Proton Radiation-induced Dark Current Increase in InGaAs Photodiodes

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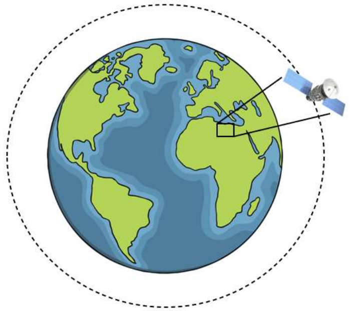
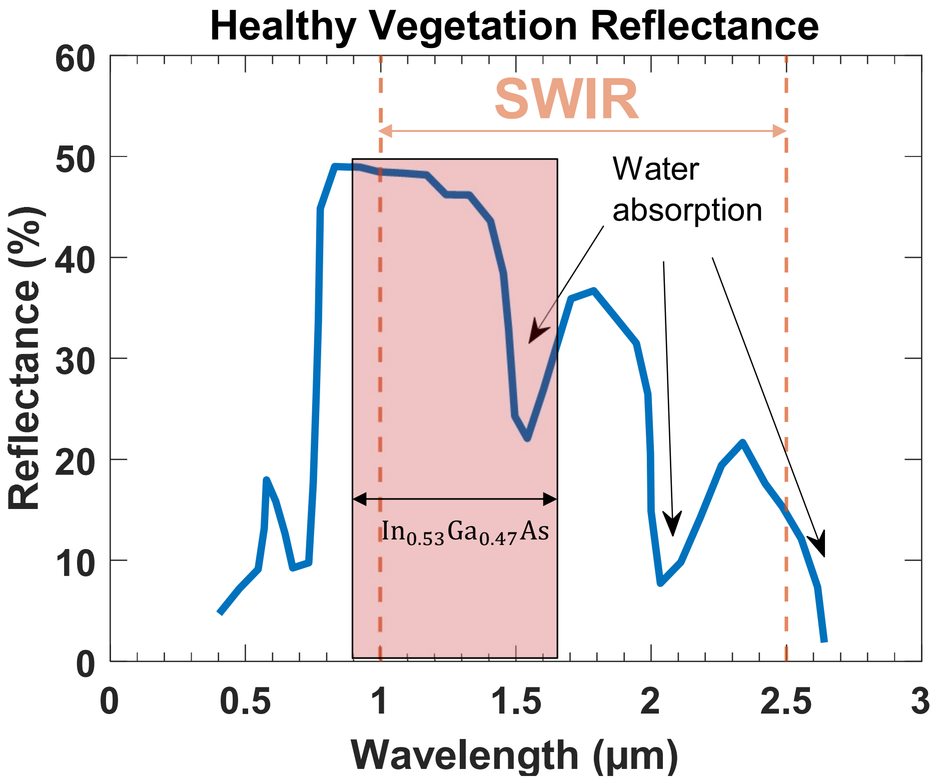
29/11/2023

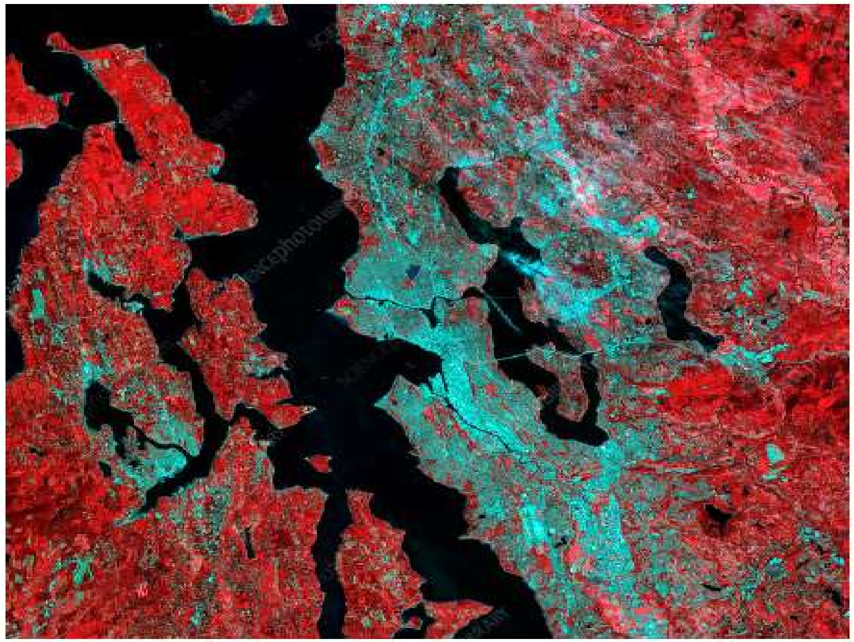
Use of InGaAs detectors in space : an illustration



