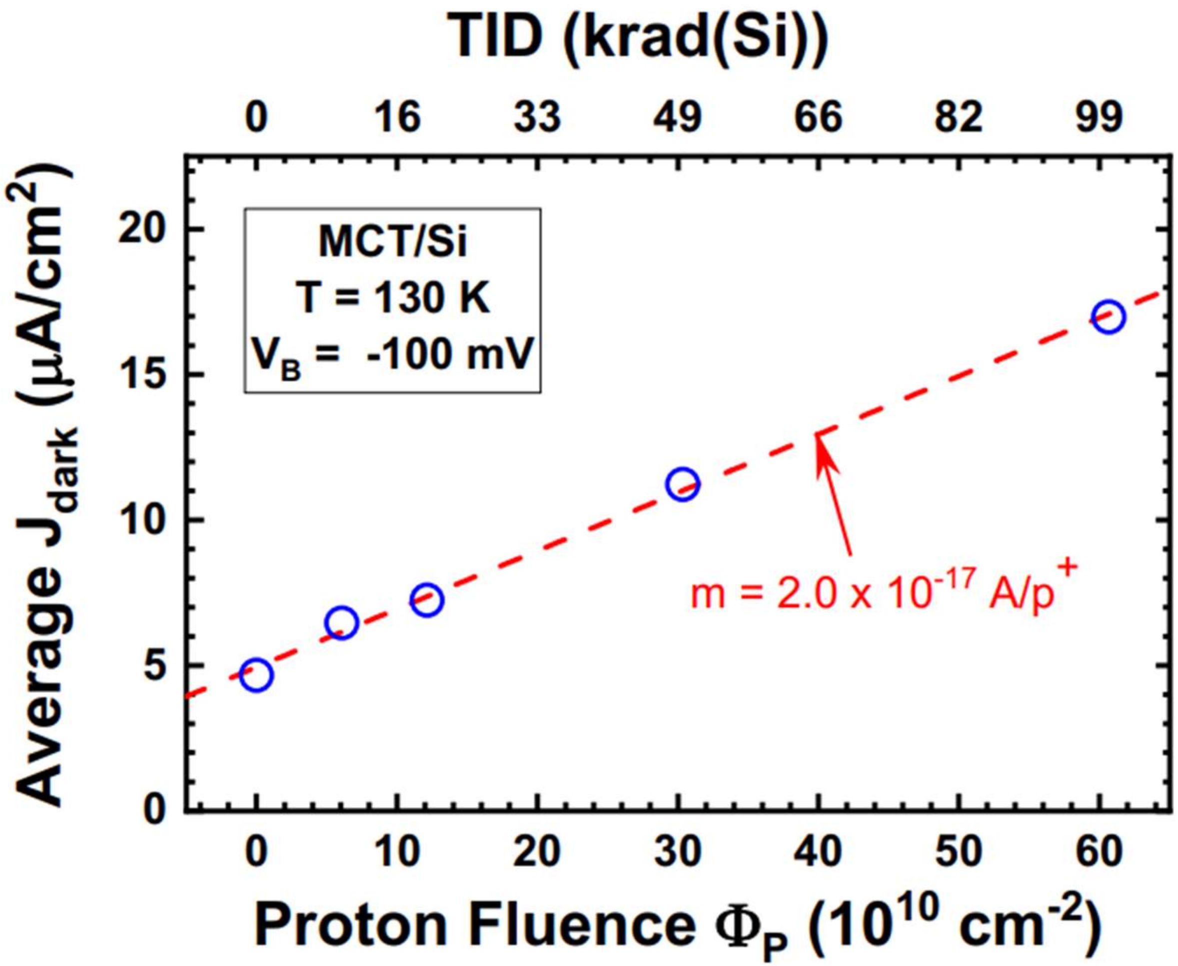
EVOLUTION OF J_{dark} AT A STANDARD PROTON FLUENCE



