MidWave Infrared type-II superlattice photodetector under proton radiation

C.Bataillon[1,2], J.P. Perez[1], O. Gilard[3], M. Bouschet[1,4], M. Tornay[1,4], O. Saint-Pé[2], P. Christol[1]

[1]: IES, University of Montpellier, Montpellier, France

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

[3]: CNES, Toulouse, France

[4]: Lynred, Veurey-Voroize, France

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

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

Infrared detectors

MCT (HgCdTe)	**InSb**	**InGaAs**	**QWIP**

Well established infrared technologies

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

Infrared detectors

MCT (HgCdTe)	InSb	InGaAs	QWIP

Well established infrared technologies

- **Investigation of a new technology :**

T2SL material

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

INSTITUT D'ÉLECTRONIQUE ET DES SYSTÈMES

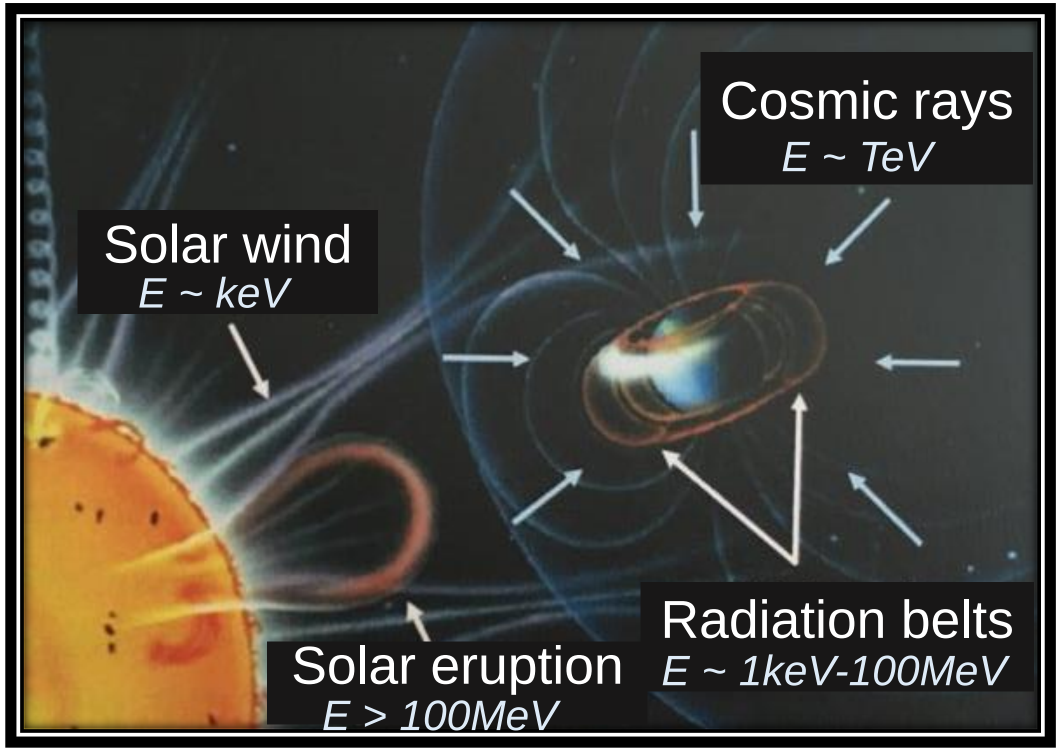
CONTEXT : T2SL IN SPACE RADIATIVE ENVIRONMENT ?

APPLICATIONS

- Environmental and climatological monitoring
- Homeland security and defence
- Research for the exploration of the galaxy and understanding of the universe

- **T2SL detectors :** for space missions ?

What about their tolerance in this harsh environment ?



CONTEXT : T2SL IN SPACE RADIATIVE ENVIRONMENT ?

APPLICATIONS

- Environmental and climatological monitoring
- Homeland security and defence
- Research for the exploration of the galaxy and understanding of the universe

- **T2SL detectors :** for space missions ?

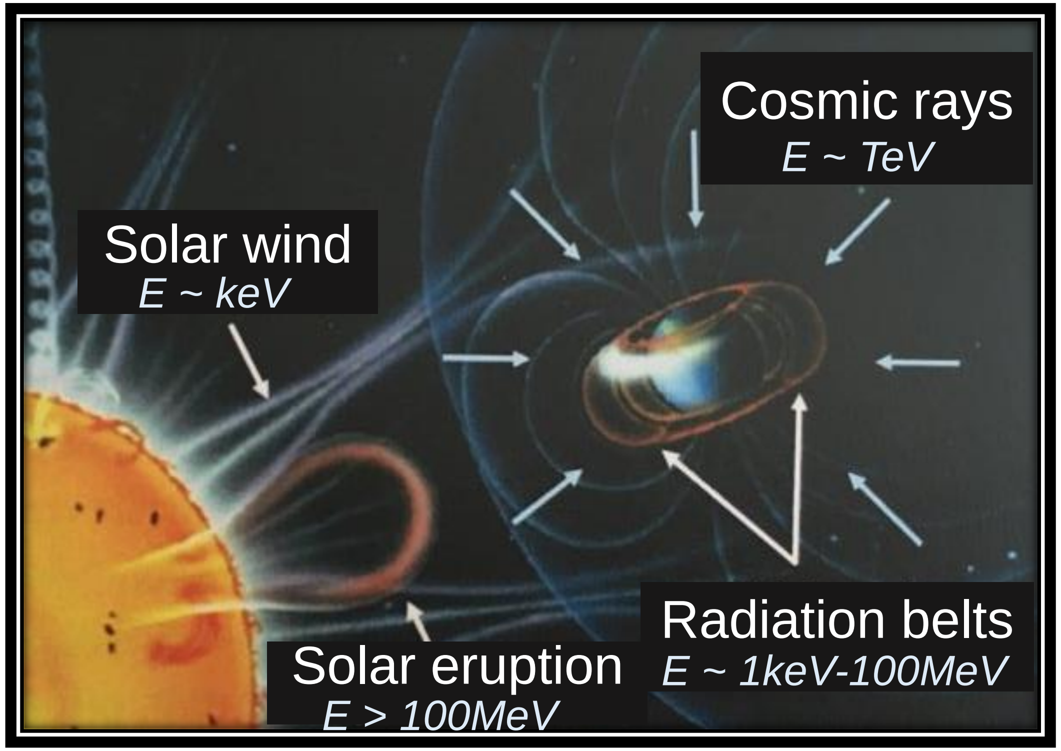
What about their tolerance in this harsh environment ?

- **Protons ➔ cumulative dose effects**
  - Displacement Damage Dose (DDD)

Impact on the semiconductor crystal structure

  - Total Ionizing Dose (TID)

Charges trapped at the SC/SiO_2 interface



CONTEXT : T2SL IN SPACE RADIATIVE ENVIRONMENT ?

APPLICATIONS

- Environmental and climatological monitoring
- Homeland security and defence
- Research for the exploration of the galaxy and understanding of the universe

- **T2SL detectors :** for space missions ?

What about their tolerance in this harsh environment ?

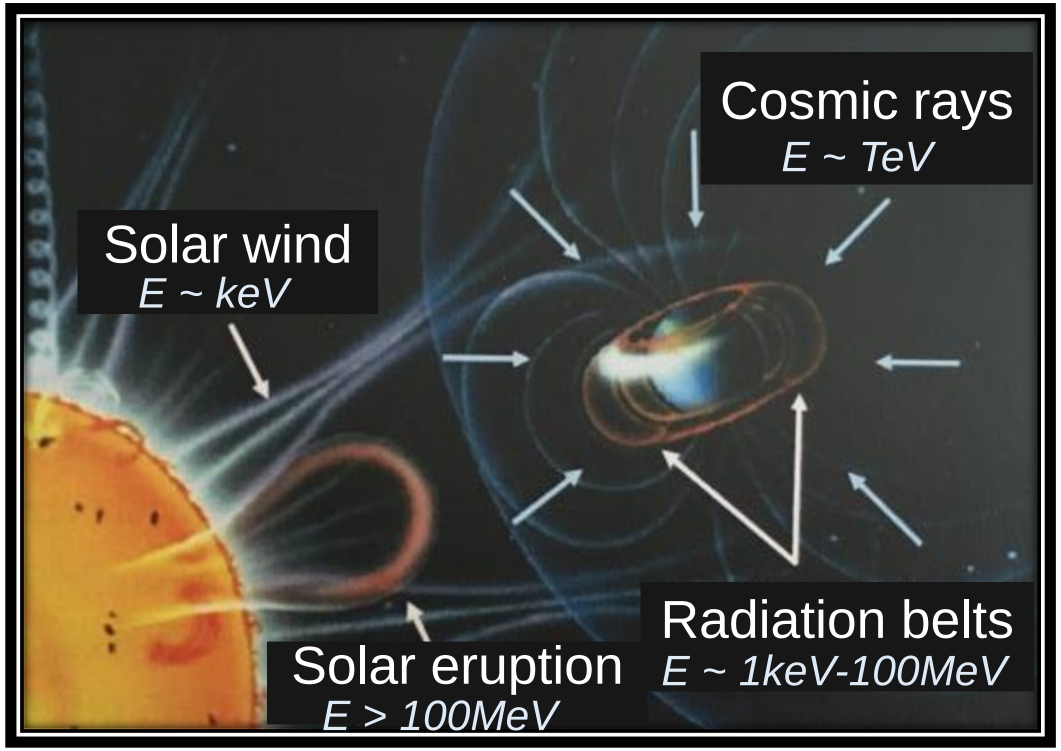
- **Protons ➔ cumulative dose effects**
  - Displacement Damage Dose (DDD)

Impact on the semiconductor crystal structure

  - Total Ionizing Dose (TID)

Charges trapped at the SC/SiO_2 interface

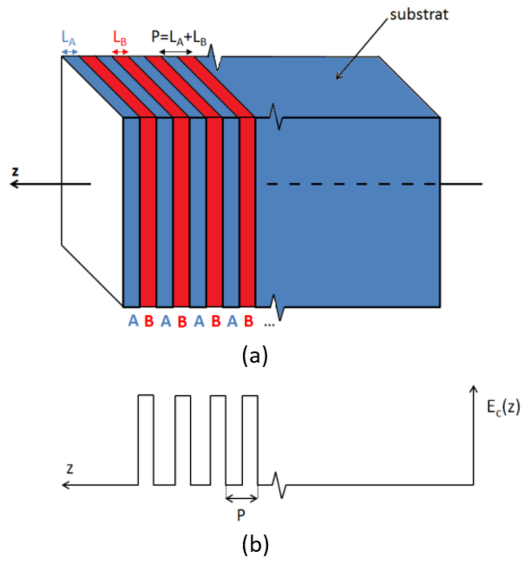
- This work investigates proton-induced performances degradation of T2SL : $\mathbf{J_{dark}}$