- The $In_{0.53}Ga_{0.47}As$ **band gap** is **0.74 eV** at 300 K → **Cutoff wavelength** of **1.67 µm**

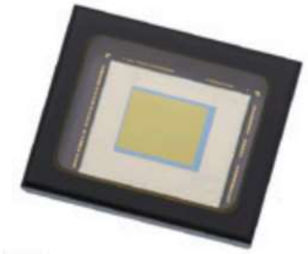


False color SWIR image of vegetation

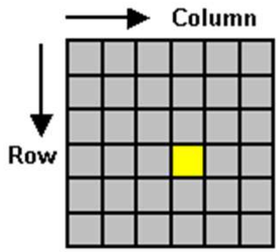


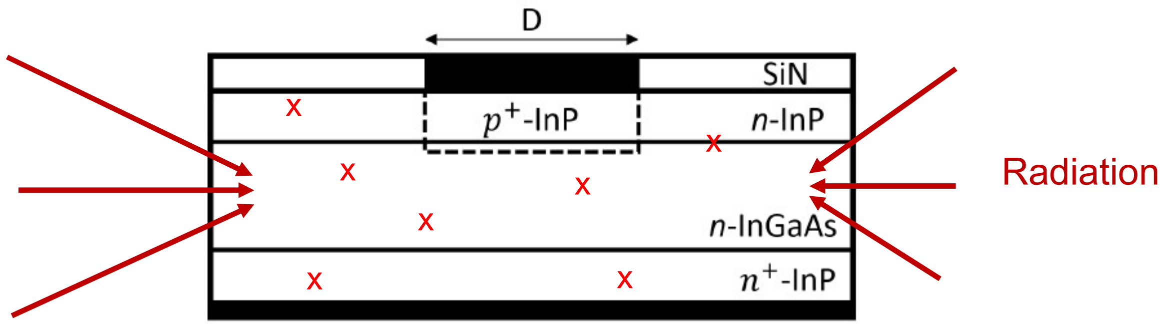
SWIR : Short Wavelength InfraRed

Effects of space radiation on InGaAs photodetectors



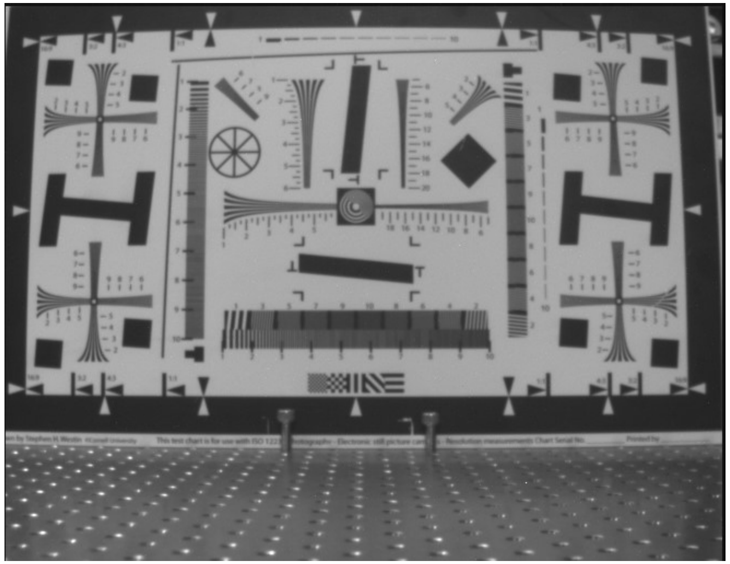
Example of InGaAs photodetector pixel array