ΔJ_{dark} (V = - 1V) = 2×10^{-4} A/cm²

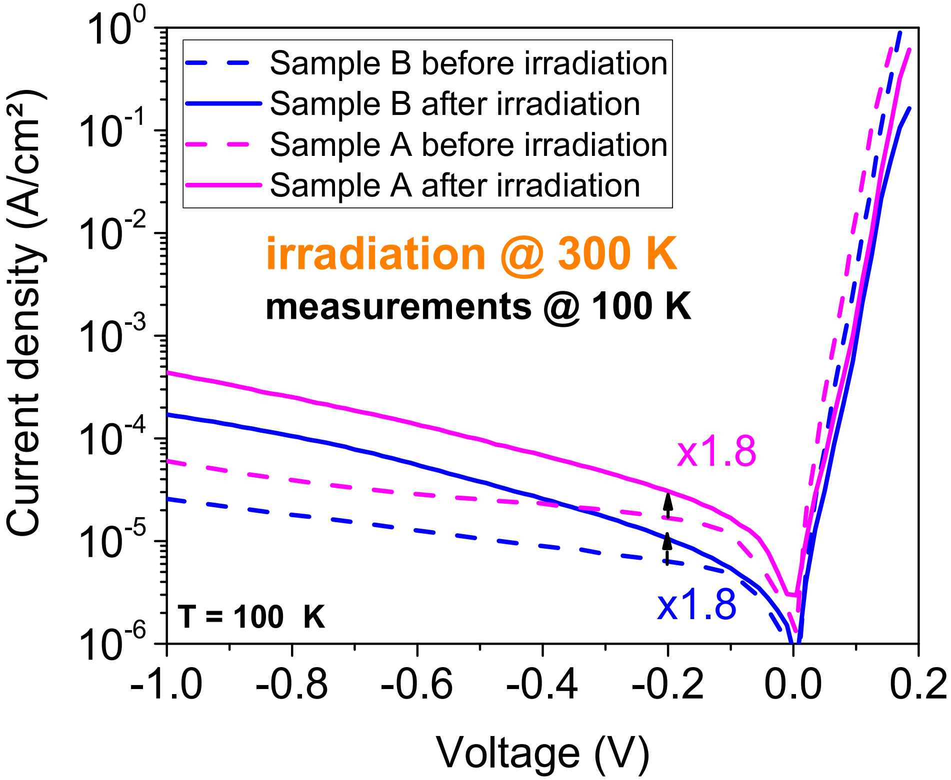
COMPARISON WITH MCT PHOTODIODE UNDER PROTON FLUENCE



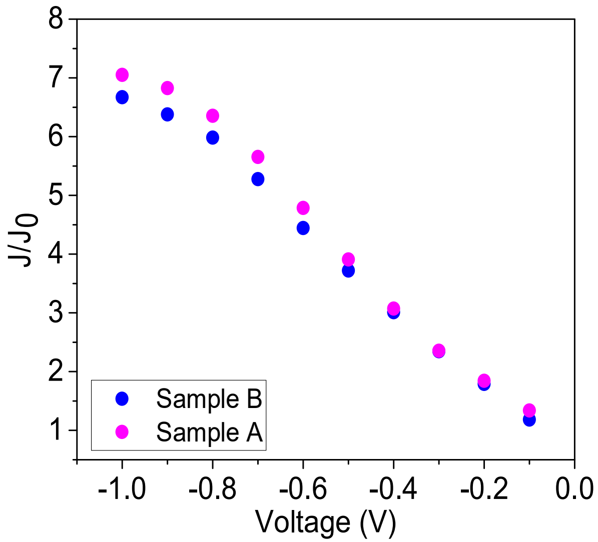
After a fluence of 6×10^{11} H^+/cm^2 :
J_{dark} x 3.8 at V = - 100 mV