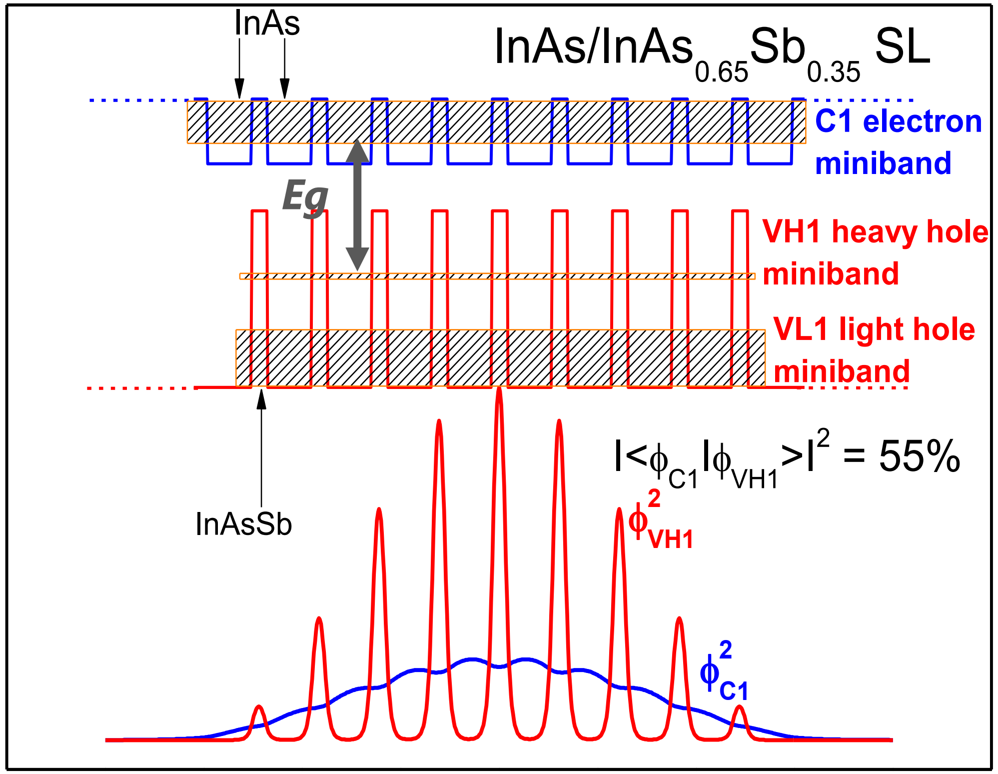
INSTITUT D'ÉLECTRONIQUE ET DES SYSTÈMES

CONTEXT : SUPERLATTICE STRUCTURE

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



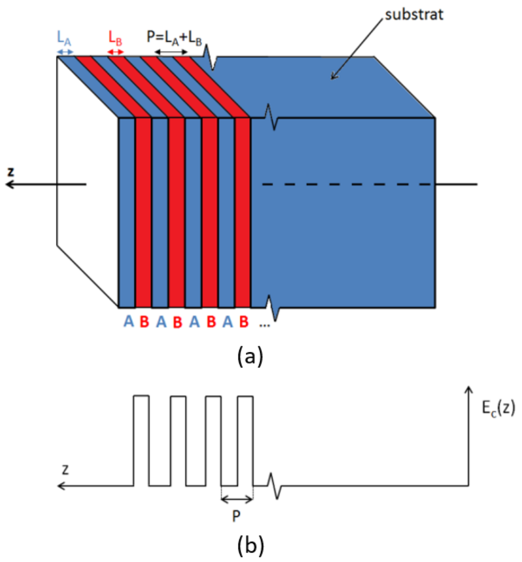
Period : $\mathbf{L_A+L_B}$



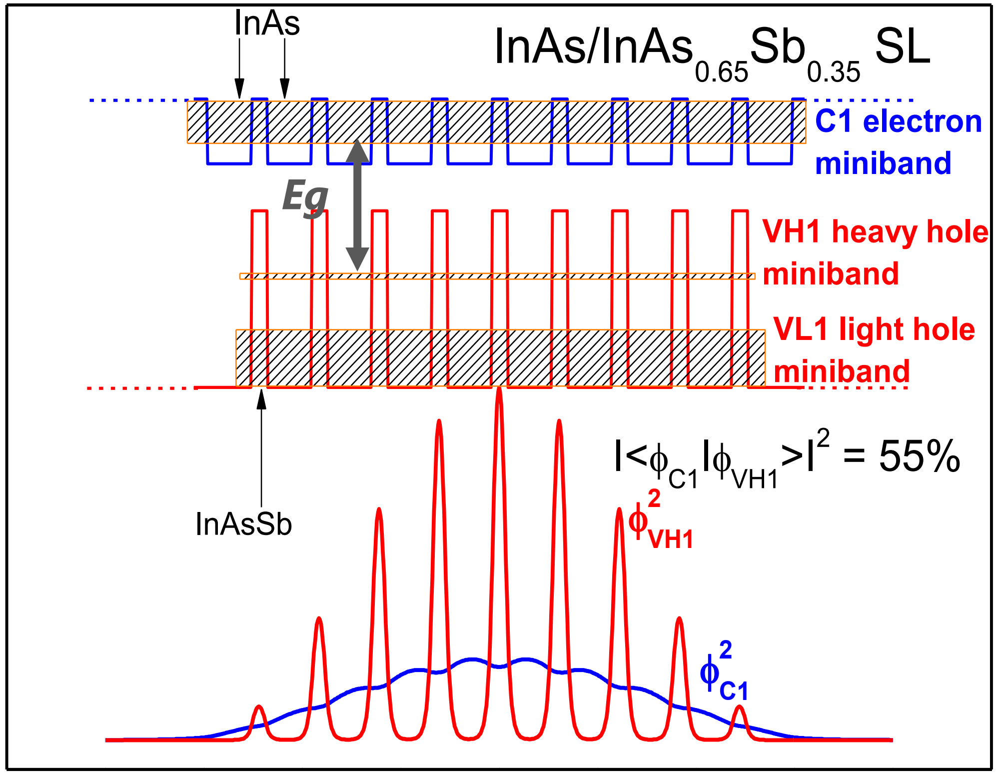
Coupled Multiple Quantum Wells

Band diagram of a InAs/InAsSb T2SL

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



Period : $\mathbf{L_A+L_B}$



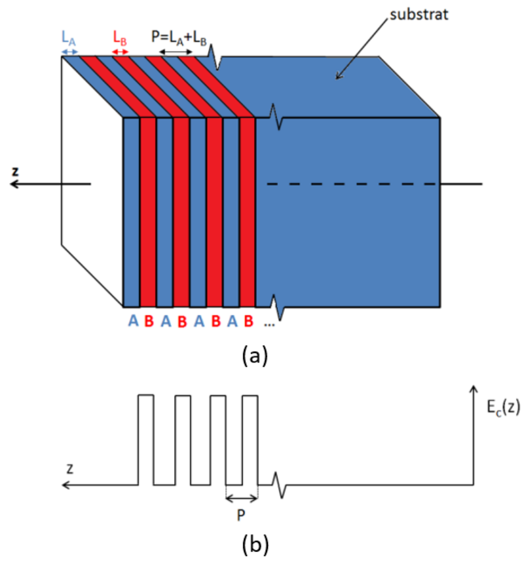
Band diagram of a InAs/InAsSb T2SL

Coupled Multiple Quantum Wells

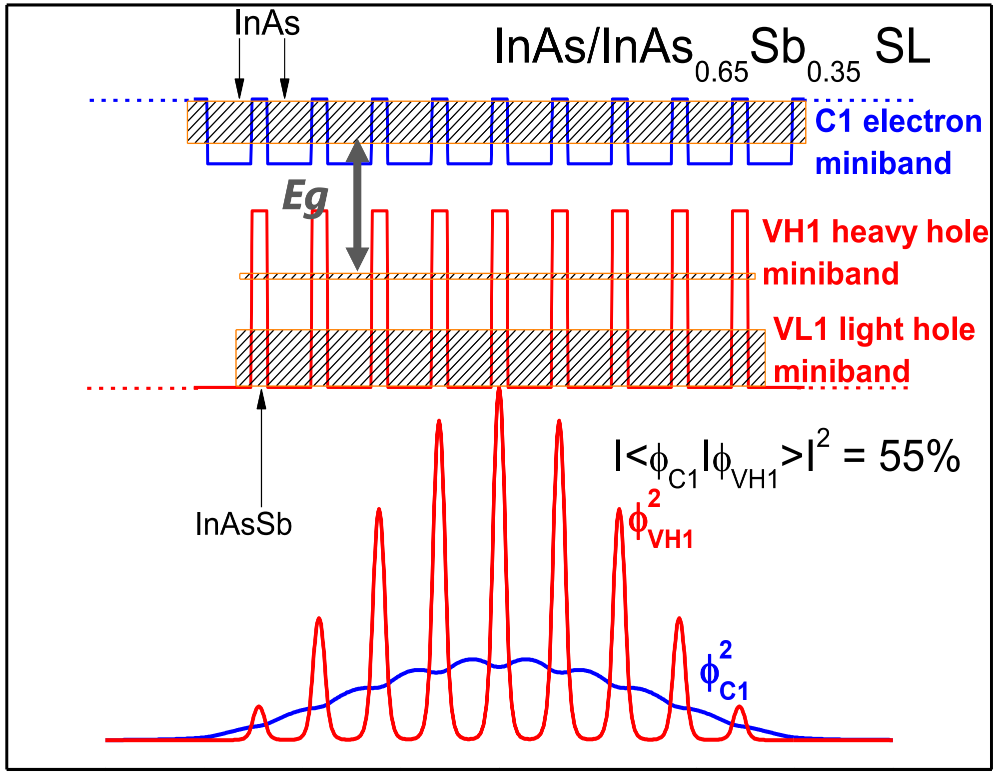
Creation of **energy minibands**

CONTEXT : SUPERLATTICE STRUCTURE

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



Period : $\mathbf{L_A+L_B}$



Band diagram of a InAs/InAsSb T2SL

Coupled Multiple Quantum Wells

Creation of **energy minibands**

➔ Creation of artificial semiconductor with a variable bandgap (E_g)

➔ E_g depends on the antimonide (Sb) concentration and superlattice period

XBn BARRIER STRUCTURE

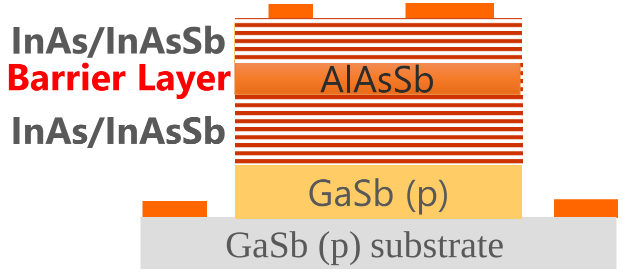
- Presence of **barrier layer** in the structure :
  - To confine electric field inside

  ➔ Diffusion dark current is expected

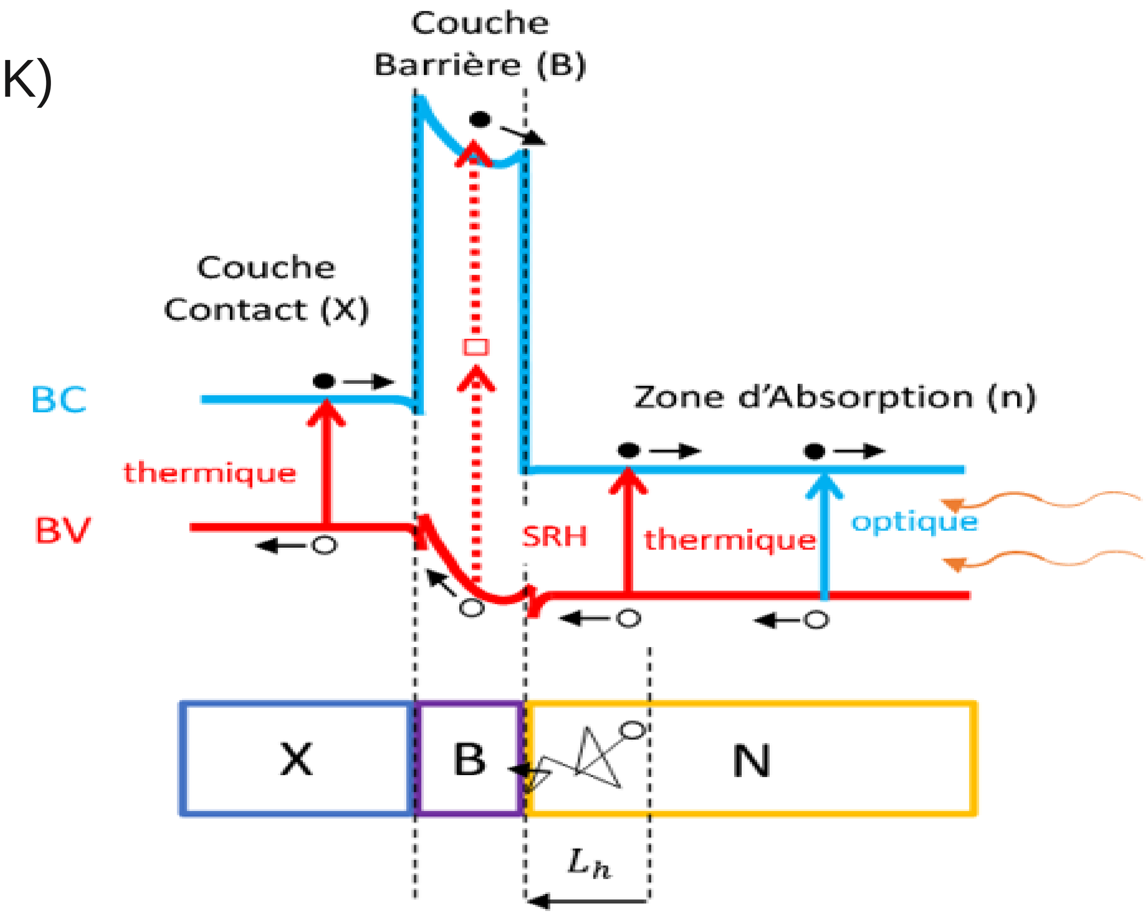
  High operating temperature possible (T > 130K)

  - To block majority carriers (electrons)

    To collect minority carriers (holes)



Pixel XBn MWIR bariode



EXPERIMENTAL DETAILS : DEVICES UNDER TEST

- 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

<u>Different objectives :</u>

INSTITUT D'ÉLECTRONIQUE ET DES SYSTÈMES

EXPERIMENTAL DETAILS : DEVICES UNDER TEST

- 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 :

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

INSTITUT D'ÉLECTRONIQUE ET DES SYSTÈMES

EXPERIMENTAL DETAILS : DEVICES UNDER TEST

- 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 :

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

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

EXPERIMENTAL DETAILS : DEVICES UNDER TEST

- 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 :

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

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

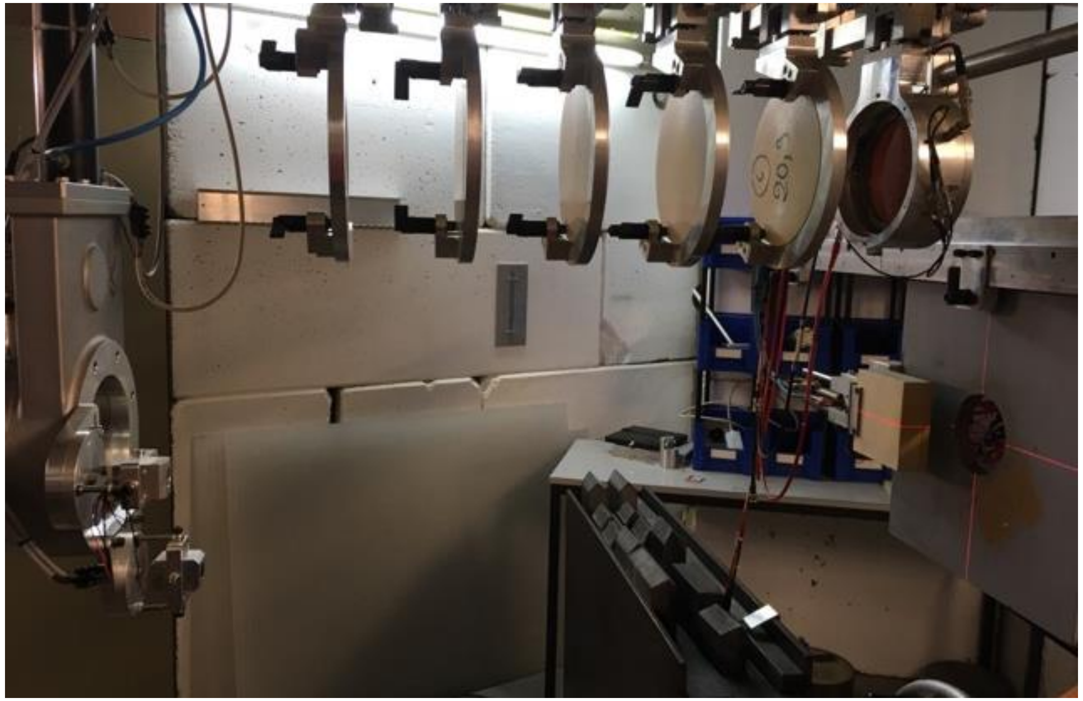
Influence of the **detector's temperature during the irradiation** (150 K / 300 K)

