Proton Radiation-induced Dark Current Increase in InGaAs Photodiodes

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4 : Isae Supaero, Toulouse, France

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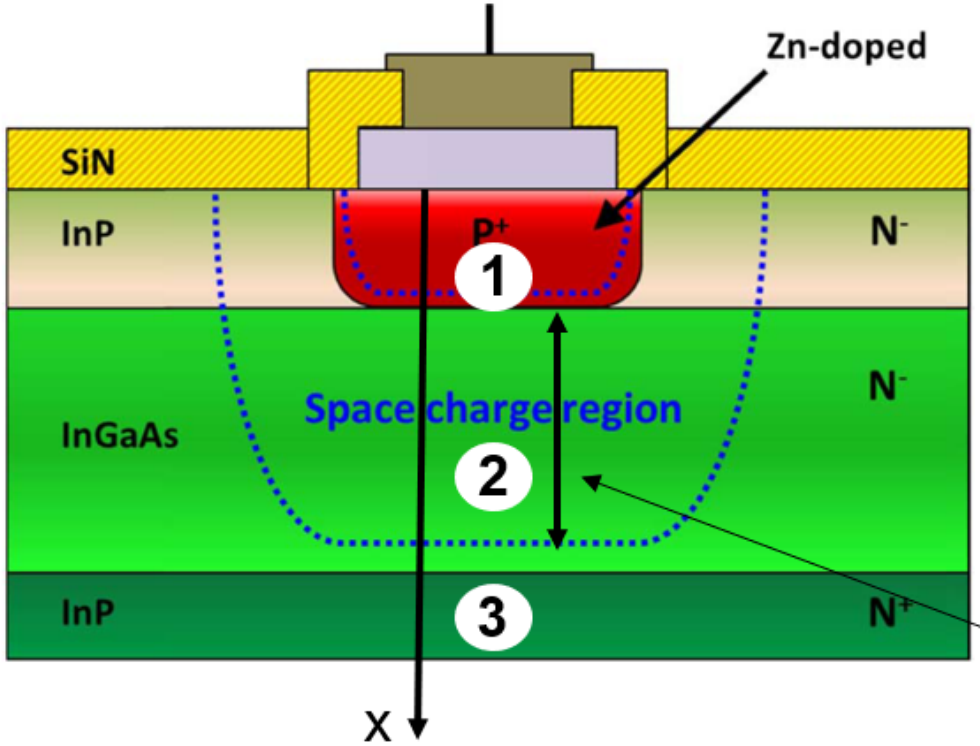
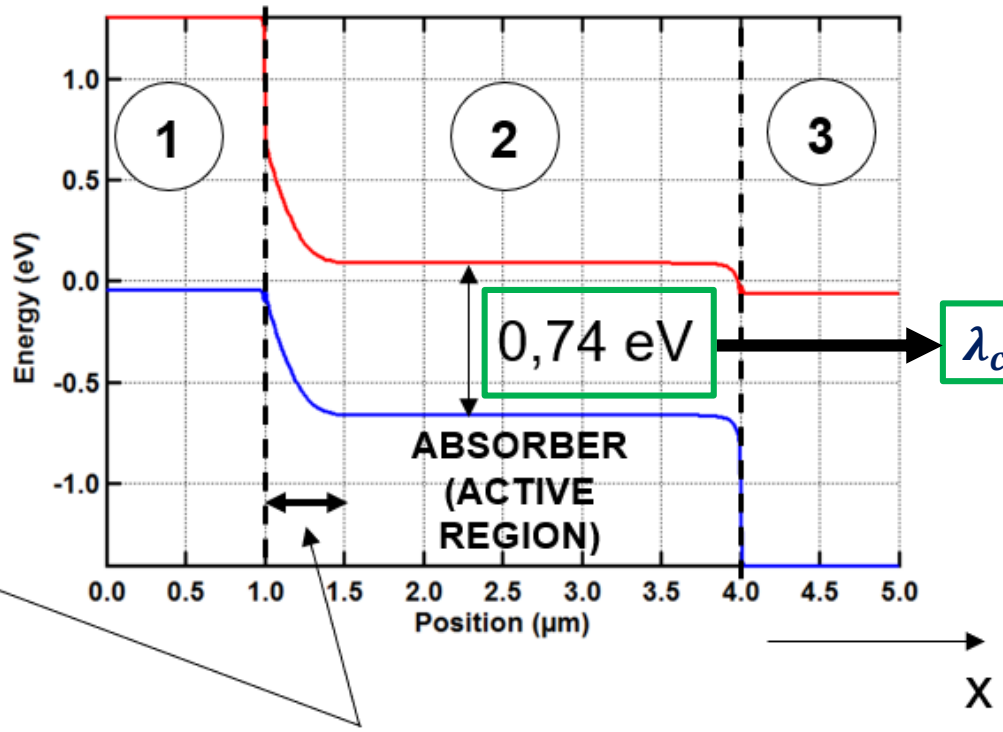
Device structure