E. H. Steenbergen *et al.* Proc. Of SPIE, **11002**, (2019)

INFLUENCE OF THE PERIOD NUMBER ON THE J_{dark} DEGRADATION

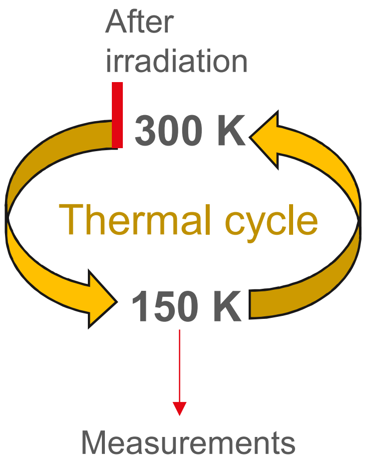


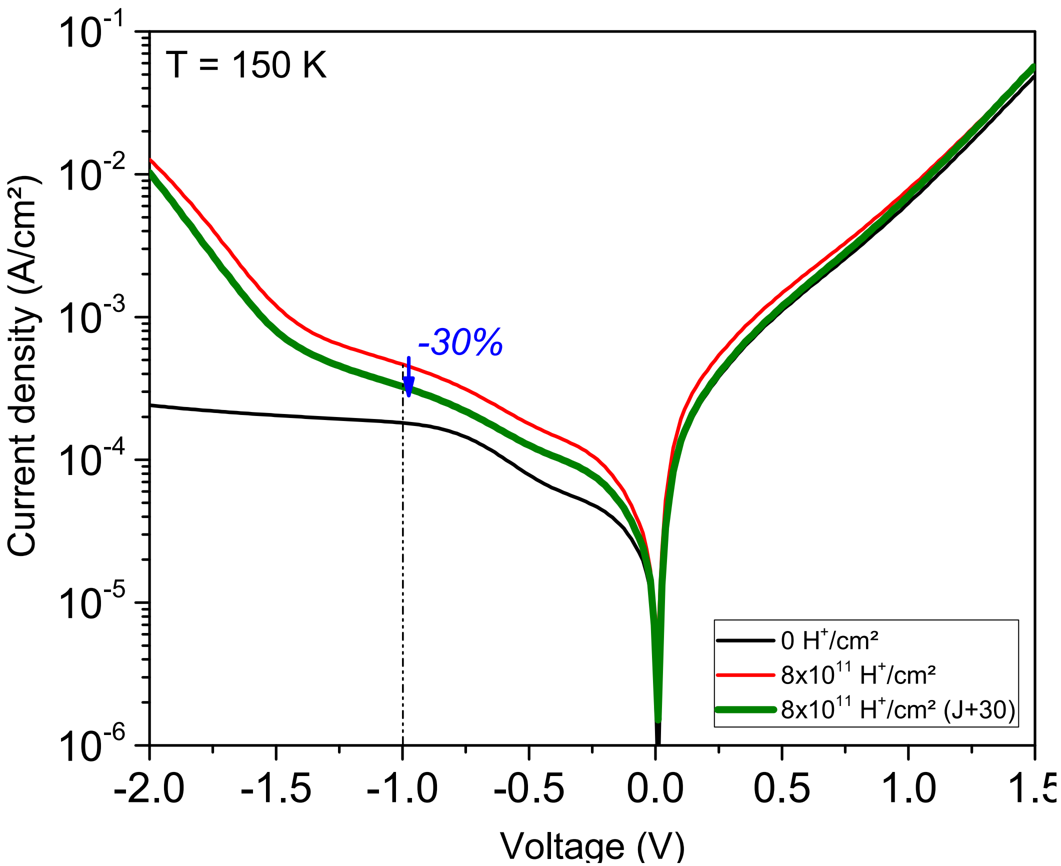
Sample	Sample	Cut-off wavelength @ 100K	AL thickness	Number of periods
PIN	A	λc = 5 µm	0.5 µm	151
PIN	B	λc = 5 µm	1 µm	303



DEGRADATION independent of the AL thickness ➔ no dependent on the number of periods

THERMAL CYCLE ON DEVICE IRRADIATED AT 300 K





CONTEXT : XBn BARRIER STRUCTURE

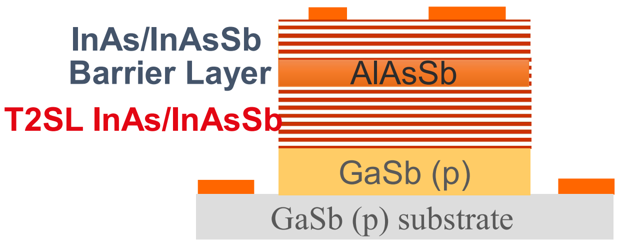
- Presence of **barrier layer** in the structure :
  - To confine electric field inside