INSTITUT D'ÉLECTRONIQUE ET DES SYSTÈMES

EXPERIMENTAL DETAILS : SETUP DESCRIPTION

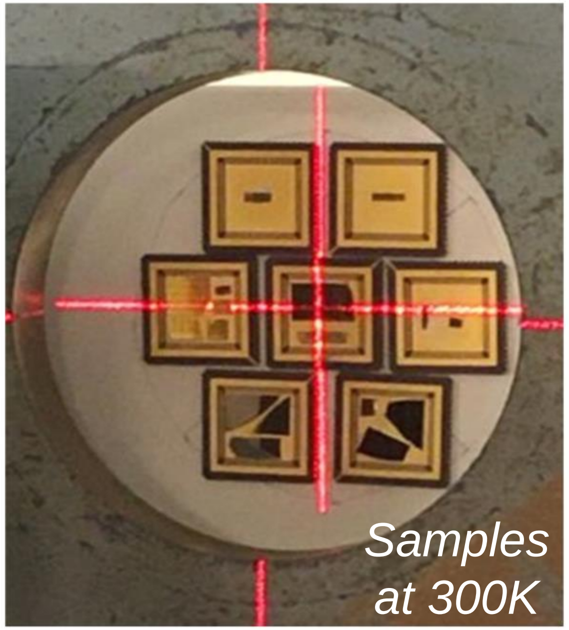
Proton irradiation

UCL Louvain (Université Catholique de Louvain), Belgium



60 MeV Protons,
fluence up to $8x10^{11}$ H^{+}/cm^{2}
Proton flux : $2x10^{8}$ $H^{+}/cm^{2}/s$

Samples at 150K



Samples at 300K

Measurements performed after each irradiation step

Measurements performed after last irradiation step ~ few days @ RT

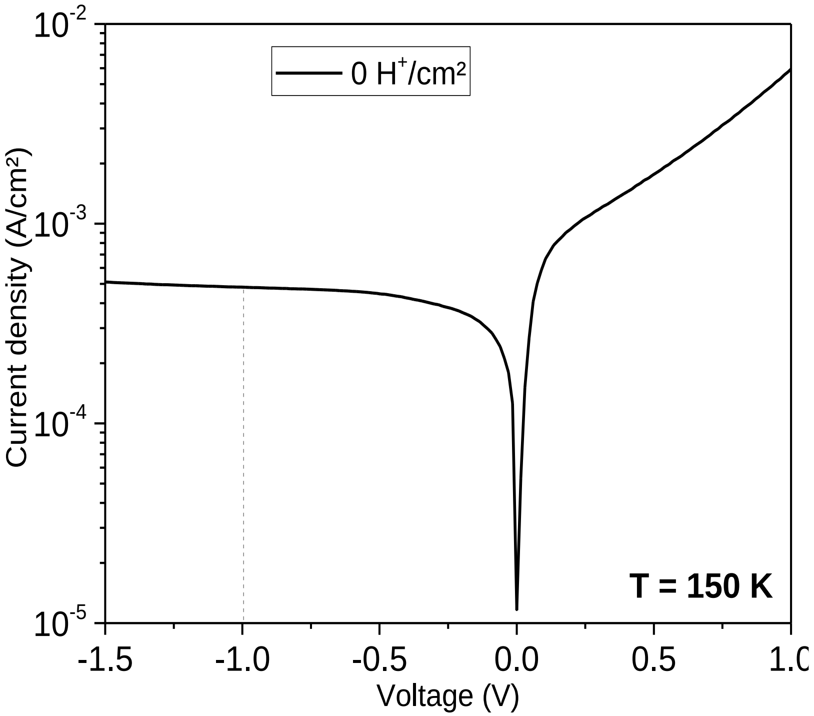
All measurements at T_{op} = 150 K

1st objective :

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

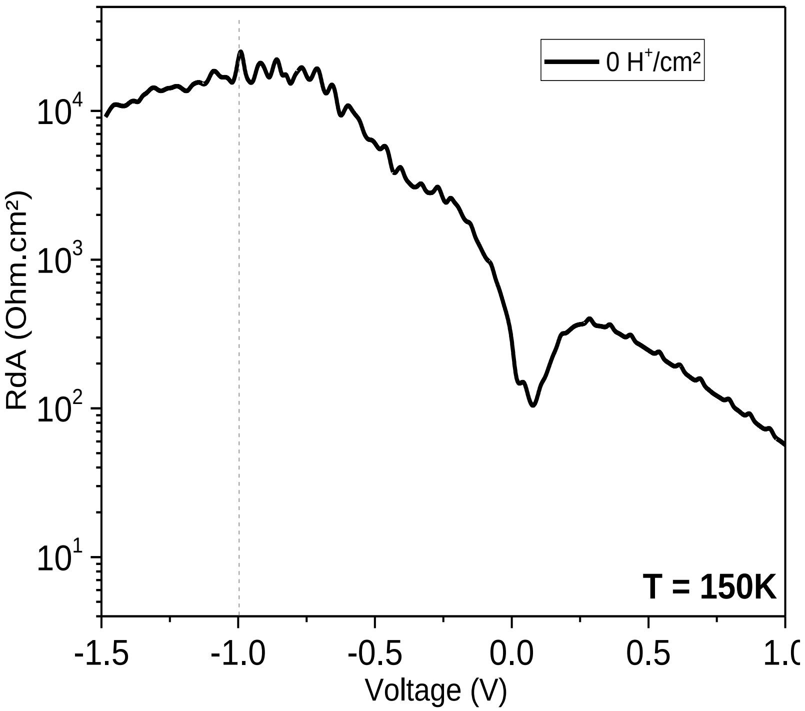
EXPERIMENTAL : EVOLUTION OF J_{DARK} UNDER PROTON FLUENCE STEPS

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



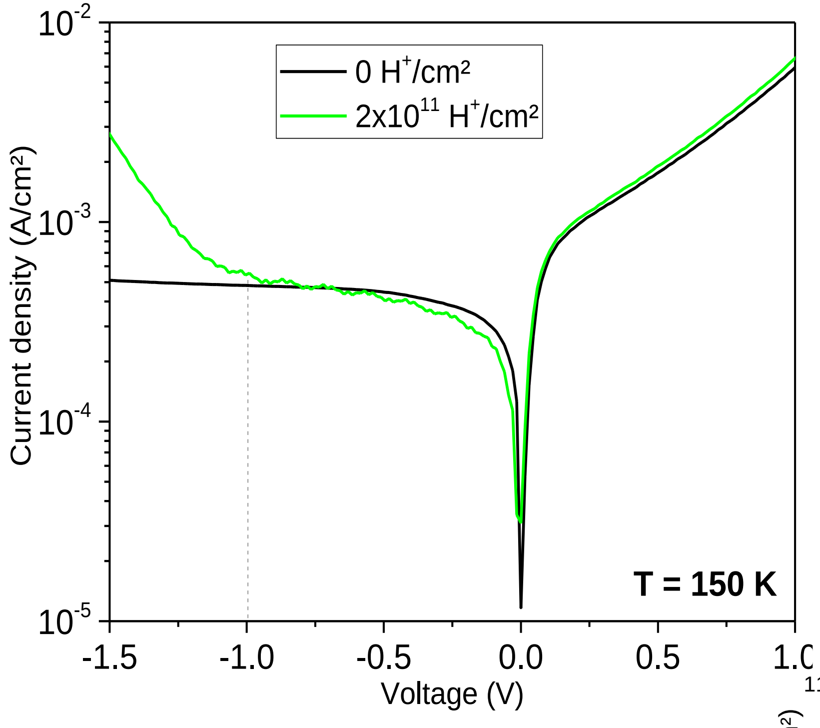
$$D^* = R_\lambda \sqrt{\frac{1}{2qJ_{dark} + \frac{4kT}{R_d A}}}$$

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



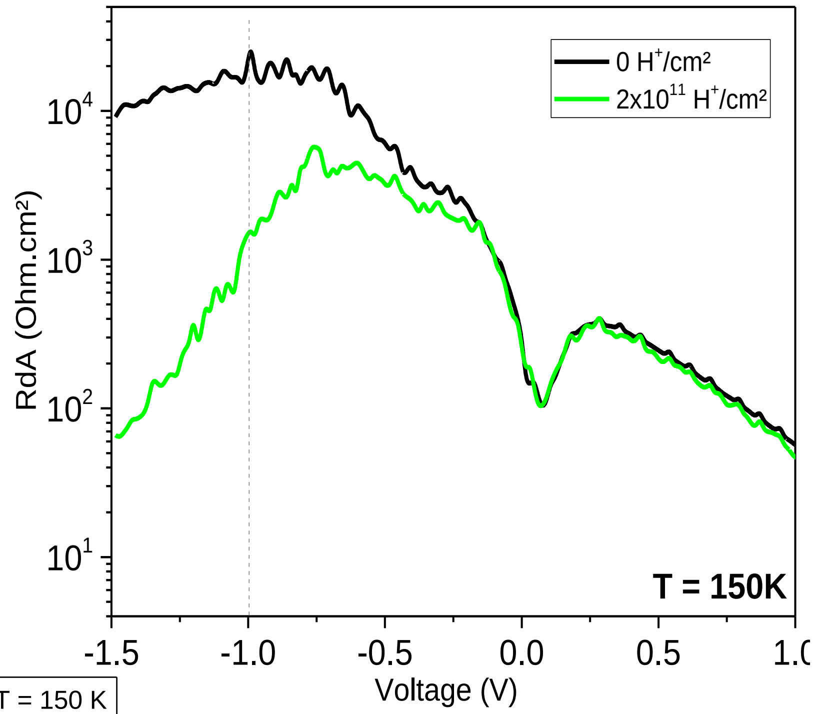
EXPERIMENTAL : EVOLUTION OF J_{DARK} UNDER PROTON FLUENCE STEPS

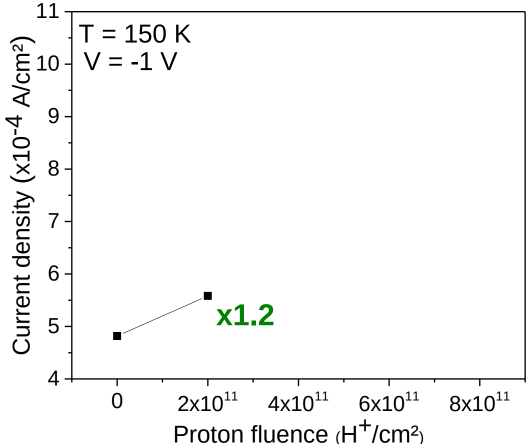
MWIR T2SL structure	Cut-off wavelength	V_{op}	AL thickness	Number of periods
Samples XBn	λc = 5 µm (150K)	- 1 V	3 µm	545