Photodiode cross section

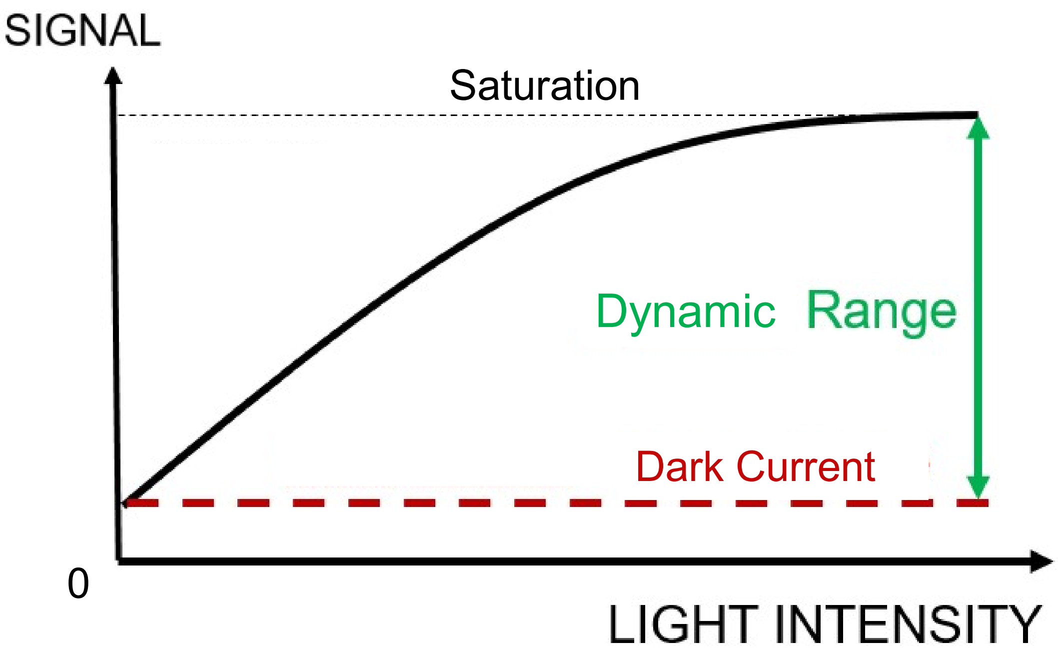
Pristine



Proton-irradiated

Why dark current?

- Why the study of dark current is important?



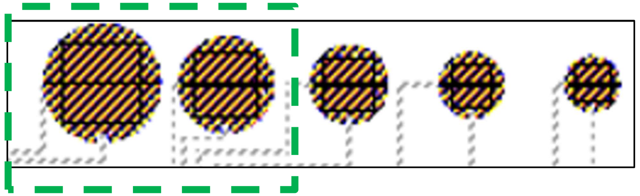
→

Lower the dark current,

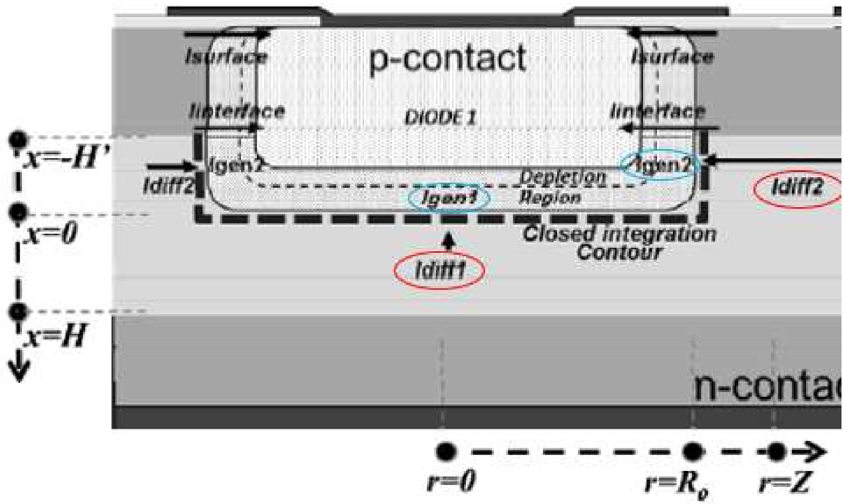
- **higher** the dynamic range (**higher** signal/noise ratio)