  ➔ Diffusion dark current is expected

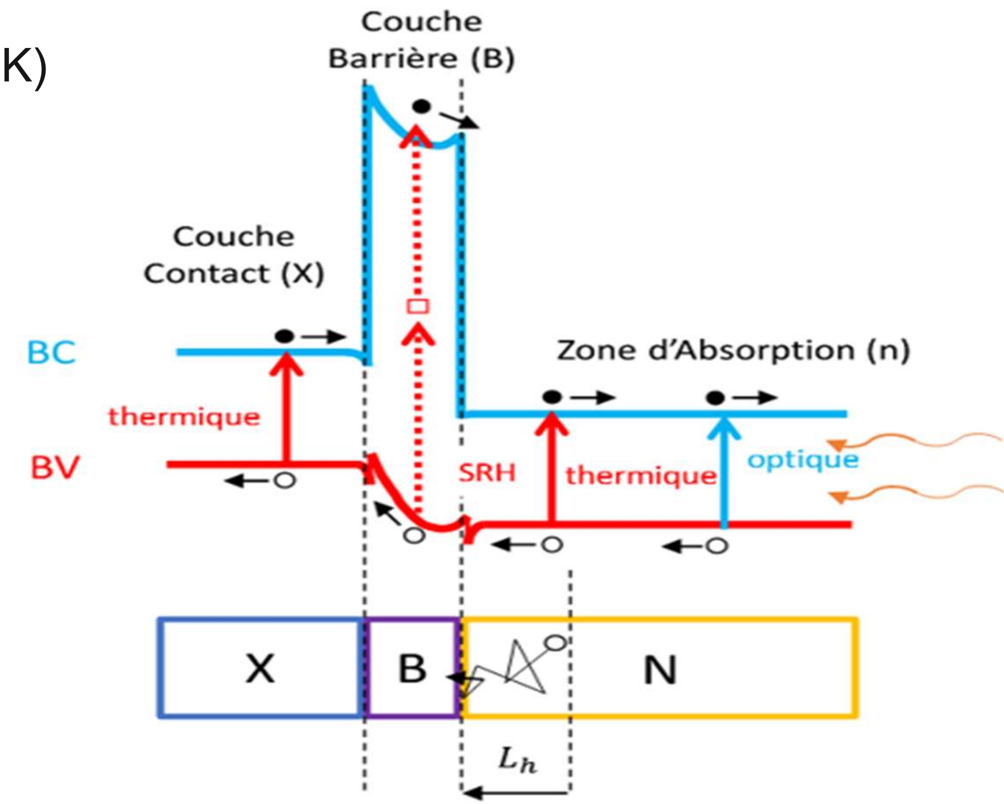
  High operating temperature possible (T > 130K)

  - To block majority carriers (electrons)

    To collect minority carriers (holes)