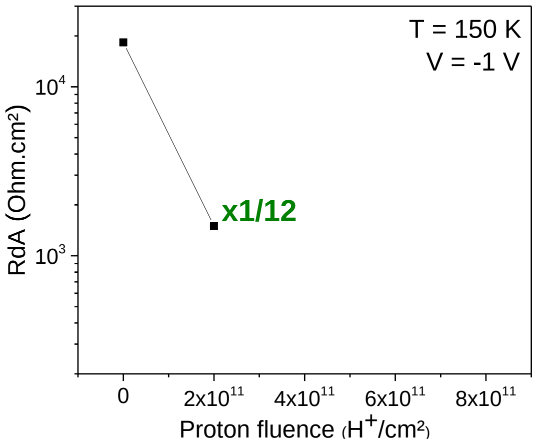


$$D^* = R_\lambda \sqrt{\frac{1}{2qJ_{dark} + \frac{4kT}{R_d A}}}$$

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



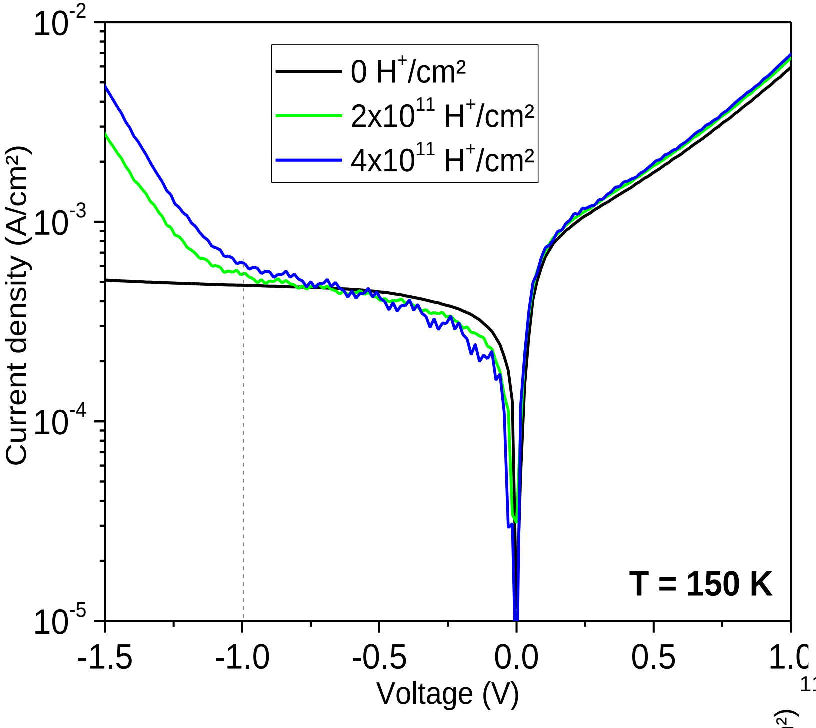




INSTITUT D'ÉLECTRONIQUE ET DES SYSTÈMES

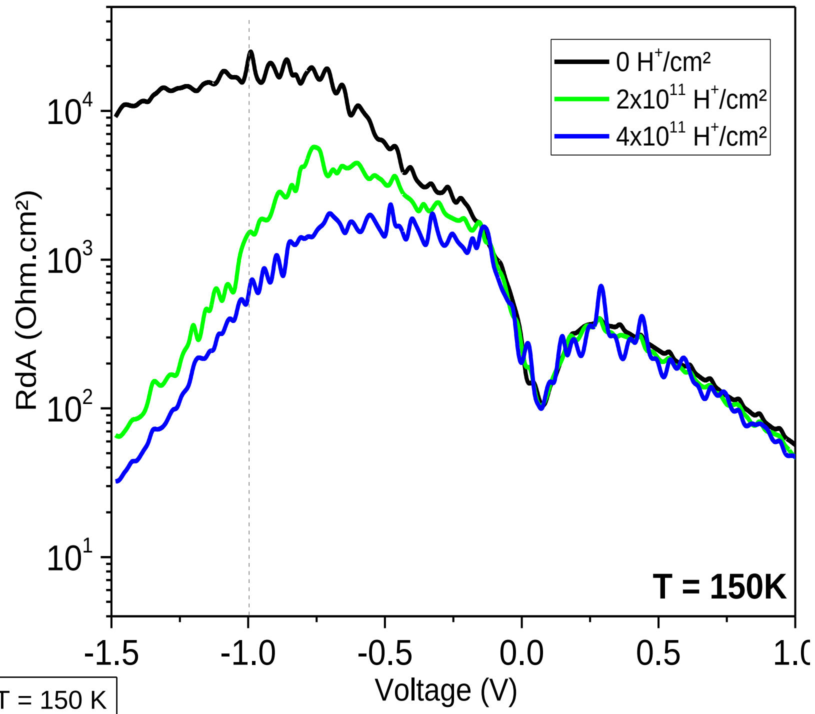
EXPERIMENTAL : EVOLUTION OF J_{DARK} UNDER PROTON FLUENCE STEPS

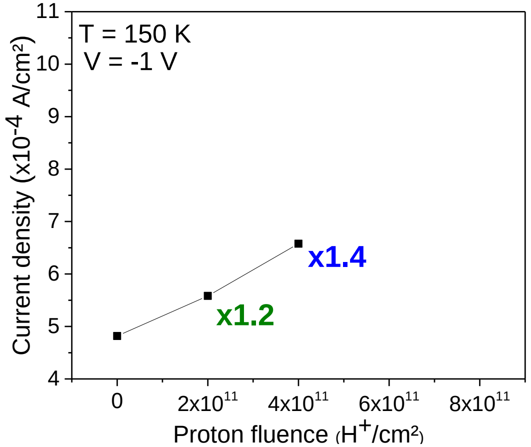
MWIR T2SL structure	Cut-off wavelength	V_{op}	AL thickness	Number of periods
Samples XBn	λc = 5 µm (150K)	- 1 V	3 µm	545

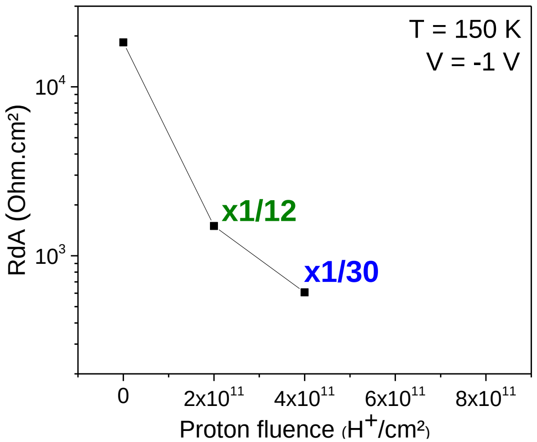


$$D^* = R_\lambda \sqrt{\frac{1}{2qJ_{dark} + \frac{4kT}{R_d A}}}$$

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



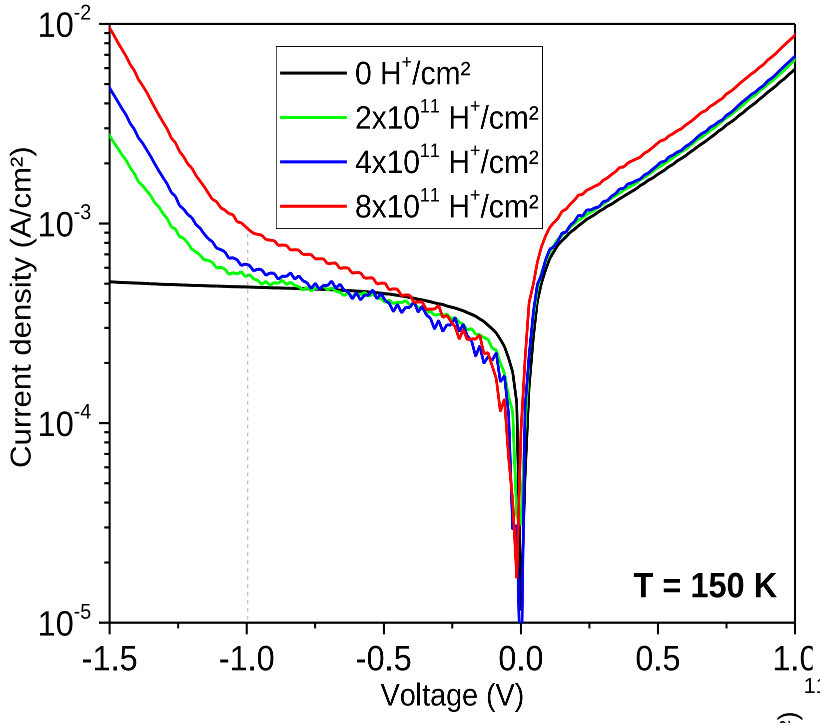




INSTITUT D'ÉLECTRONIQUE ET DES SYSTÈMES

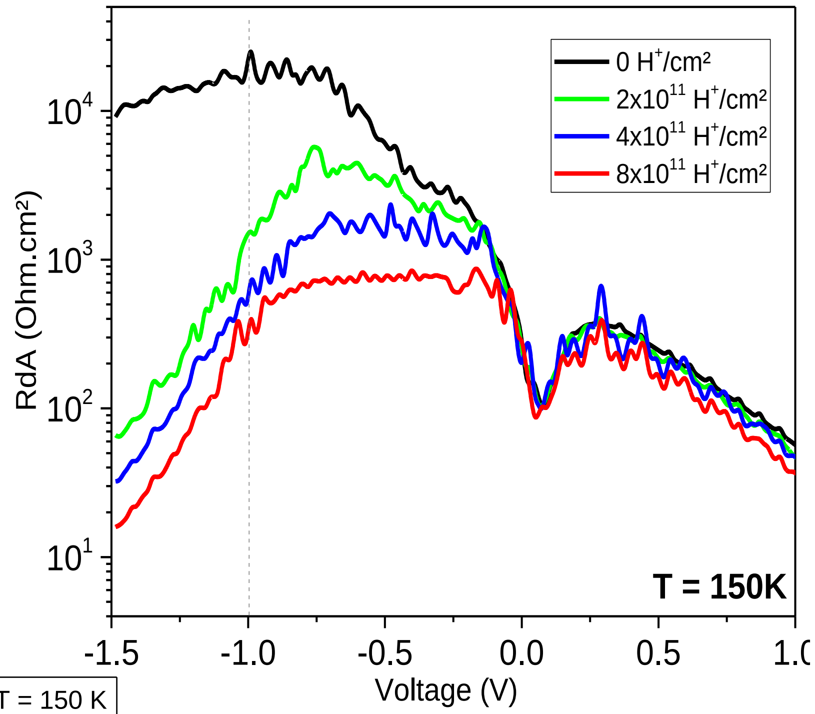
EXPERIMENTAL : EVOLUTION OF J_{DARK} UNDER PROTON FLUENCE STEPS

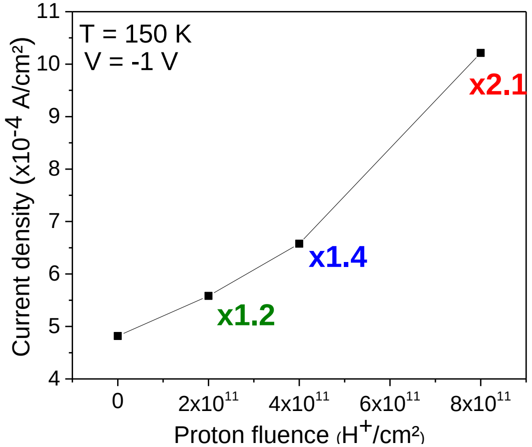
MWIR T2SL structure	Cut-off wavelength	V_{op}	AL thickness	Number of periods
Samples XBn	λc = 5 µm (150K)	- 1 V	3 µm	545

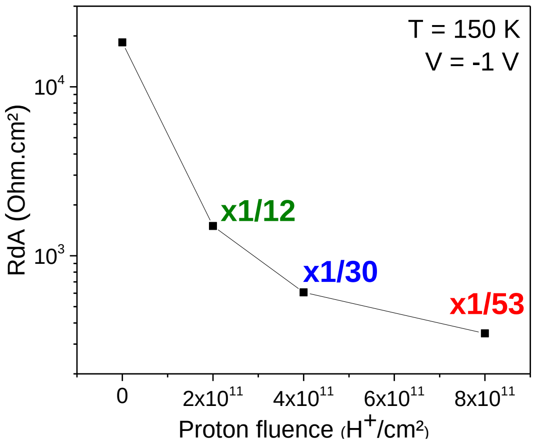


$$D^* = R_\lambda \sqrt{\frac{1}{2qJ_{dark} + \frac{4kT}{R_d A}}}$$

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







INSTITUT D'ÉLECTRONIQUE ET DES SYSTÈMES

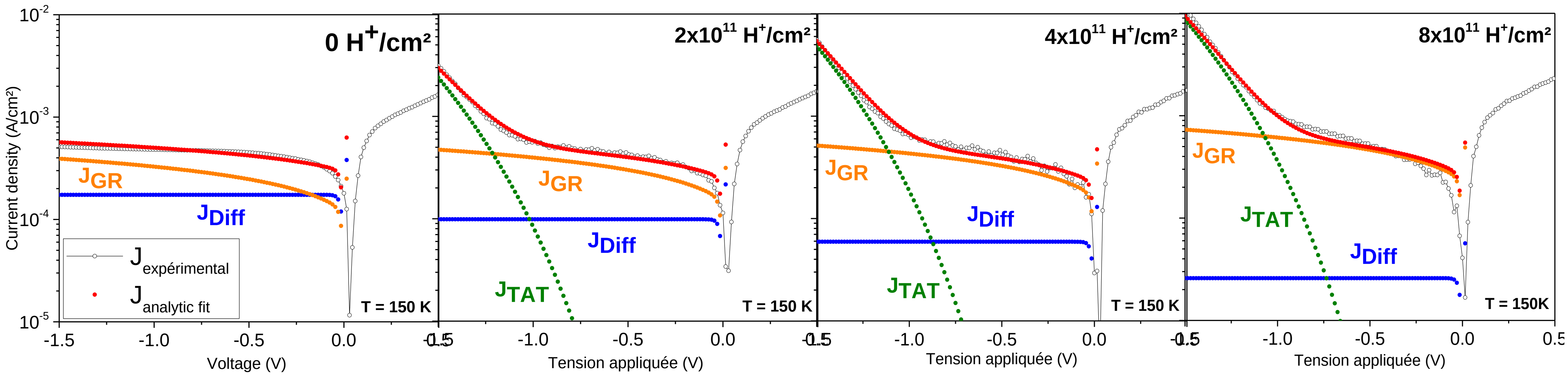
2^{nd} objective :

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

INSTITUT D'ÉLECTRONIQUE ET DES SYSTÈMES

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

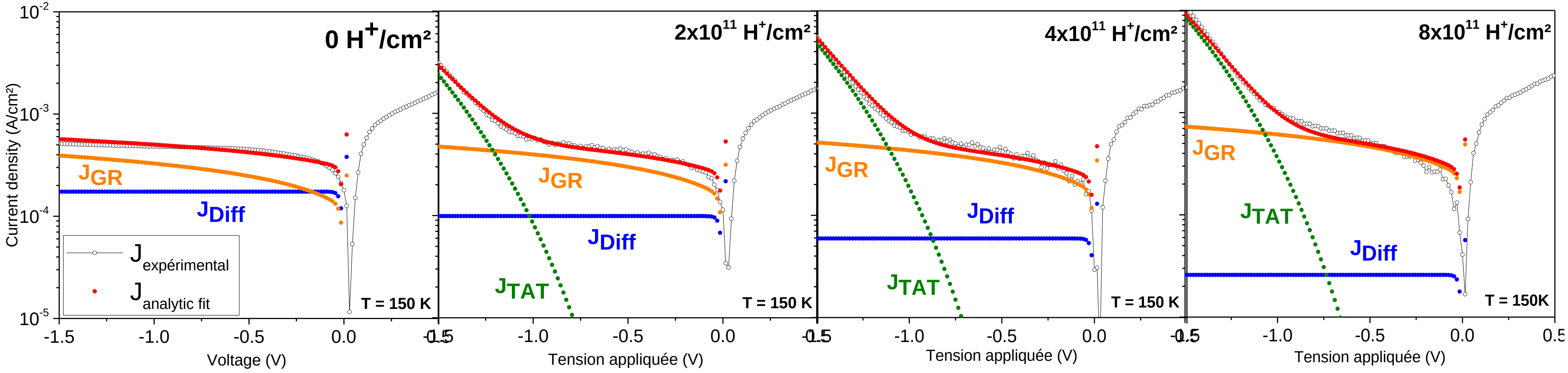
$$I_{dark} = I_{diff} + I_{GR} + I_{TAT}$$