Analysis pre-irradiation

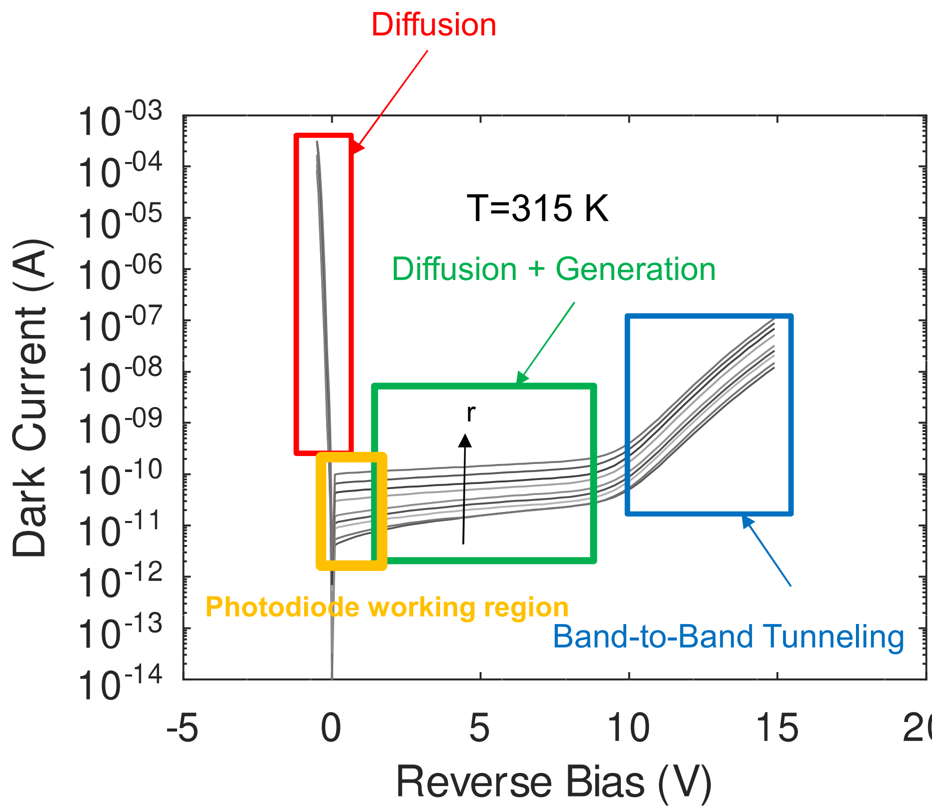
Test cell top view



Cross Section



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

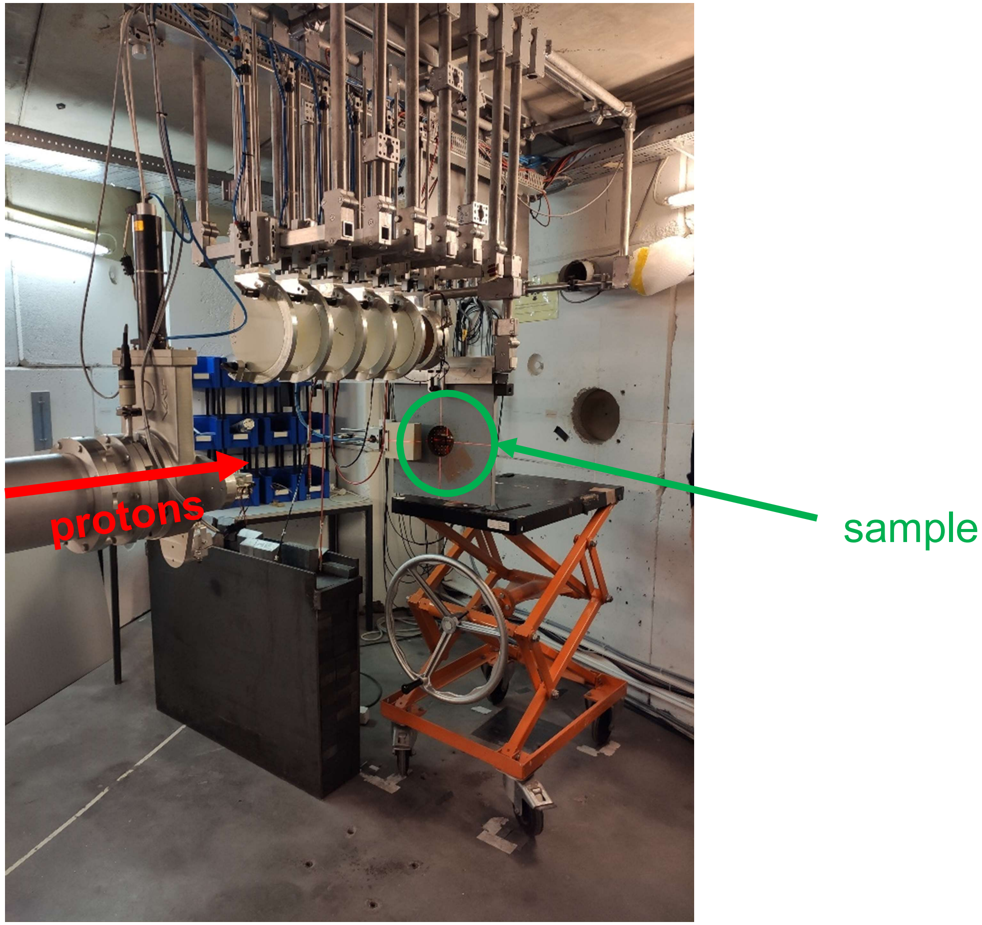