Photodiode structure

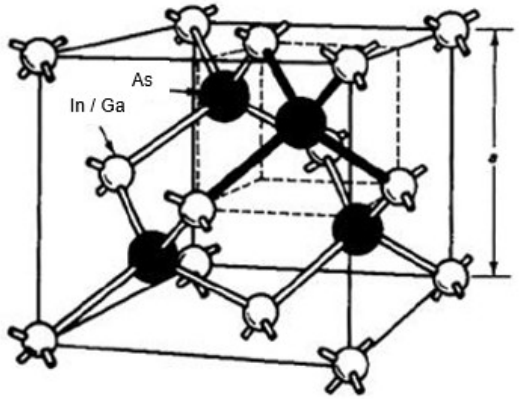


Band diagram

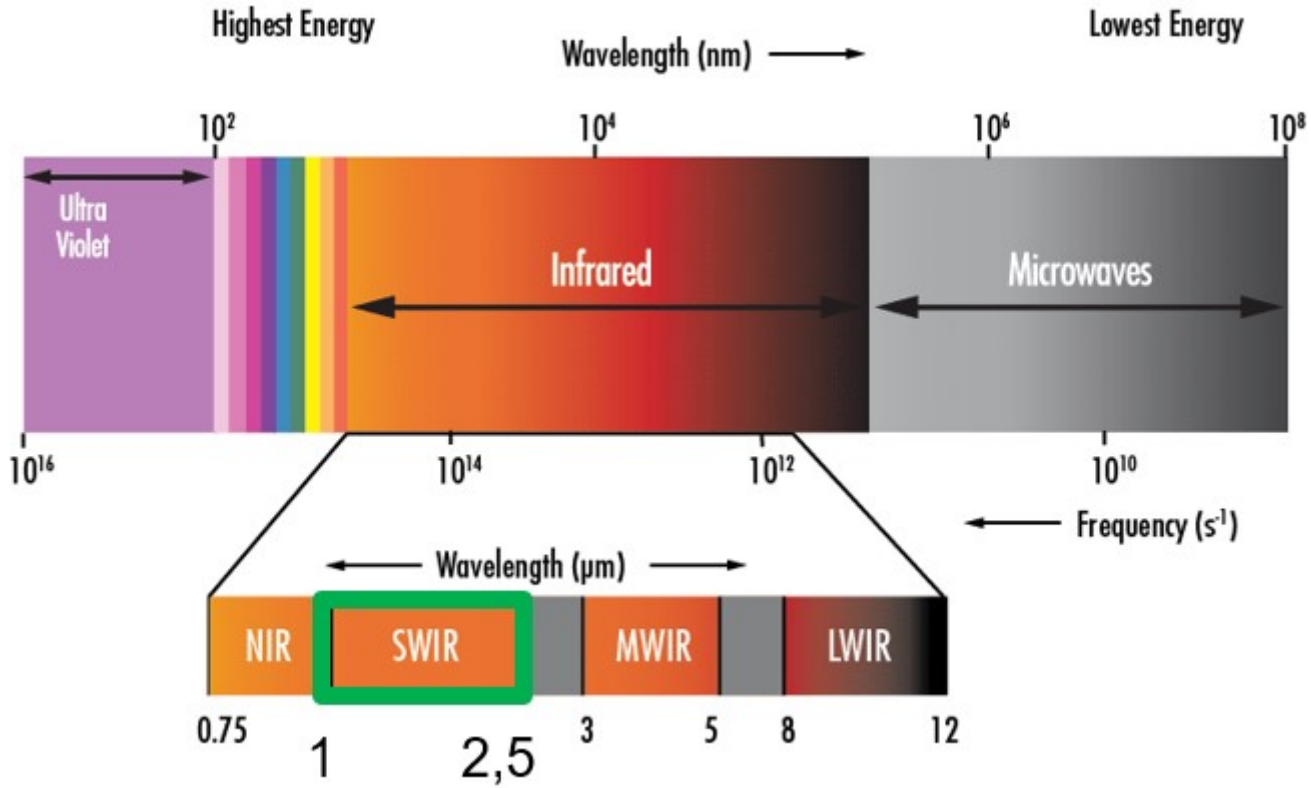


$\lambda_c = 1,65$ µm

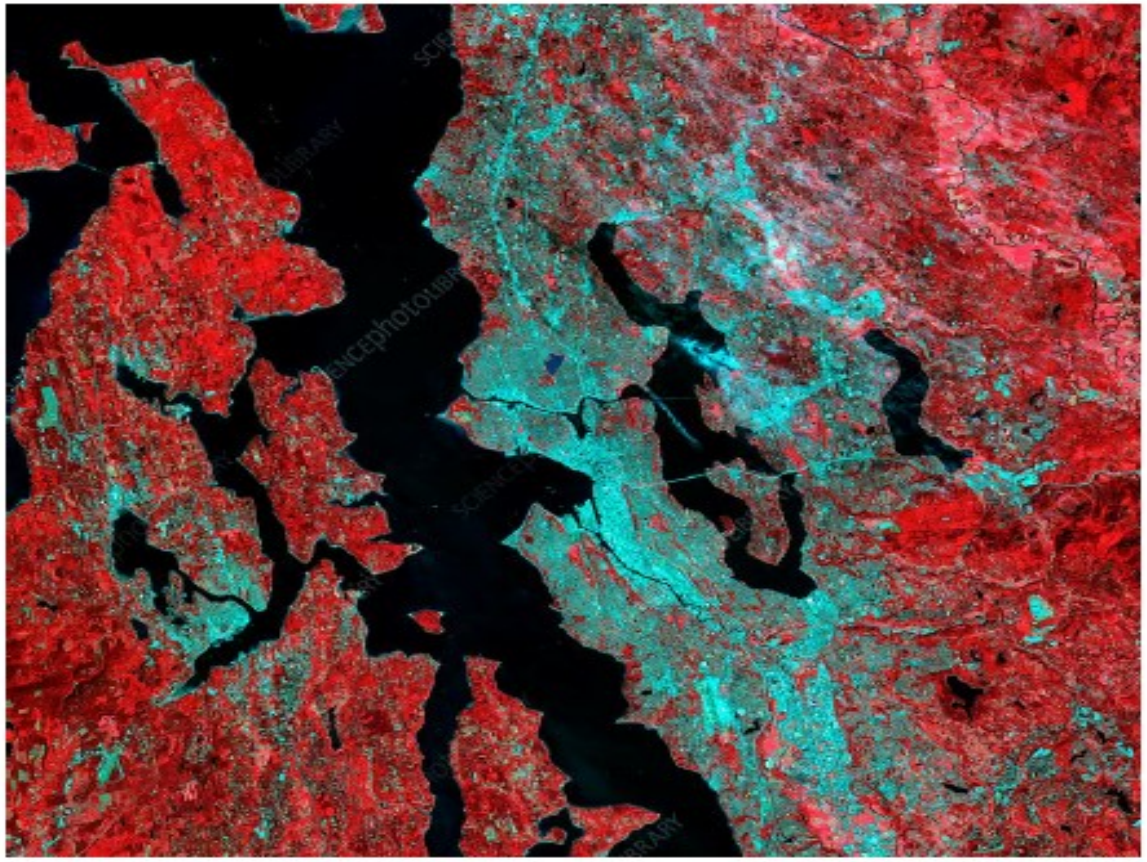
Electric Field Region



$\lambda_c = 1,65\ \mu m$ → SWIR (Short Wavelength InfraRed)