GR and TAT currents increase with proton fluence

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

$$J_{dark} = J_{Diff} + J_{GR} + J_{TAT}$$



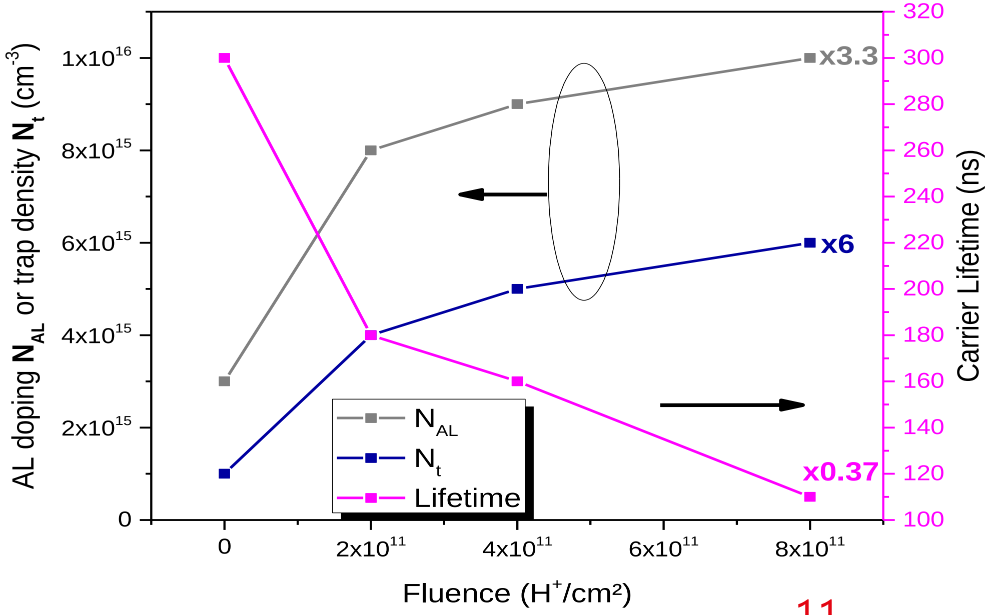
GR and TAT currents increase with proton fluence

$$J_{diff} \propto q \frac{L_{diff}}{\tau \times N_{AL}} n_i^2$$

$$J_{GR} \propto q \frac{W(V)}{2 \times \tau} n_i$$

$$J_{TAT} \propto q^2 \frac{V m_t M^2 N_t}{8\pi\hbar^3 (E_g - E_t)}$$

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



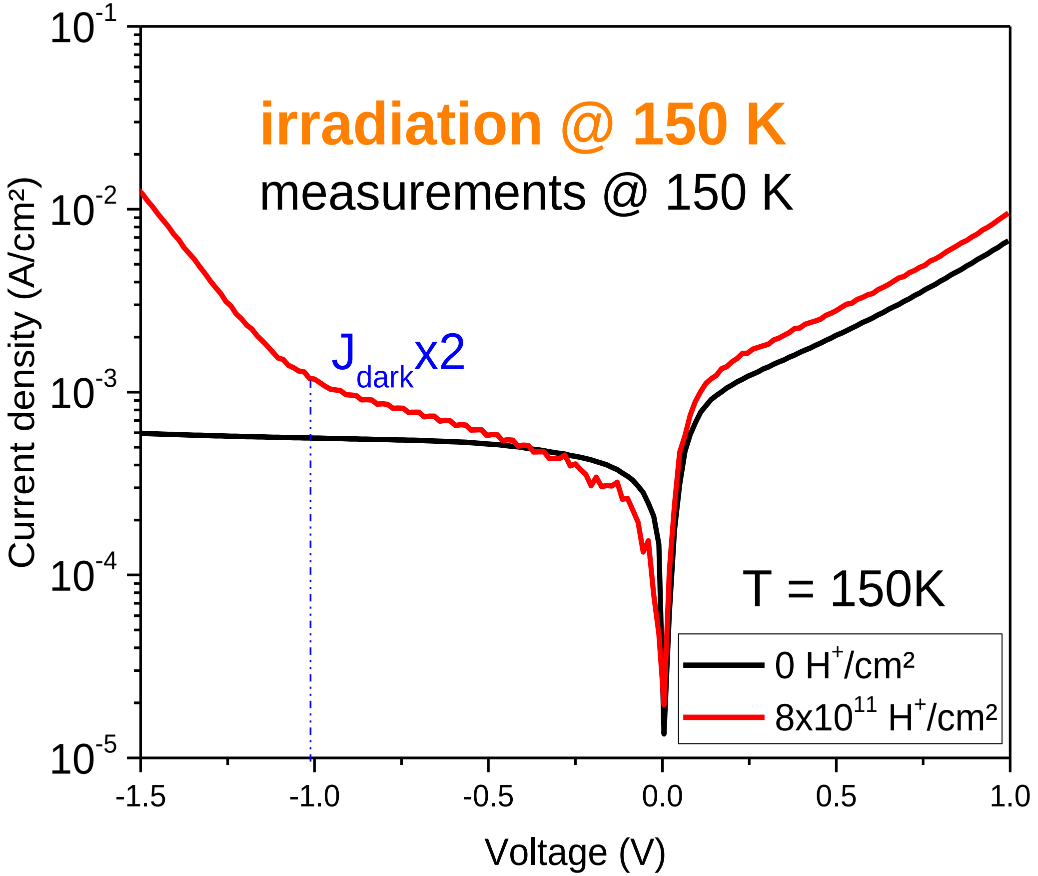
INSTITUT D'ÉLECTRONIQUE ET DES SYSTÈMES

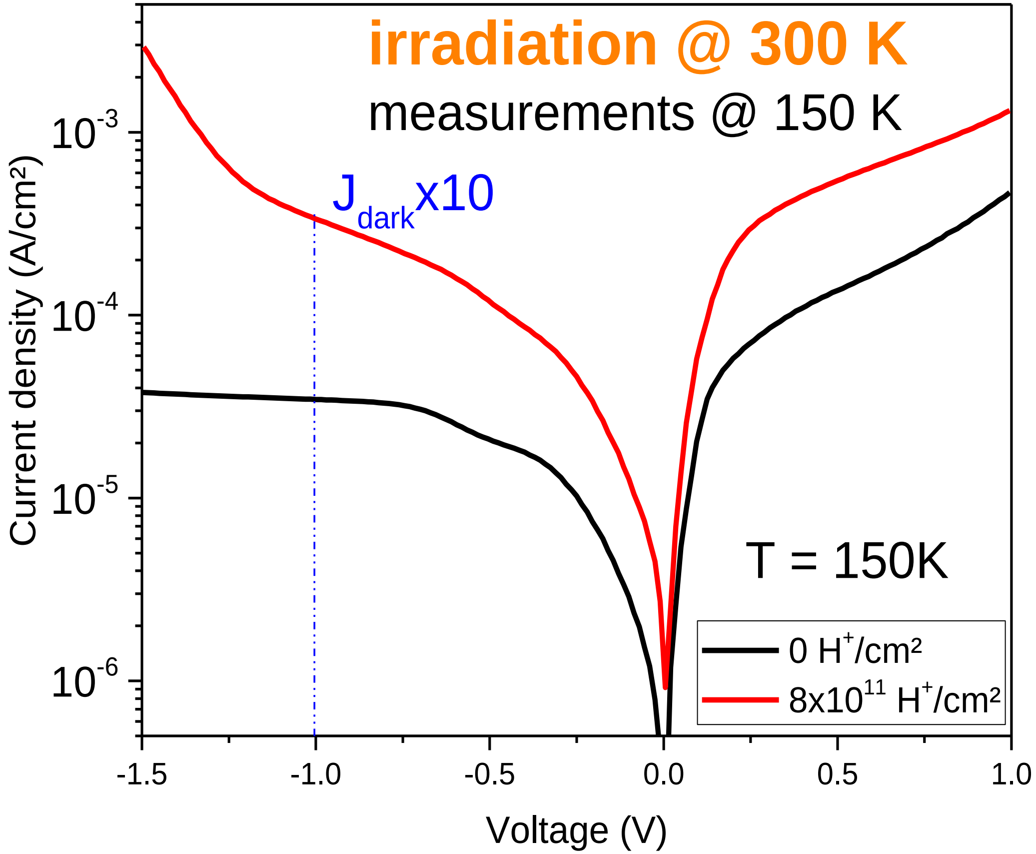
3rd objective :

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

INFLUENCE OF THE TEMPERATURE DURING IRRADIATION

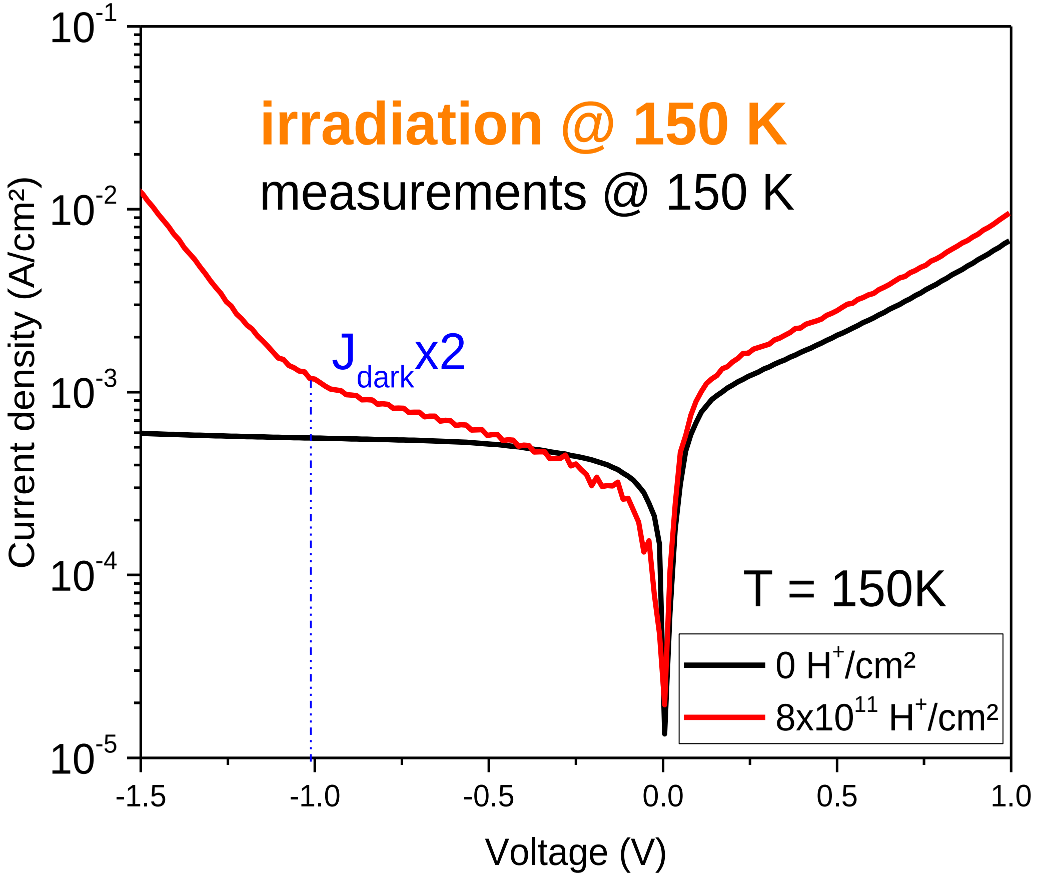
MWIR T2SL structure	Cut-off wavelength	V_{op}	AL thickness	Number of periods
Samples XBn	λc = 5 µm (150K)	- 1 V	3 µm	545

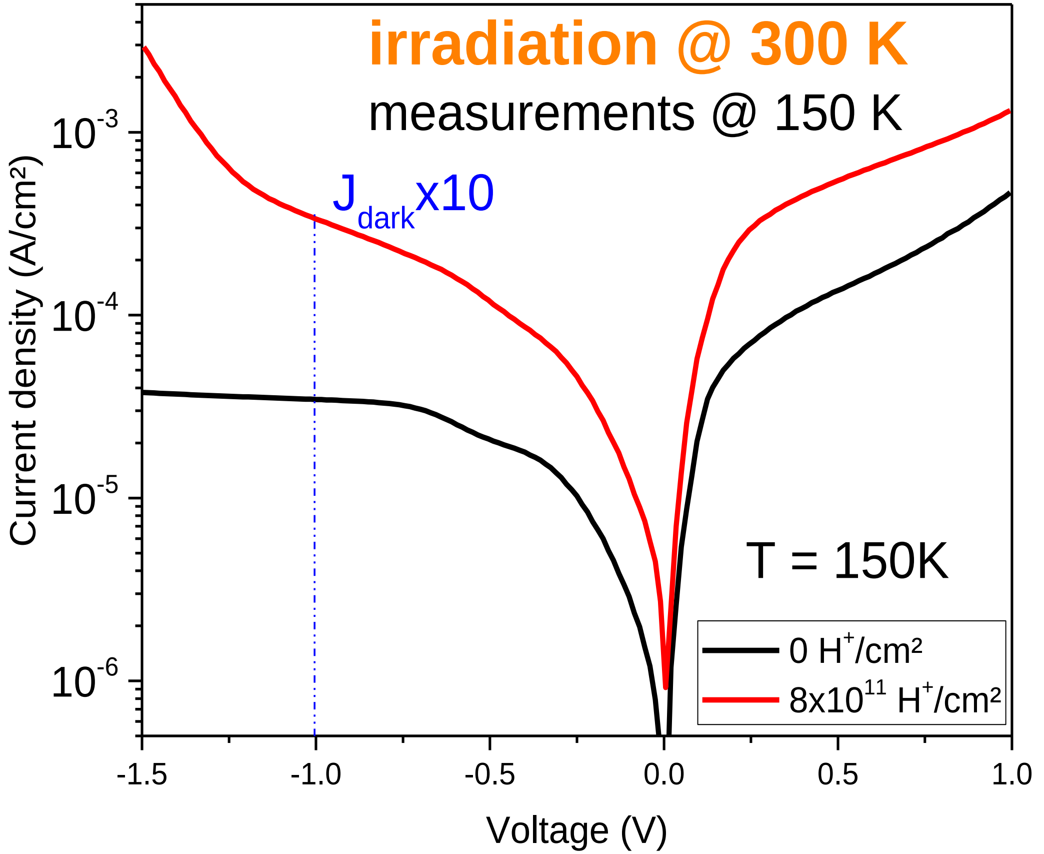




INFLUENCE OF THE TEMPERATURE DURING IRRADIATION

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





Degradation depends on the detector's temperature during the irradiation

CONCLUSION

- **XBn InAs/InAsSb MWIR T2SL** detectors were irradiated by **proton at fluence up to 8×10^{11} H^+/cm^2**