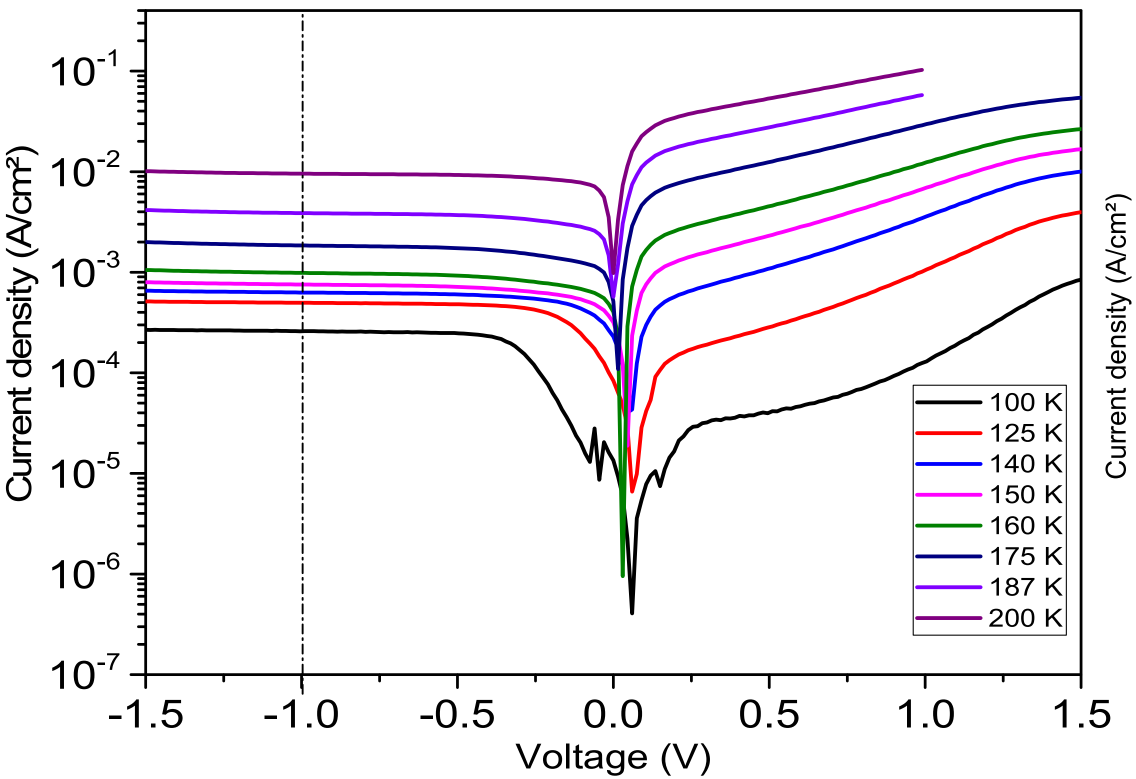


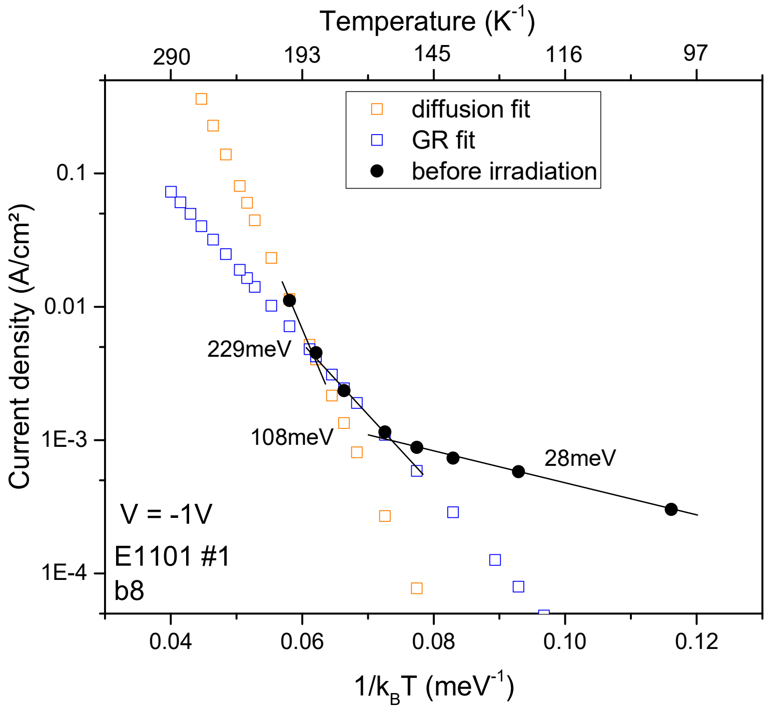
Pixel XBn MWIR bariode



DARK CURRENT TEMPERATURE DEPENDENCE

RADOPT





$$J_{GR} \cong q \frac{W_{dep}}{\tau_{SRH}} n_i$$

$$k = Ae^{-\frac{Ea}{kT}}$$

Before irradiation → Presence of GR current

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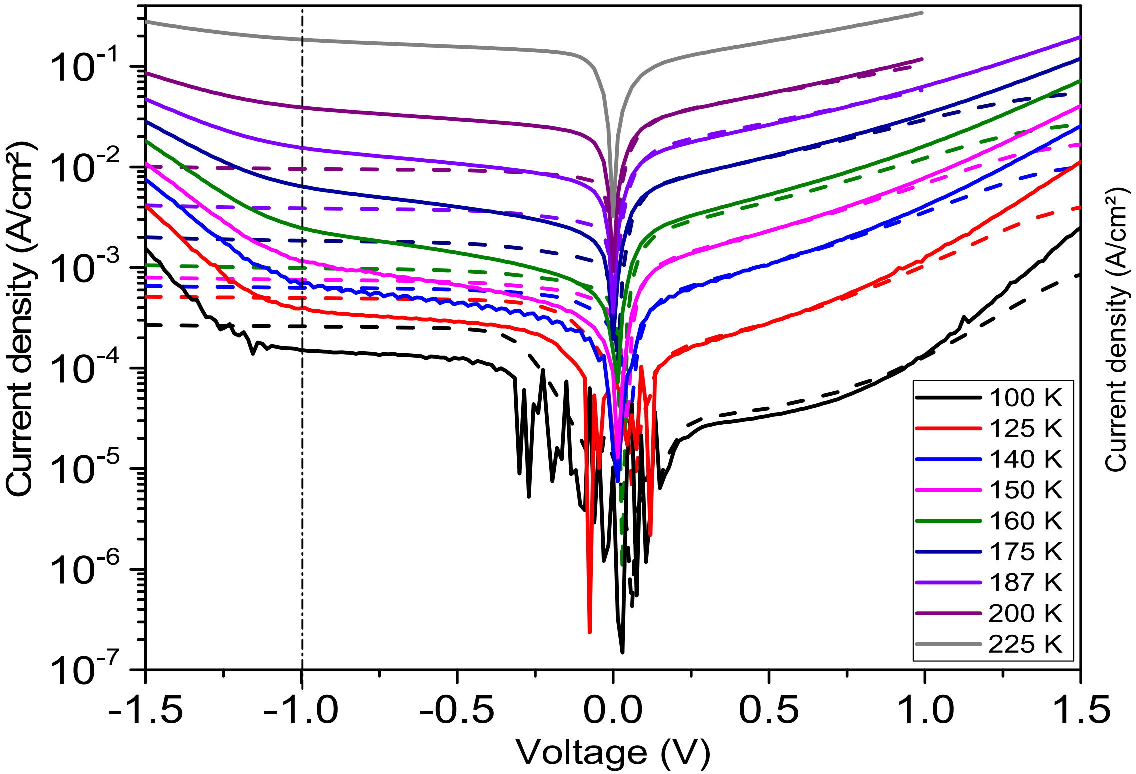