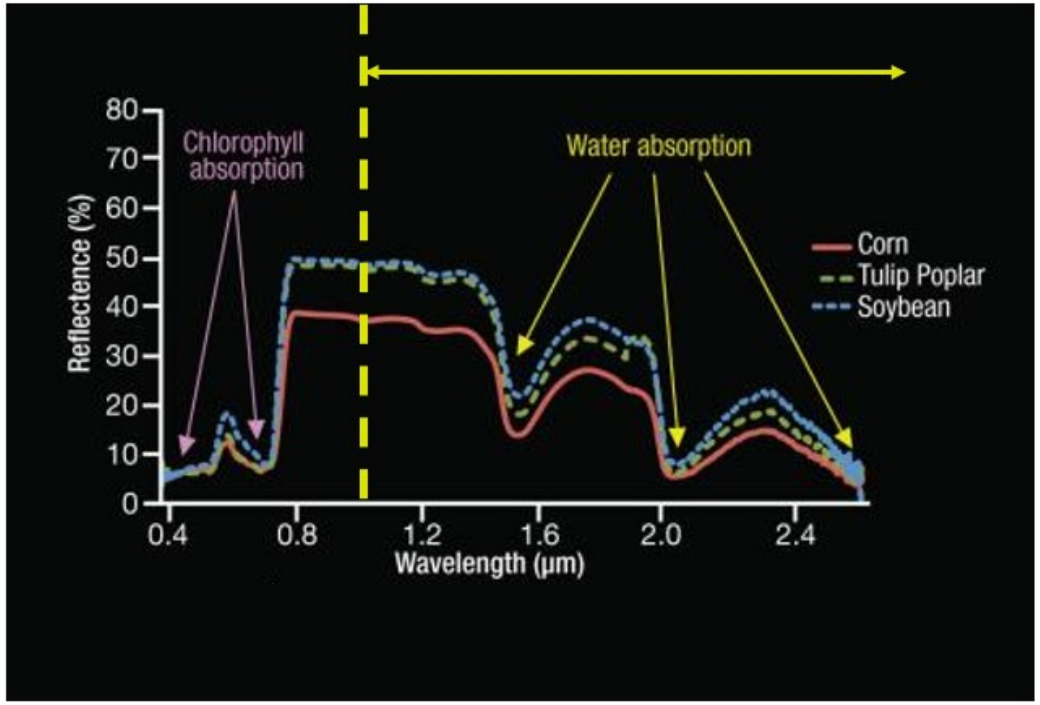
Space Application Example



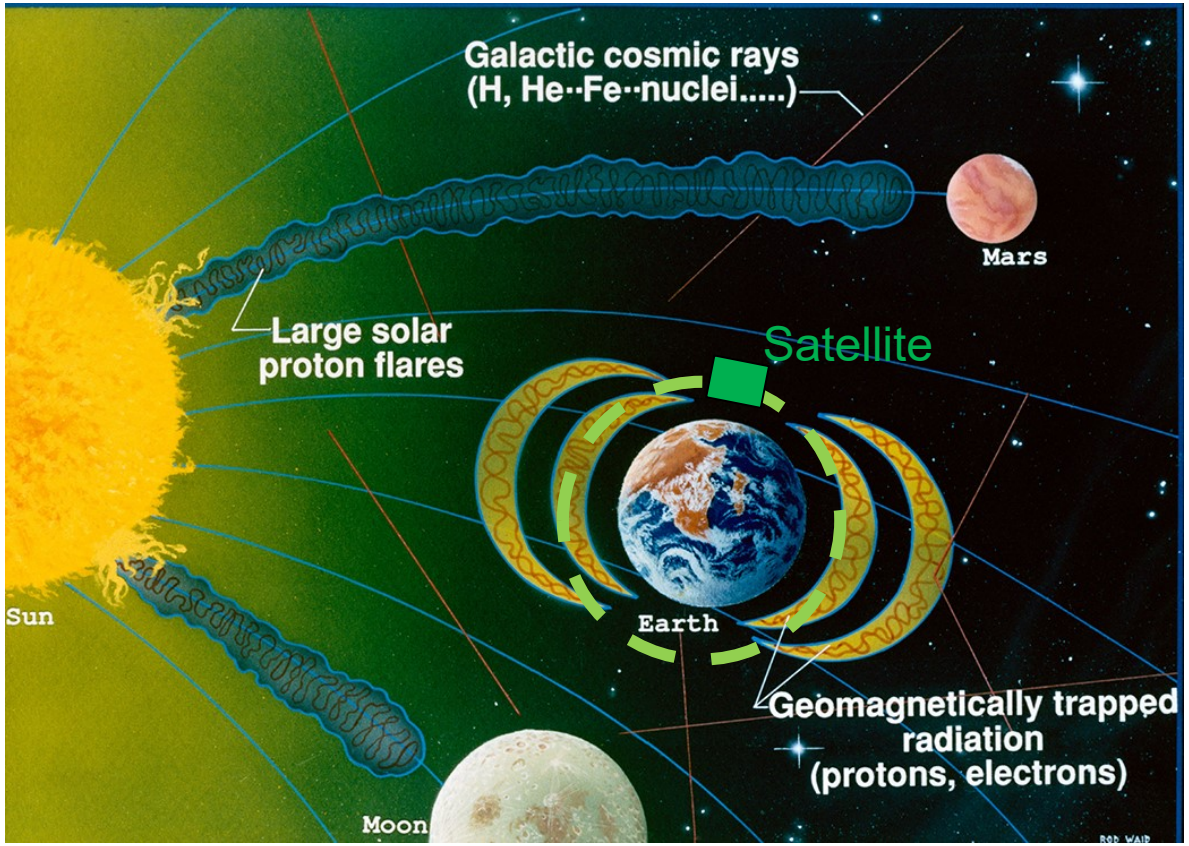
Remote Sensing
(e.g. **Earth Vegetation**)

False color SWIR image

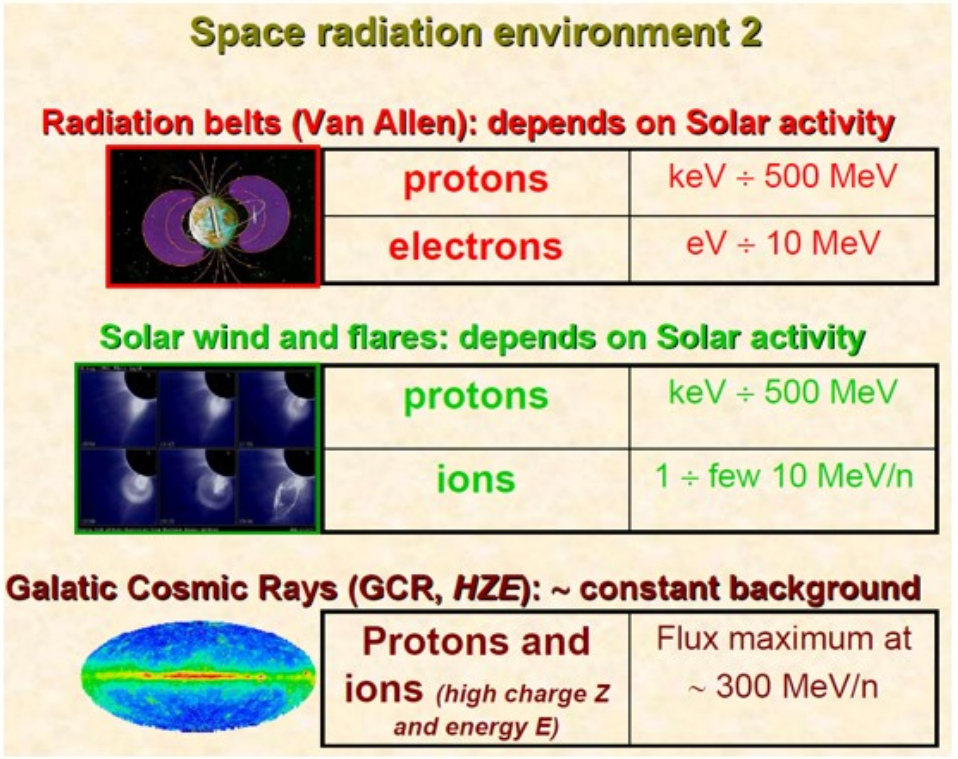
Red : Healthy
Blue : Unhealthy



Space radiation environment



https://www.nasa.gov/sites/default/files/thumbnails/image/edu_stem_ll_radiation.jpg

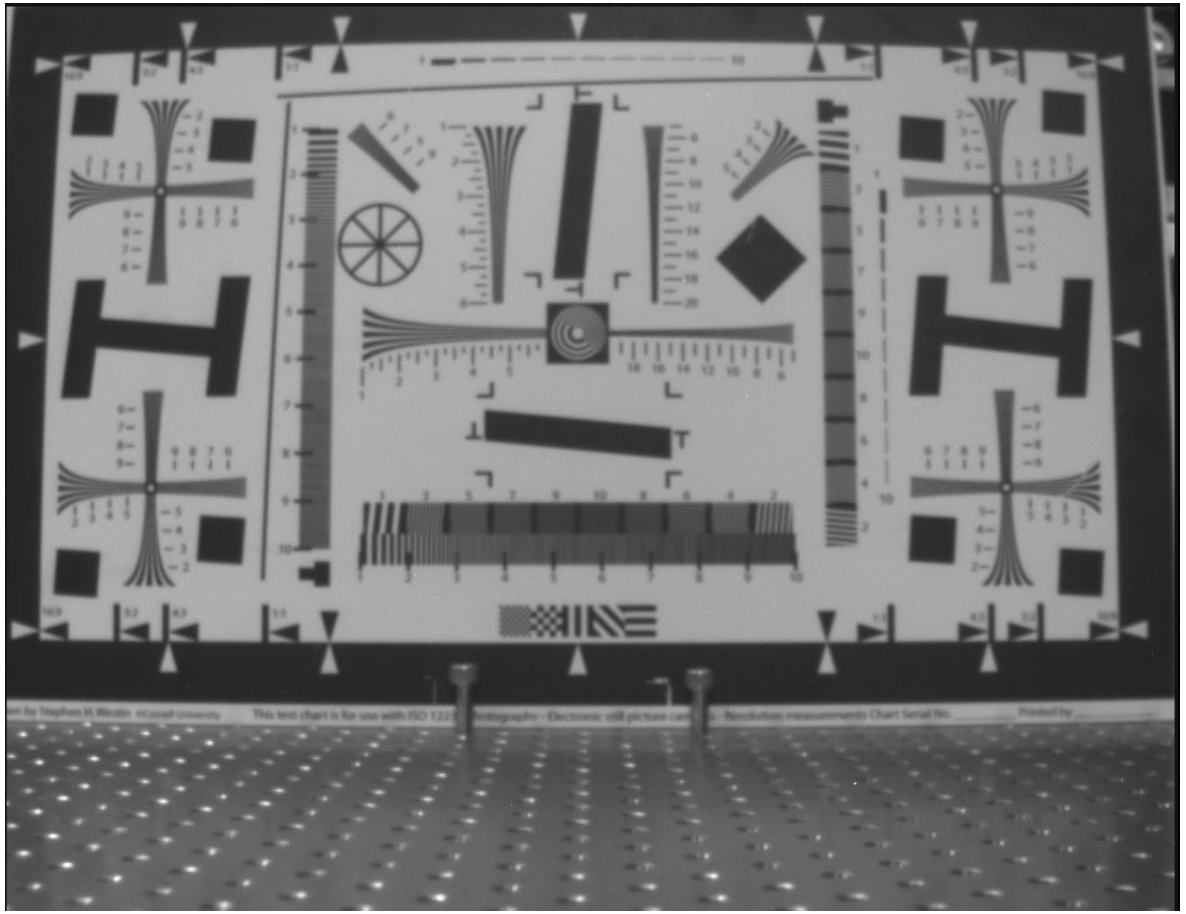


Introduction to radiation damage: concepts, physical quantities, radiation environment, Prof. Jeffery Wyss, Padova 2007