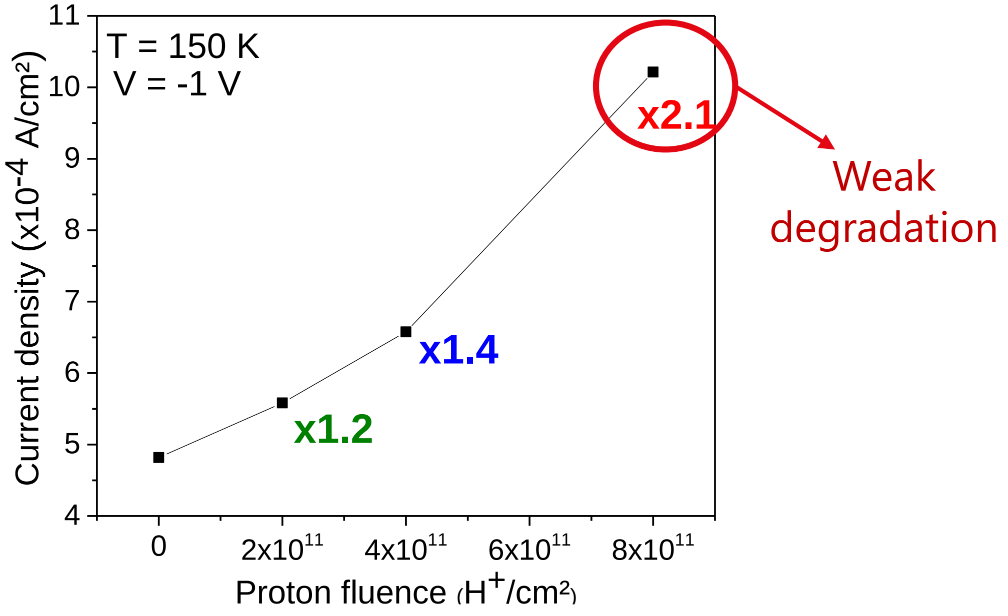
CONCLUSION

- **XBn InAs/InAsSb MWIR T2SL** detectors were irradiated by **proton at fluence up to 8×10^{11} H^+/cm^2**

✓ **Weak degradation of dark current** under proton fluence

  ✓ Increase of **GR current** ⟹ τ ↘

  ✓ Apparition of **TAT current** ⟹ $\mathbf{N_t}$ ↗



CONCLUSION

- **XBn InAs/InAsSb MWIR T2SL** detectors were irradiated by **proton at fluence up to 8×10^{11} H^+/cm^2**

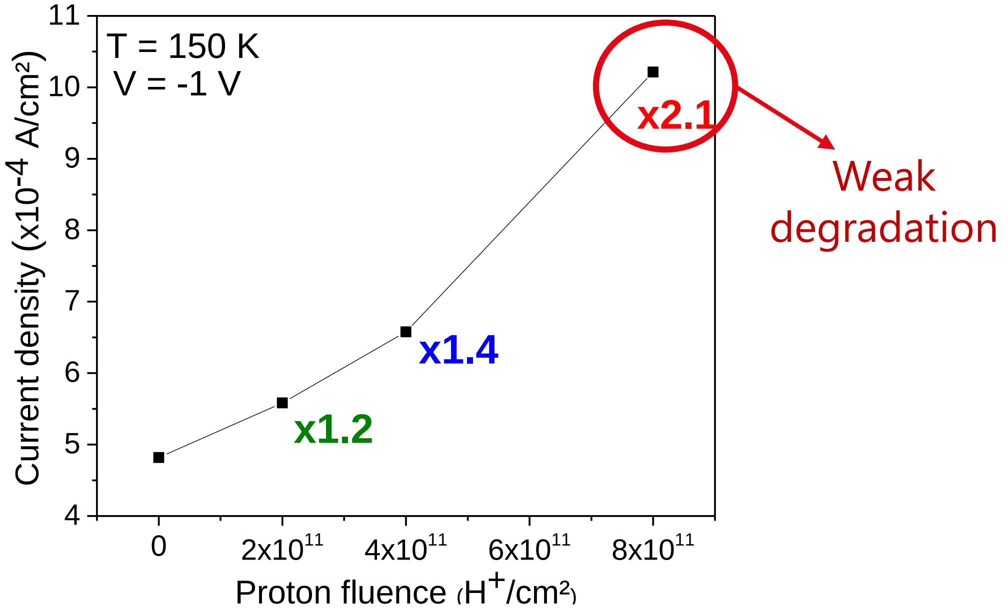
✓ **Weak degradation of dark current** under proton fluence

  ✓ Increase of **GR current** ⇨ τ ↘

  ✓ Apparition of **TAT current** ⇨ N_t ↗

✓ Influence of **detector's temperature during irradiation :**

- 150 K : J_{dark} **x2**
- 300 K : J_{dark} **x10**

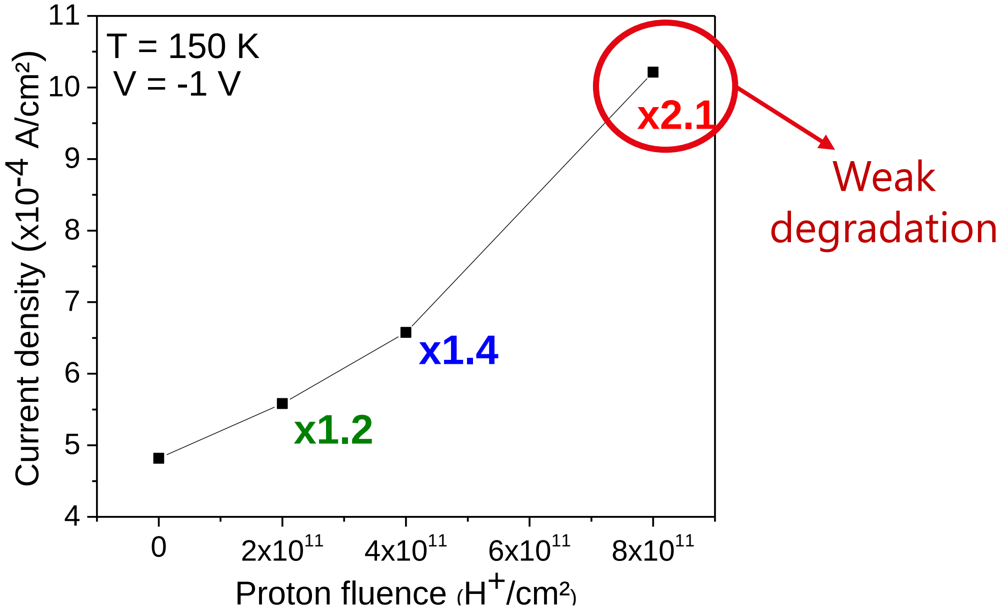


CONCLUSION

- ❑ **XBn InAs/InAsSb MWIR T2SL** detectors were irradiated by **proton at fluence up to 8x10^{11} H$^+$/cm²**

✓ **Weak degradation of dark current** under proton fluence
  - ✓ Increase of **GR current** ⟹ τ ↘
  - ✓ Apparition of **TAT current** ⟹ N_t ↗

✓ Influence of **detector's temperature during irradiation :**
  - 150 K : J_{dark} **x2**
  - 300 K : J_{dark} **x10**

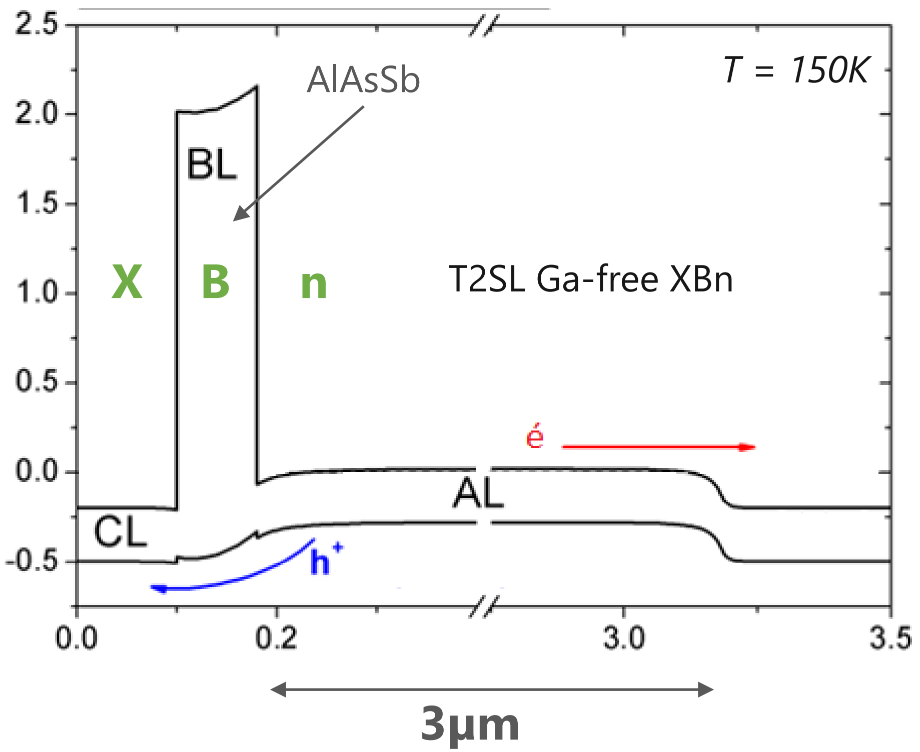


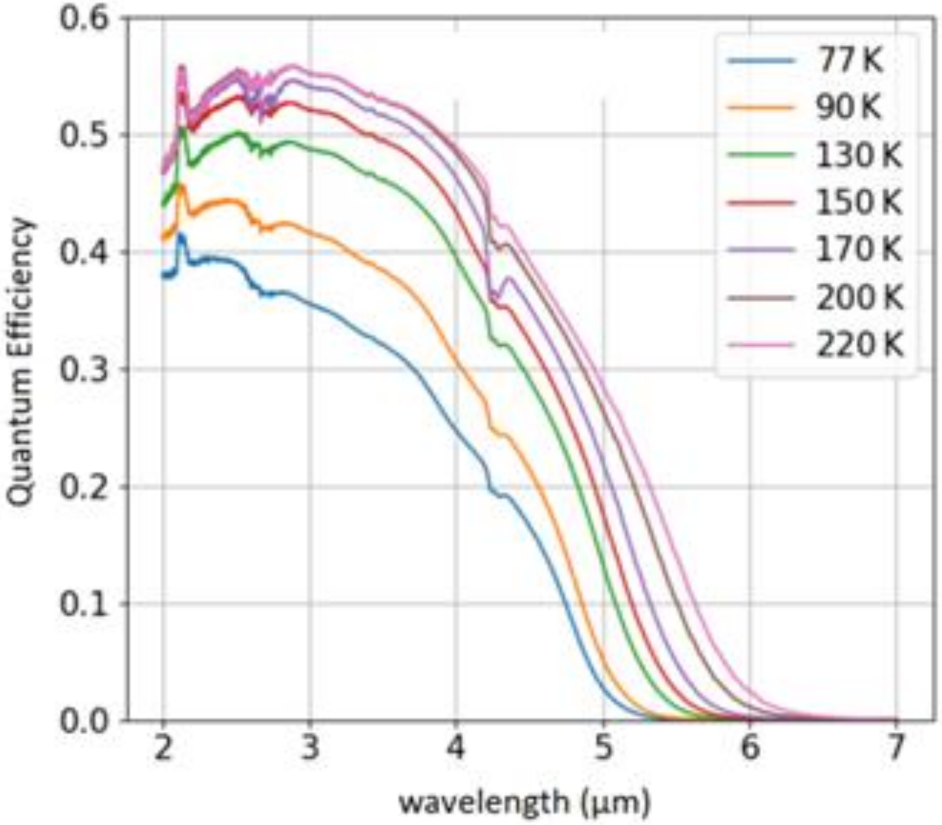
❑ **Perspectives :**
- Better understanding of dark current behavior
- Investigation of thermal annealing influence