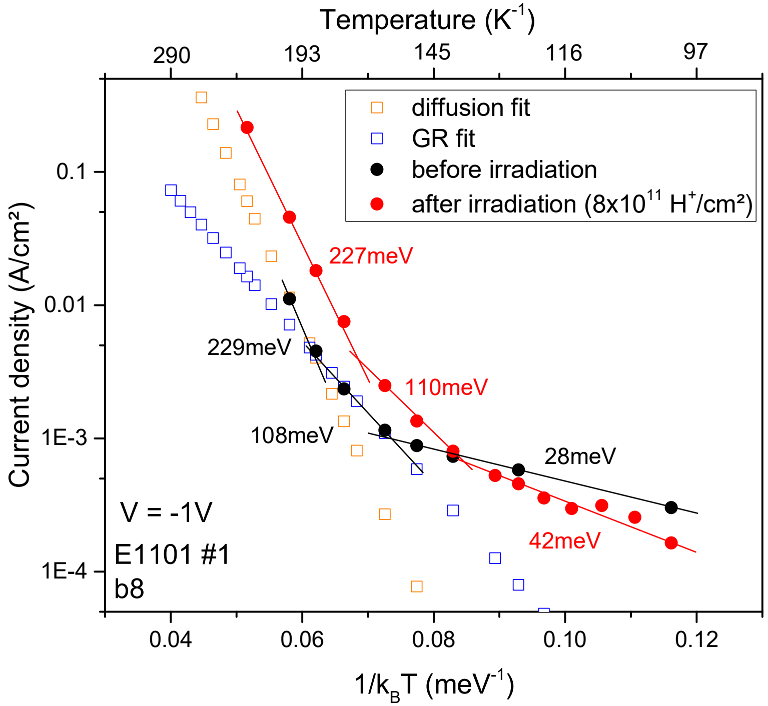

$$J_{GR} \cong q \frac{W_{dep}}{\tau_{SRH}} n_i$$

$$k = Ae^{-\frac{Ea}{kT}}$$

Before irradiation ➔ Presence of GR current

After irradiation :

➔ dark current increases (T > 100 K)

➔ dark current decreases (T < 100 K)

➔ TAT current appears (V < 0 and V > 0)

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