Space radiation **degrade** the InGaAs Photodiodes

Image examples

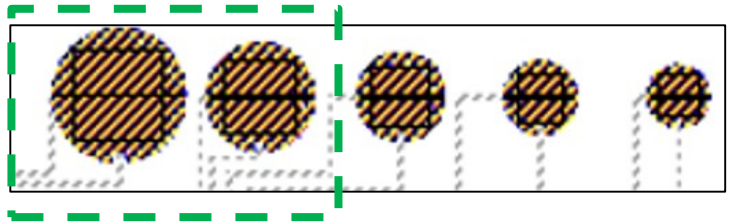
Pristine



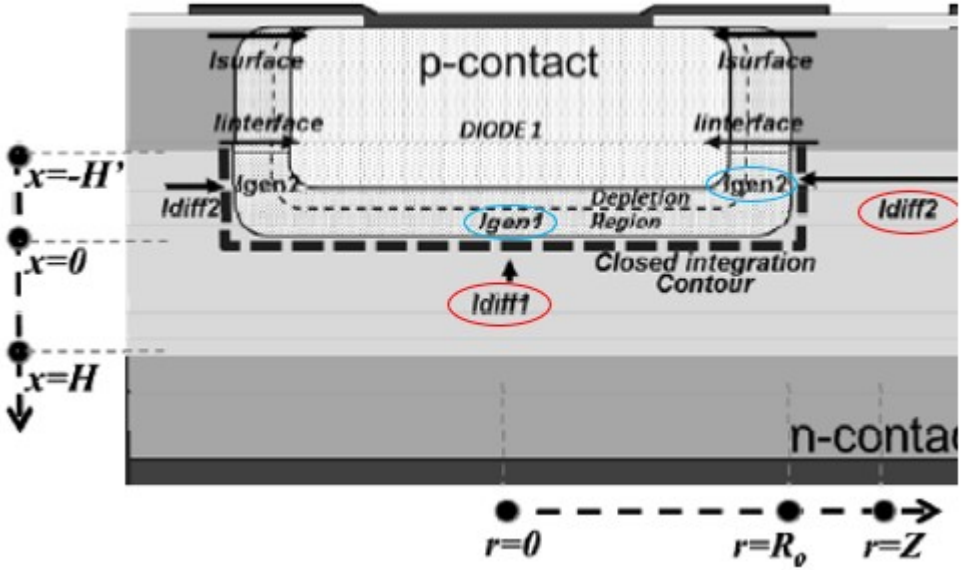
Proton-irradiated

Analysis pre-irradiation

Test cell top view



Cross Section

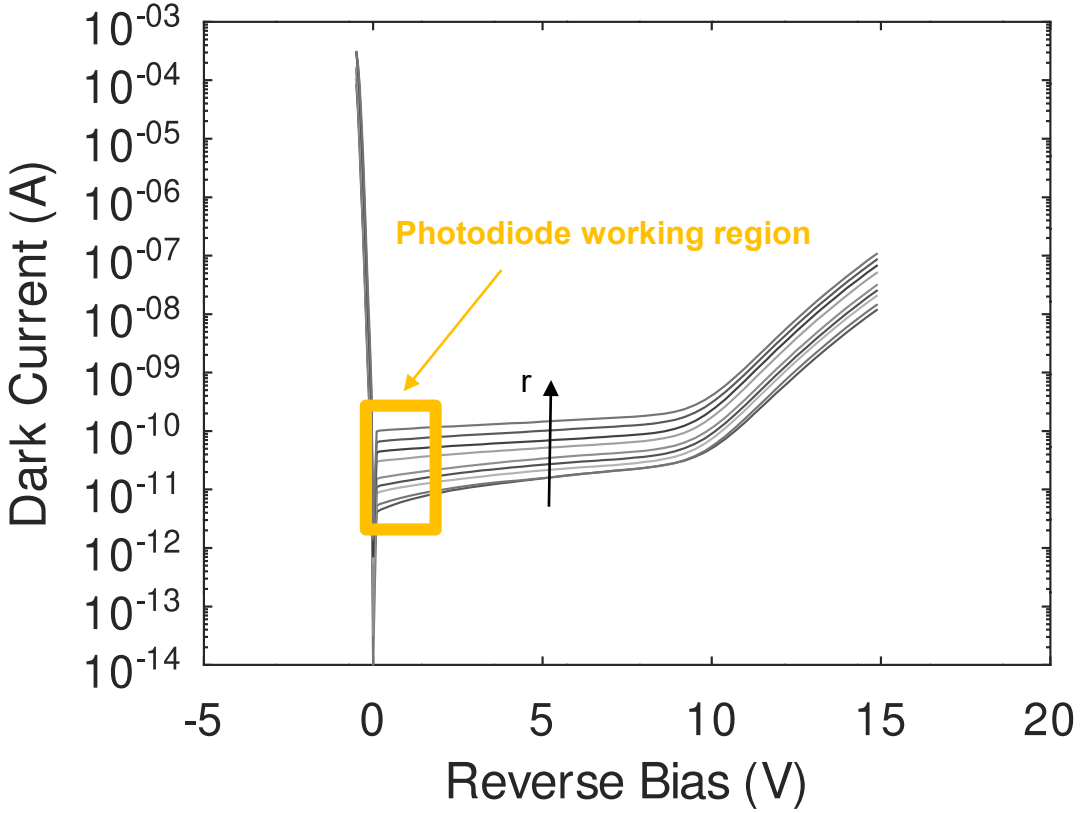


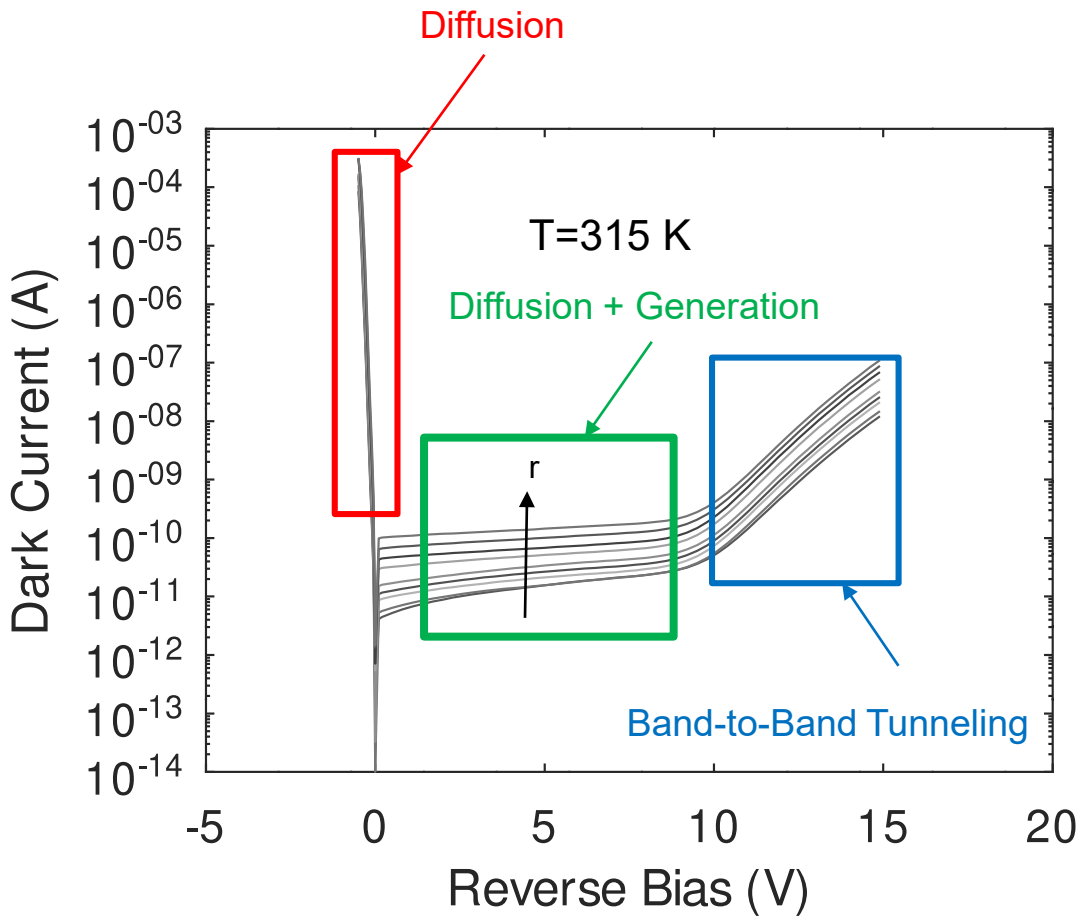
Trezza et al. "Analytic modeling and explanation of ultra-low noise in dense SWIR detector arrays." 2011.