THANK YOU FOR YOUR ATTENTION

ANNEXES

MWIR InAs/InAsSb T2SL DETECTORS





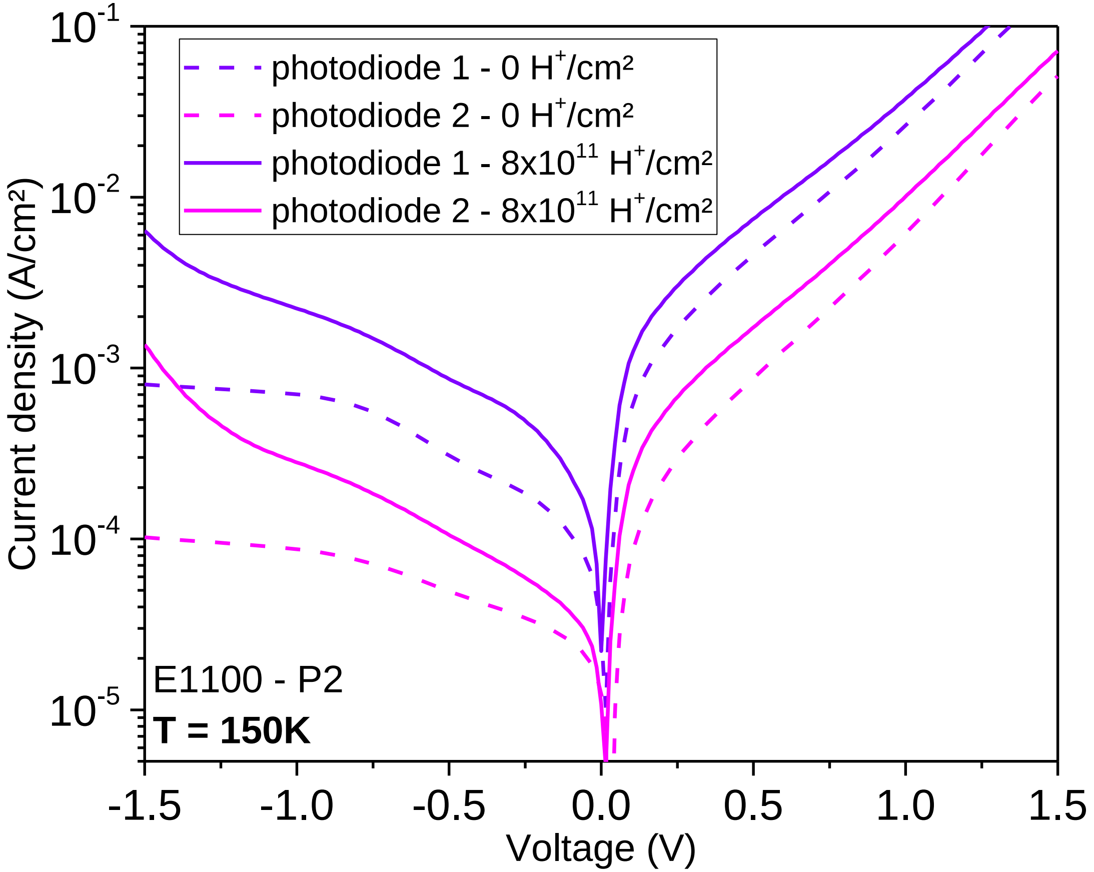
E_g(T=150 K) = 241 meV

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

INSTITUT D'ÉLECTRONIQUE ET DES SYSTÈMES

INFLUENCE OF THE INITIAL DARK CURRENT LEVEL

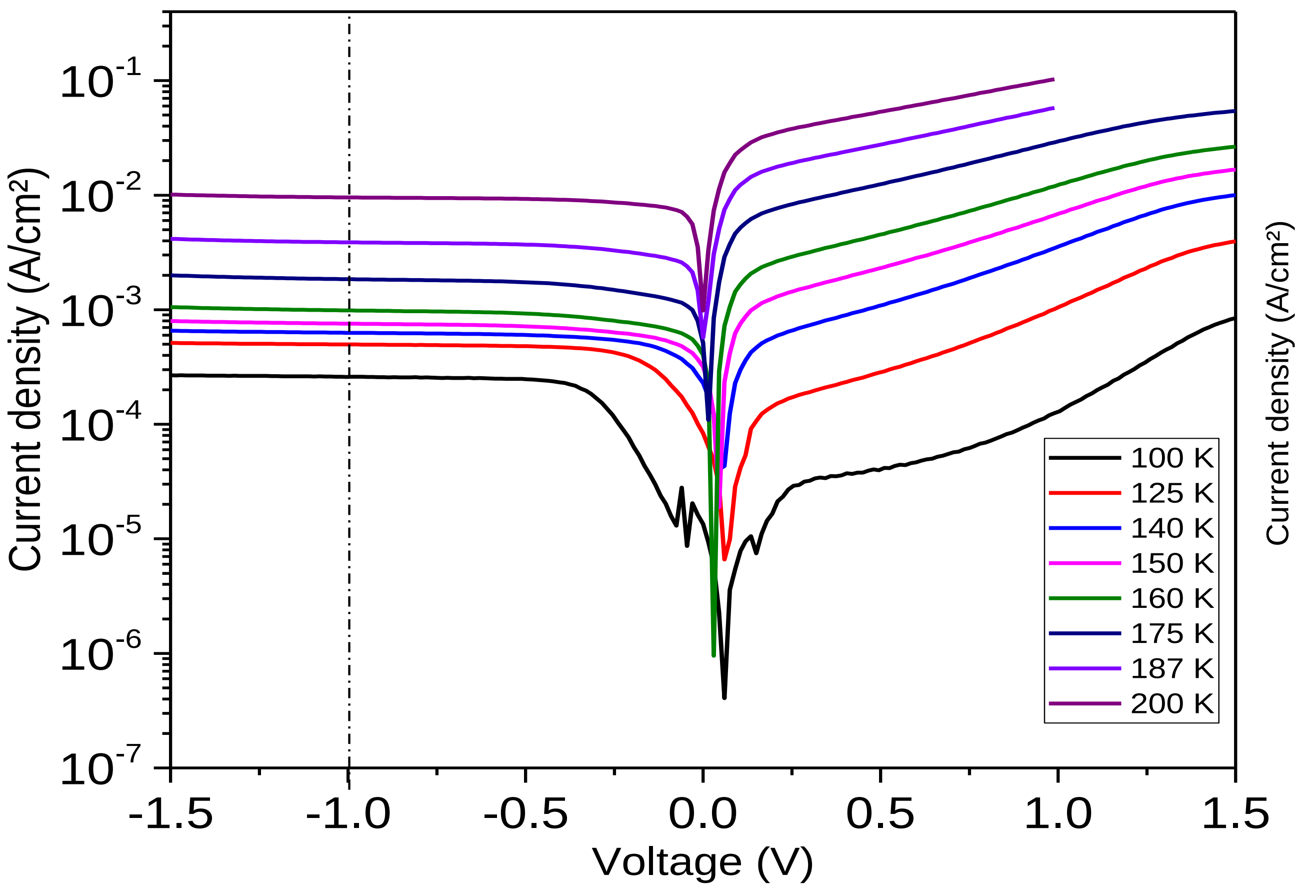
Temperature of detector during irradiation = 300 K

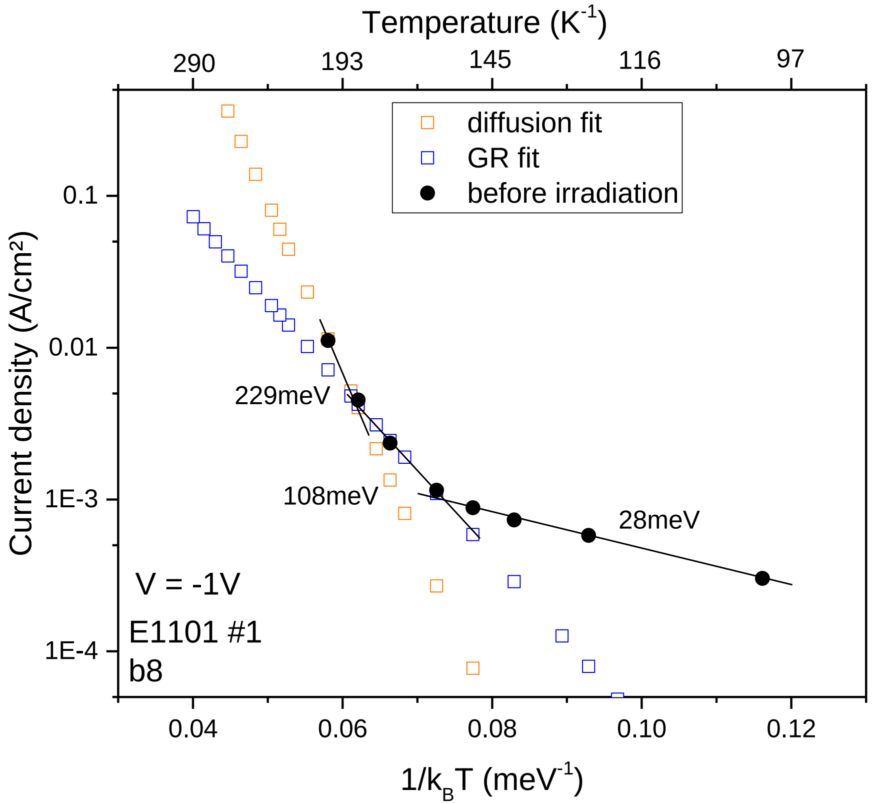


J / J_0	Photodiode 1	Photodiode 2
V = -0.75 V	x 2.7	x 2.6
V = -1 V	x 3.1	x 3.2
V = -1,25 V	x 4.4	x 4.6

INSTITUT D'ÉLECTRONIQUE ET DES SYSTÈMES

DARK CURRENT TEMPERATURE DEPENDENCE



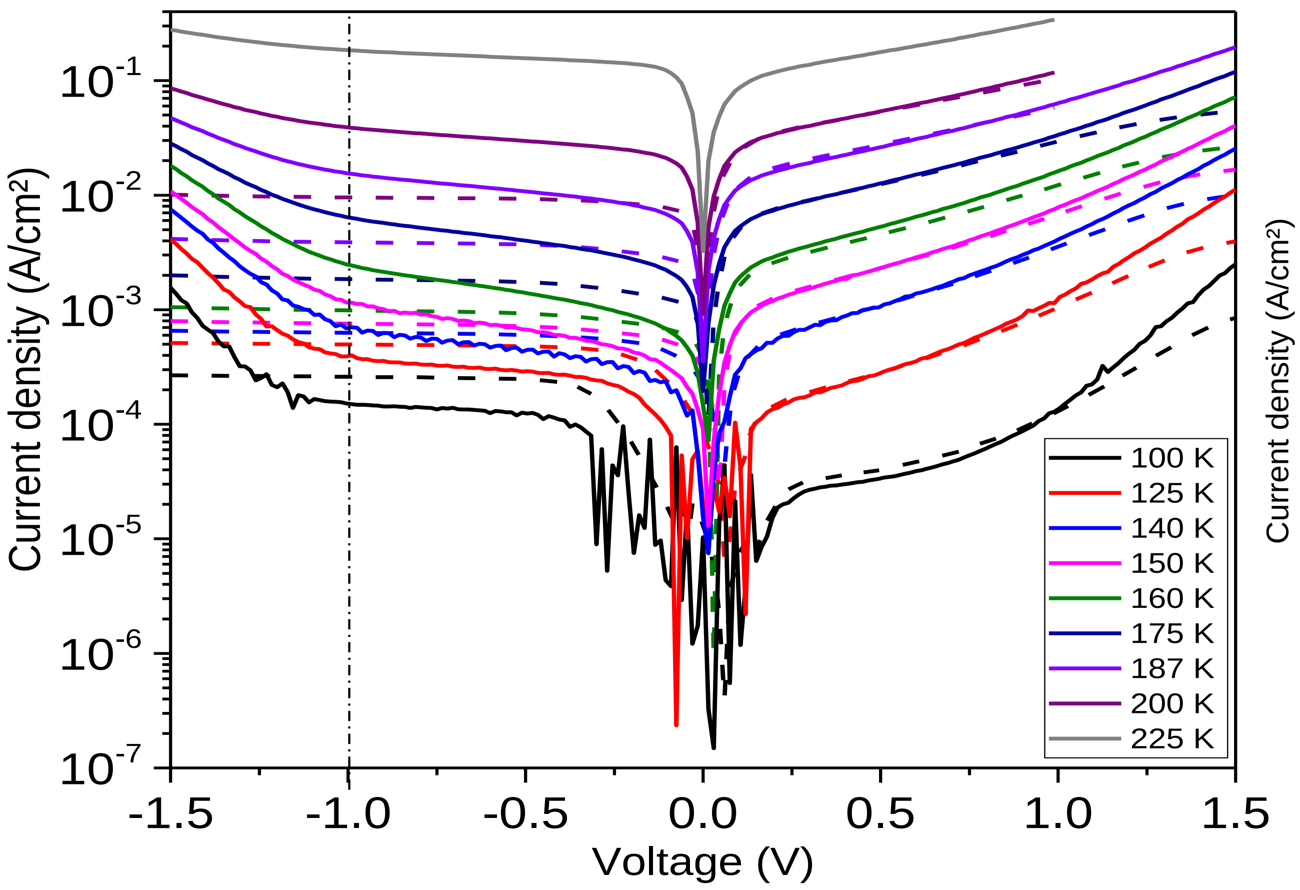


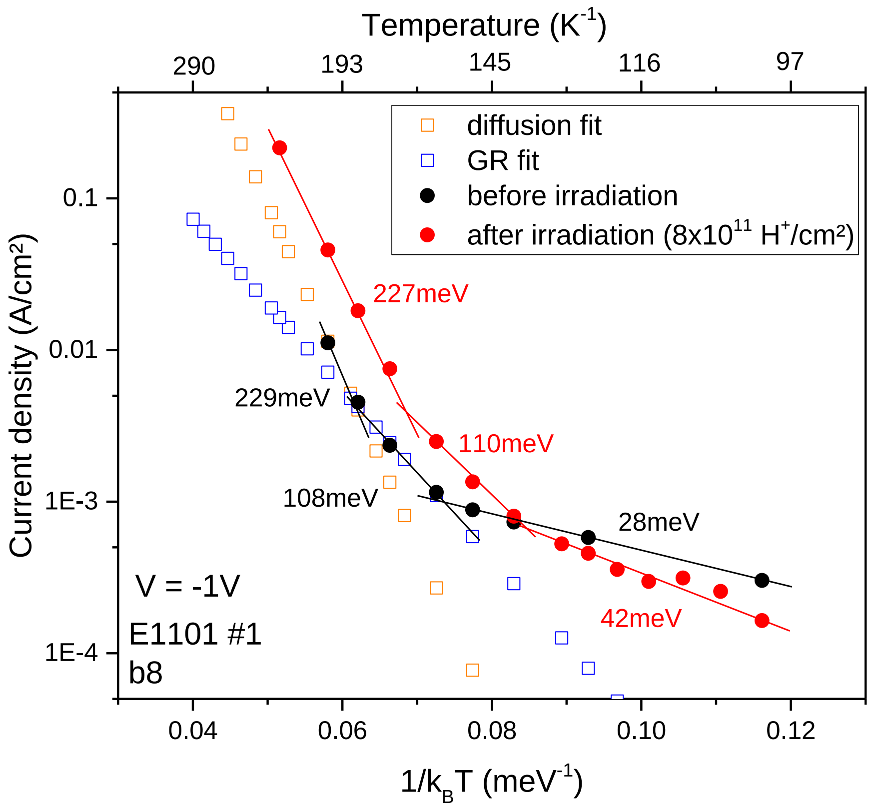
$$J_{GR} \cong q \frac{W_{dep}}{\tau_{SRH}} n_i$$