Before Irradiation : the Dark Current

Considered diode diameters

[30 40 65 85 110 185 240 310 400] µm



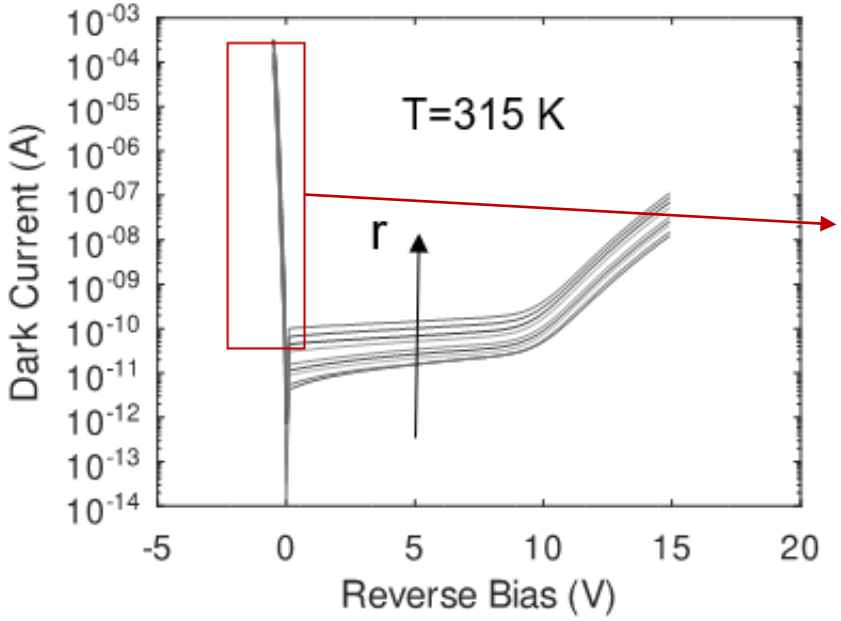


Diffusion current extraction

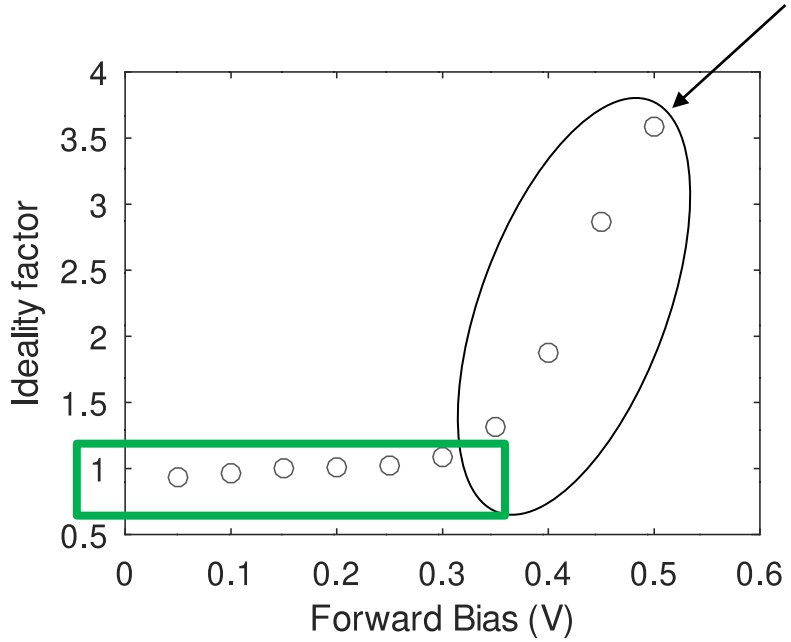
$$I = I_{diff} + I_{rec} - I_{BTBT} = I(e^{\frac{V}{nV_T}} - 1) - I_{BTBT}$$

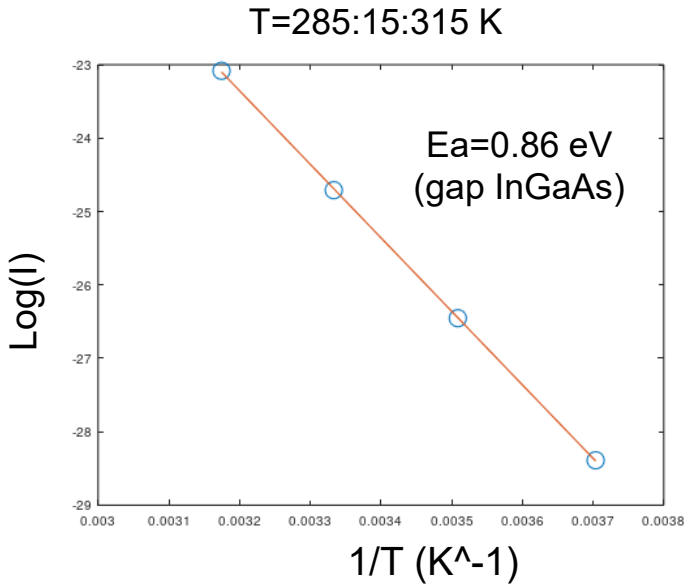
n : ideality factor (=1 if diffusion dominates)

Forward Bias → $I = I_0 e^{\frac{V}{V_T}}$ where $I_0 = I_{diff,0}$

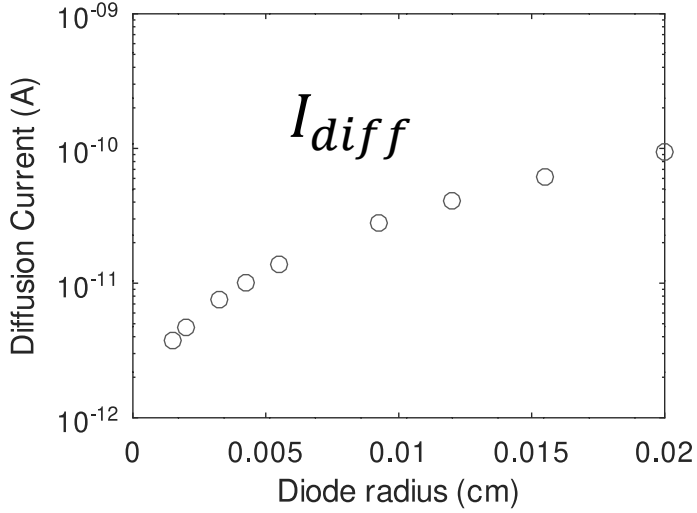


Series resistance



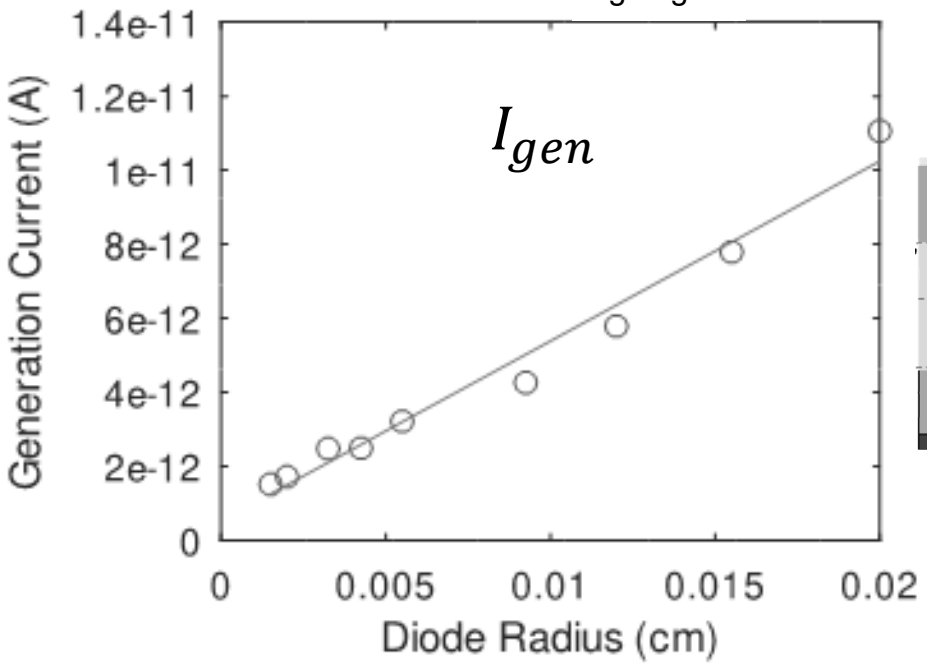


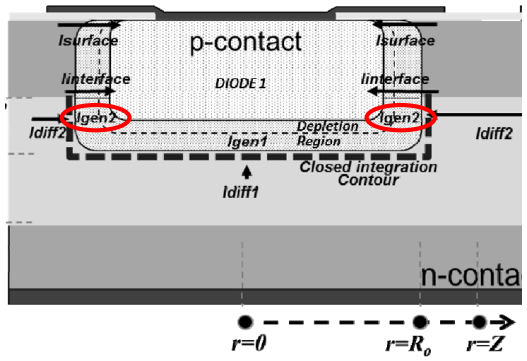
Reverse bias : Generation Current



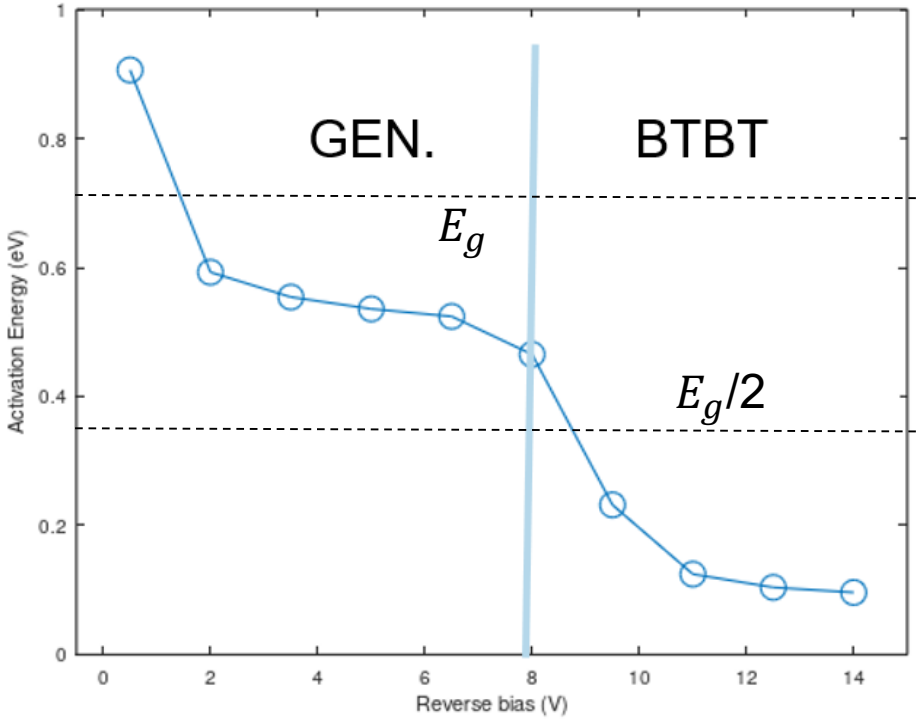
$$I - I_{diff} = I_{gen} + I_{BTBT}$$

Diode Guard Ring at ground





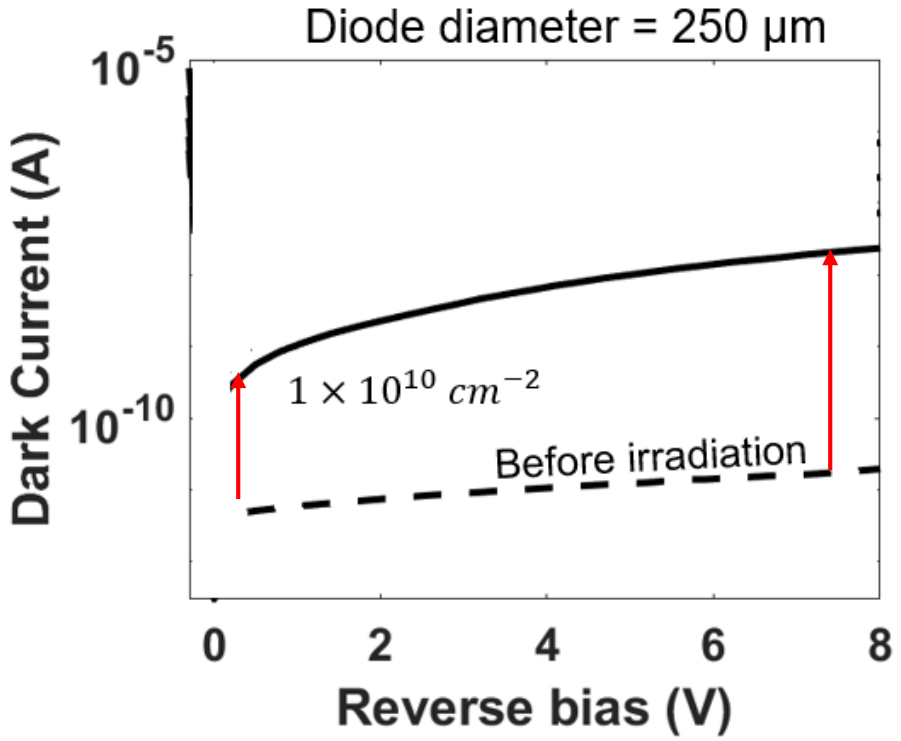
Activation Energy

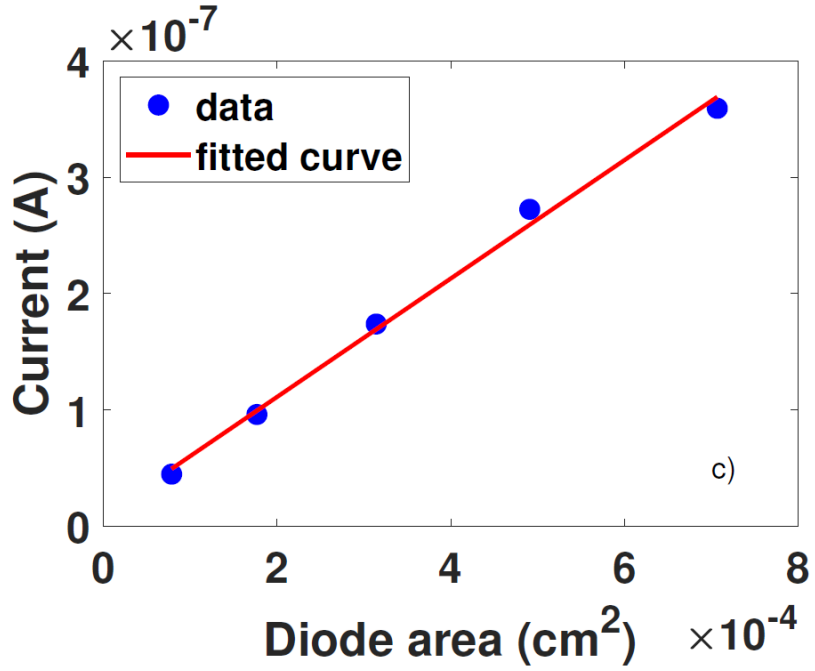


- The diffusion current has perimeter and bulk contribution
- The generation current has mainly peripheric contribution

What about after proton irradiation?