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

Before irradiation ➔ Presence of GR current

DARK CURRENT TEMPERATURE DEPENDENCE





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

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

Before irradiation ➔ Presence of GR current

After irradiation :

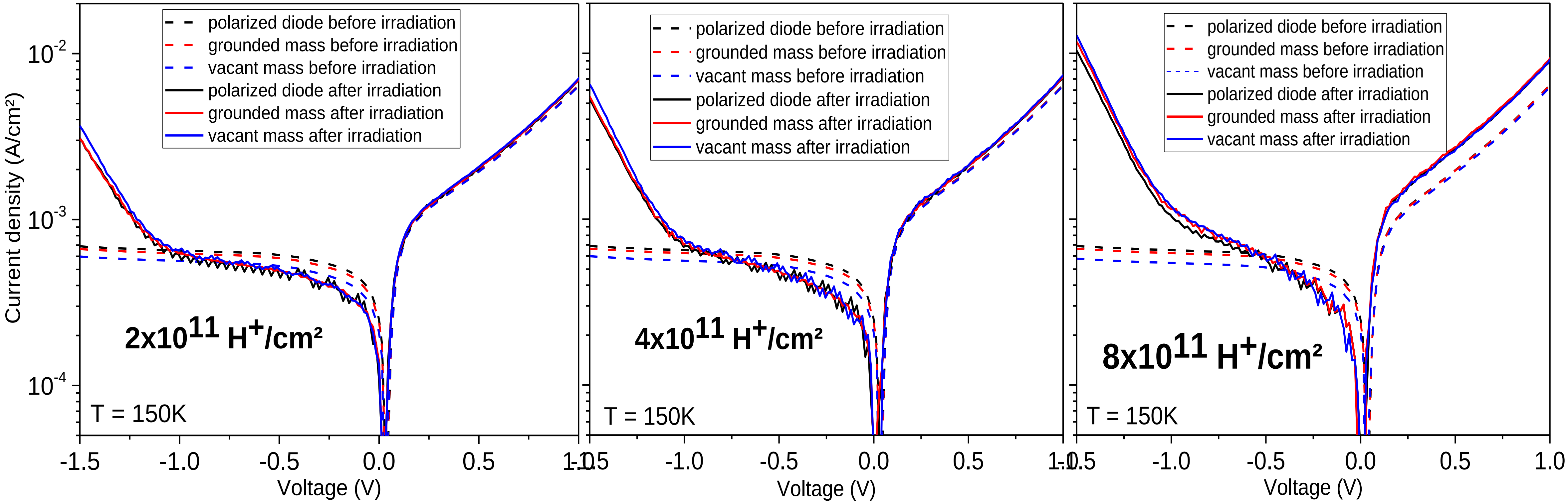
➔ **dark current increases (T > 100 K)**

➔ dark current decreases (T < 100 K)

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

INFLUENCE OF THE POLARIZATION AND MASS GROUNDED DURING IRRADIATION

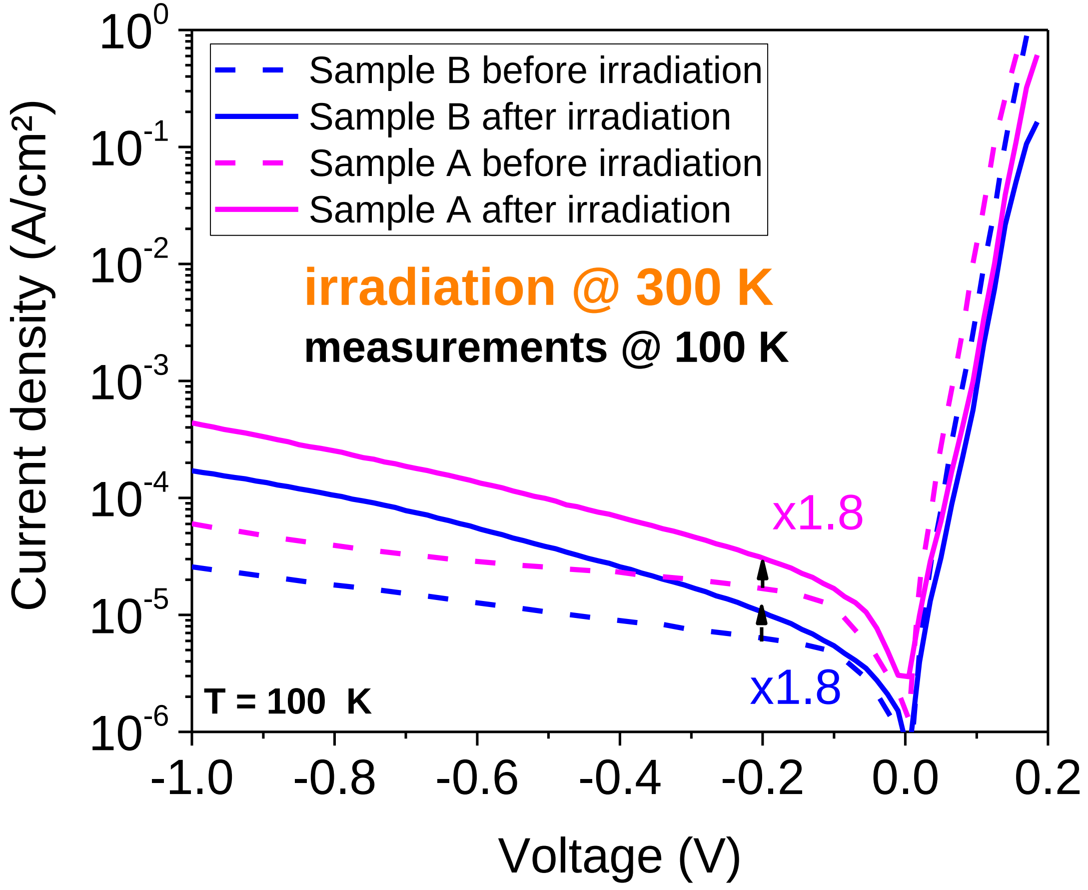
Sample	Cut-off wavelength @ 150K	AL thickness	Number of periods
XBn	λc = 5 µm	3 µm	545



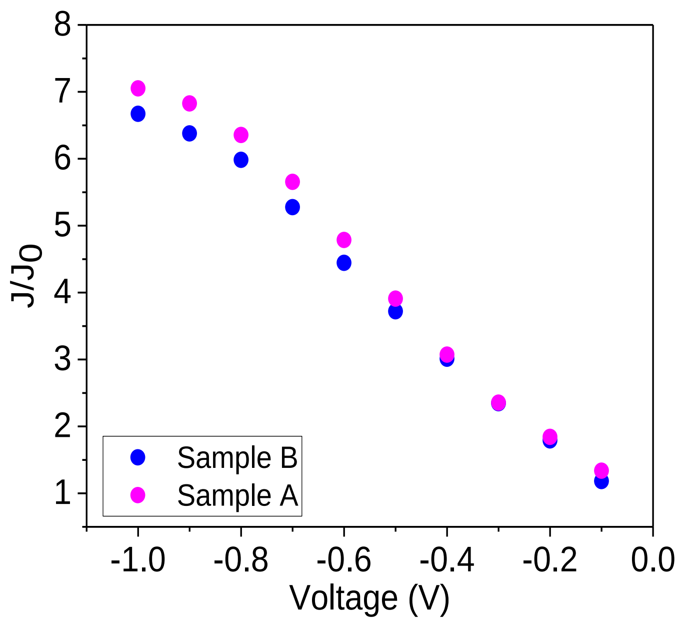
Degradation independent of the polarization ON/OFF during the irradiation

INSTITUT D'ÉLECTRONIQUE ET DES SYSTÈMES

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

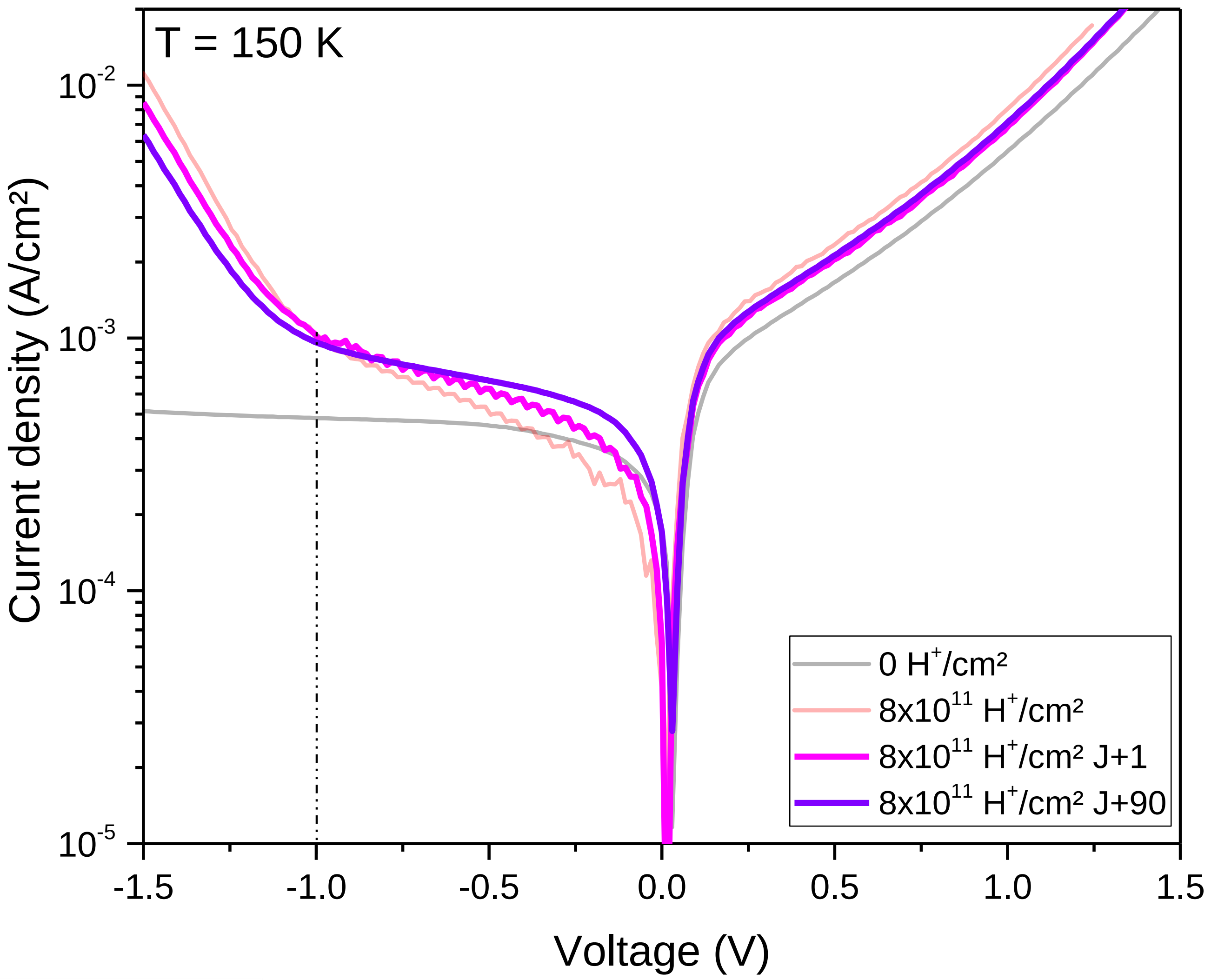


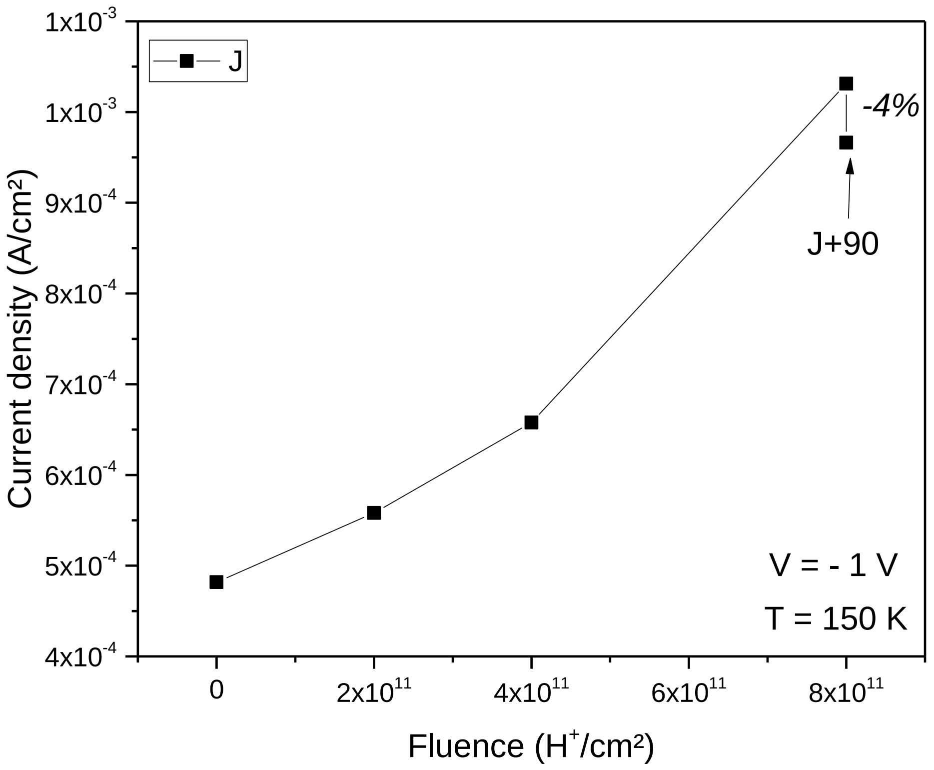
Sample	Sample	Cut-off wavelength @ 100K	AL thickness	Number of periods
PIN	A	λc = 5 µm	0.5 µm	151
PIN	B	λc = 5 µm	1 µm	303



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

ANNEALING WITH THERMAL CYCLES





INSTITUT D'ÉLECTRONIQUE ET DES SYSTÈMES

SPACE CHARGE REGION AND MAXIMAL ELECTRIC FIELD