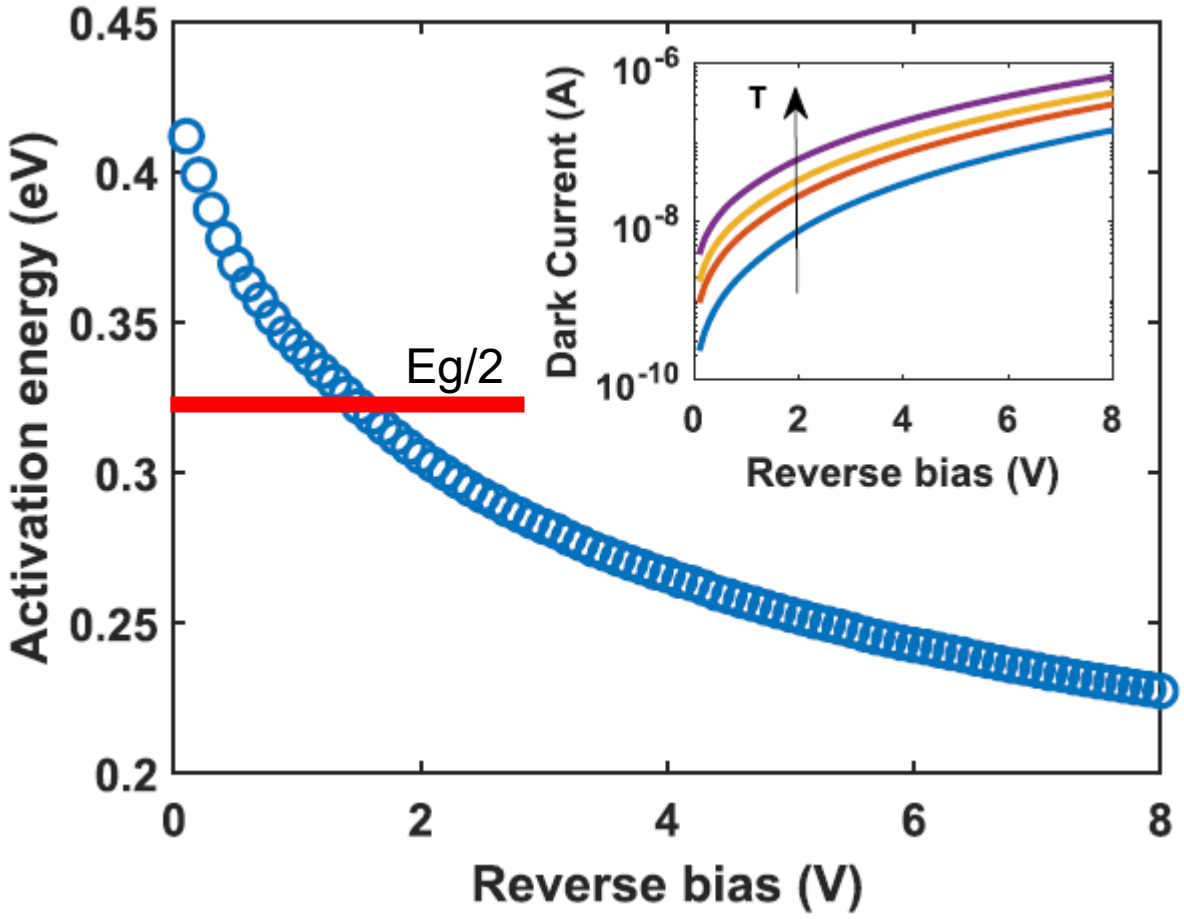
Radiation-Induced Dark Current





- Current **increase** and higher **bias dependence**
- Reverse current proportional to **diode surface**

Post irradiation : activation energy

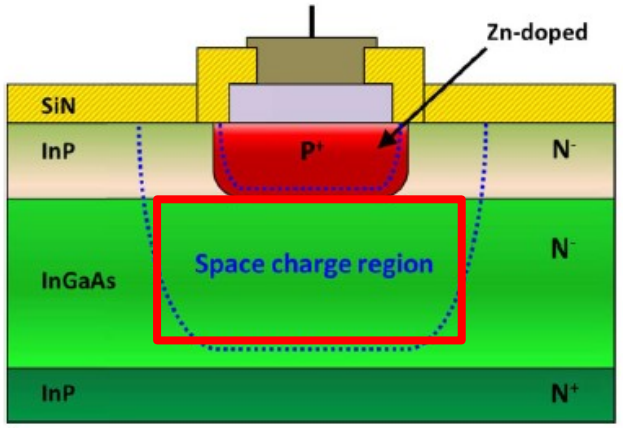


Before Irradiation : Diffusion + Generation

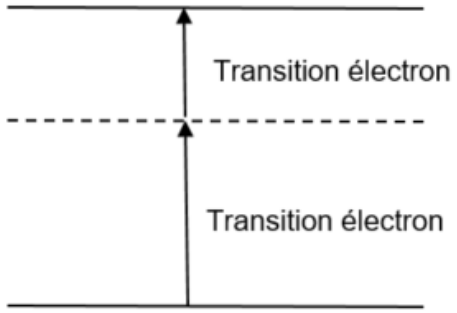
After Irradiation : Generation

Electric Field Mechanisms?

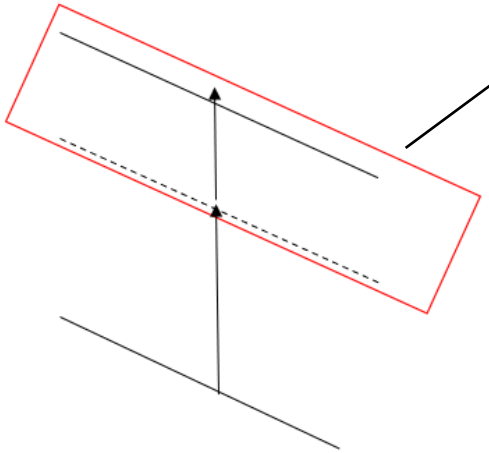
Field Enhancement Mechanisms

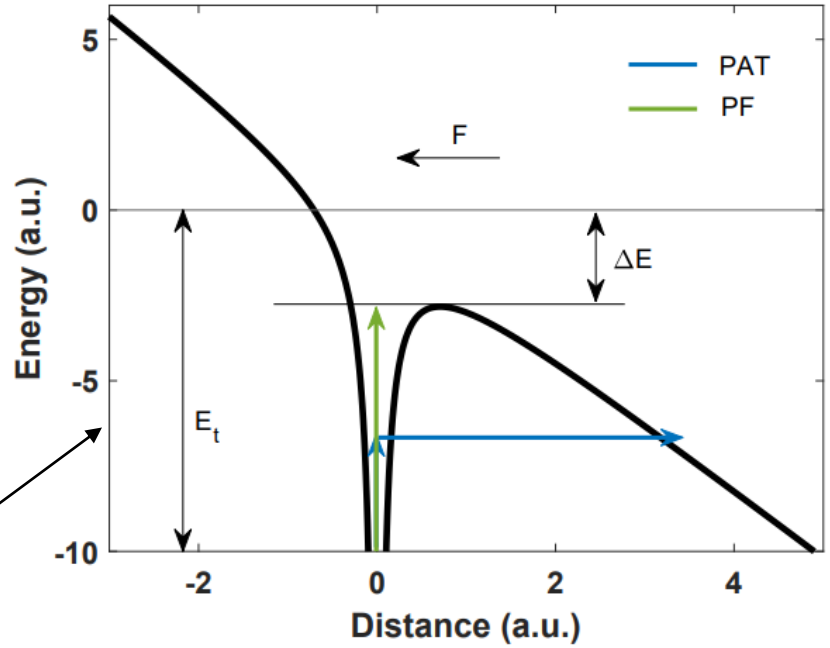


Cas : $F = 0$



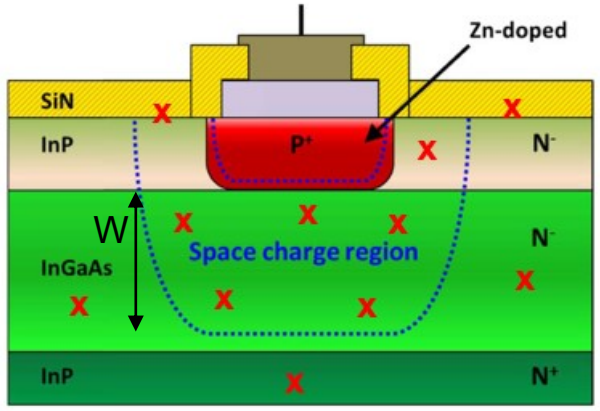
Cas : $F \neq 0$





Field Enhanced Mechanisms:

- Poole-Frenkel
- Phonon-Assisted Tunneling



W : Depletion Region Width

$$\Delta J(V) = J_G = \int_W G\, dx$$

$$G = G_0 \times \boldsymbol{\Gamma}(F)$$

$$\frac{d\Delta J}{dW} \propto \boldsymbol{\Gamma}(F_{max})$$

$$J_G = G_0 \int_W \boldsymbol{\Gamma}(F) dx$$

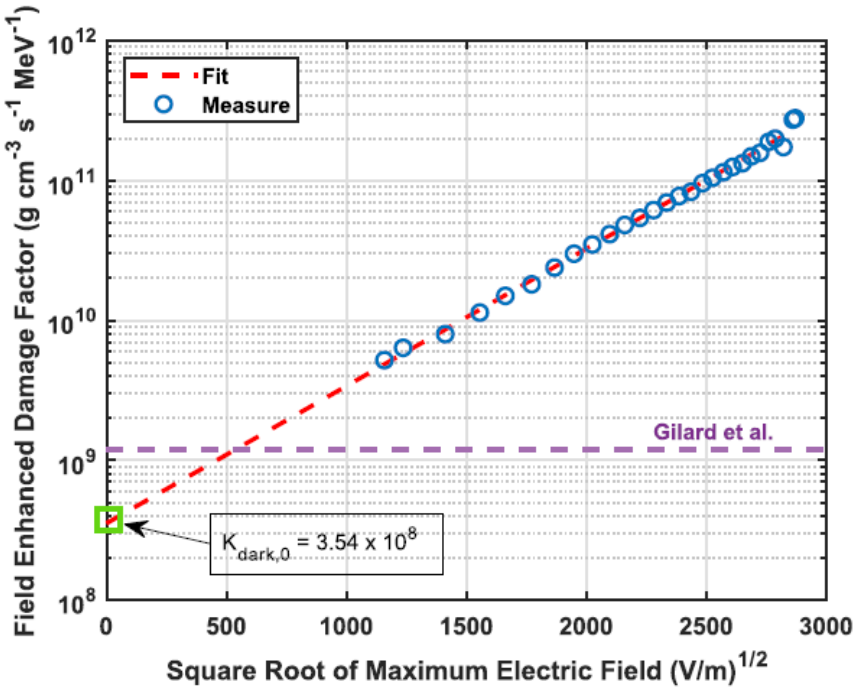
G : generation rate $\left[\frac{\#e/h}{(time)\times(volume)}\right]$

$\boldsymbol{\Gamma}$ **: Field Enhancement Factor**

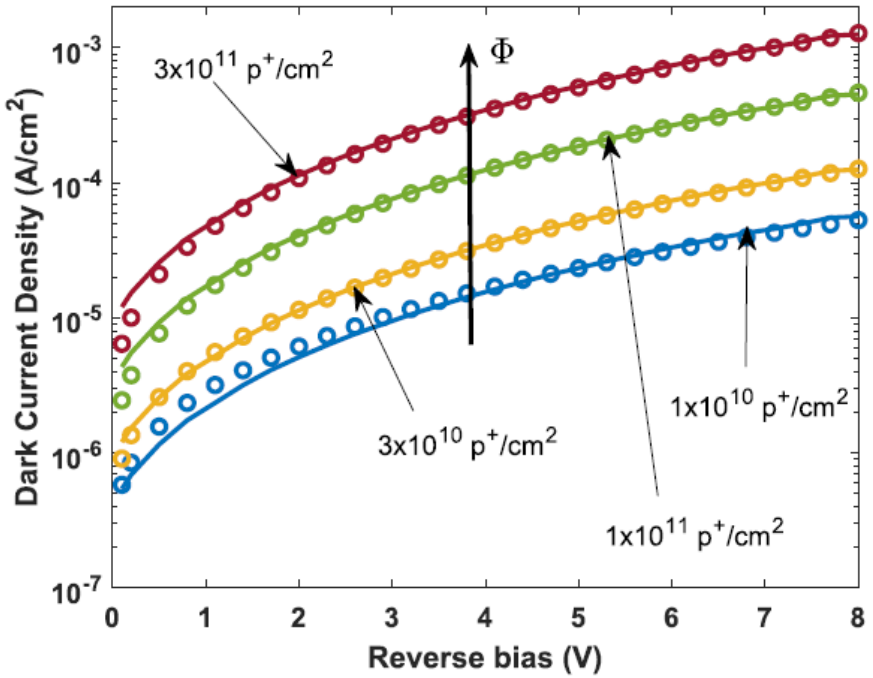
F_{max}: Maximum Electric Field

Results

Field Enhancement Factor



Dark Current Model Fit



$$F_{max} = \frac{q}{\epsilon} \times N \times W(N, V)$$

The electric field has to be reduced!

Fitted Low Field Dark Current Generation Lifetime

Fluence (cm^{-2})	Generation Lifetime (µs)
1×10^{10}	91
3×10^{10}	36
1×10^{11}	11
3×10^{10}	3.71

*M. **Benfante** et al., "Electric Field-Enhanced Generation Current in Proton Irradiated InGaAs Photodiodes," in IEEE Transactions on Nuclear Science, vol. 70, no. 4, pp. 523-531, April 2023, doi: 10.1109/TNS.2023.3244416.*

Conclusion

- Modeling of dark current **before irradiation**
  - Extraction of **minority carrier diffusion length**
  - Extraction of **generation current** and its activation energy
- Modeling of dark current **after irradiation**
  - Extraction of **Damage Factor** (not shown)
  - Extraction of **Field Enhancement Factor**
  - Extraction of **Low Field Dark Current Generation Lifetime**

Ongoing works

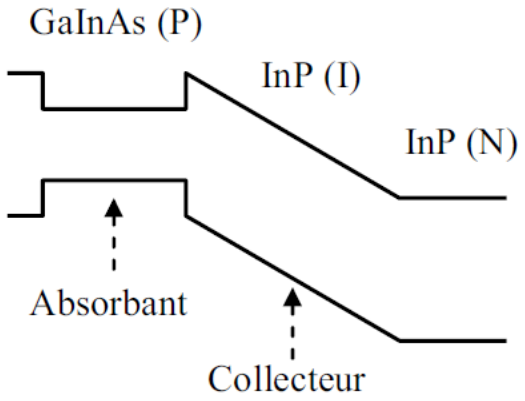
- **Dark Current Random Telegraph Signal** on Commercial InGaAs sensors and single diodes

- **Photoluminescence** measurement **for extraction of carrier lifetimes** in Shockley-Read-Hall processes

Perspectives

- Design of **Radiation-Hard InGaAs** sensors : **low electric field** in the **InGaAs layer**

Uni-Travelling Carrier Diodes (UTC)



Thank you !

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