First proton irradiation campaign

Irradiation steps

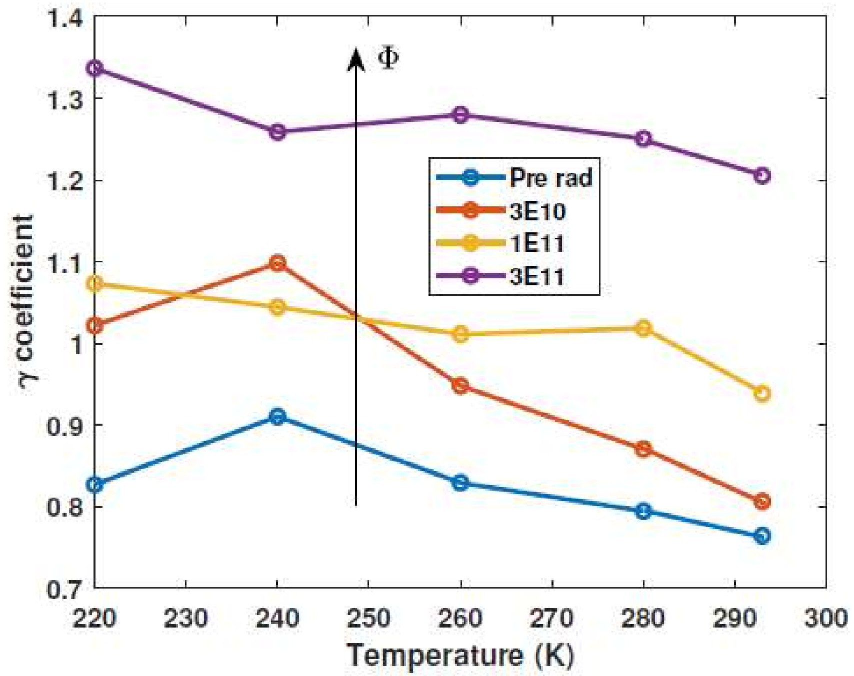
Step	Cumulated fluence (cm^{-2})
1	1×10^{10}
2	3×10^{10}
3	1×10^{11}
4	3×10^{11}

Proton kinetic energy : **49,7 MeV**



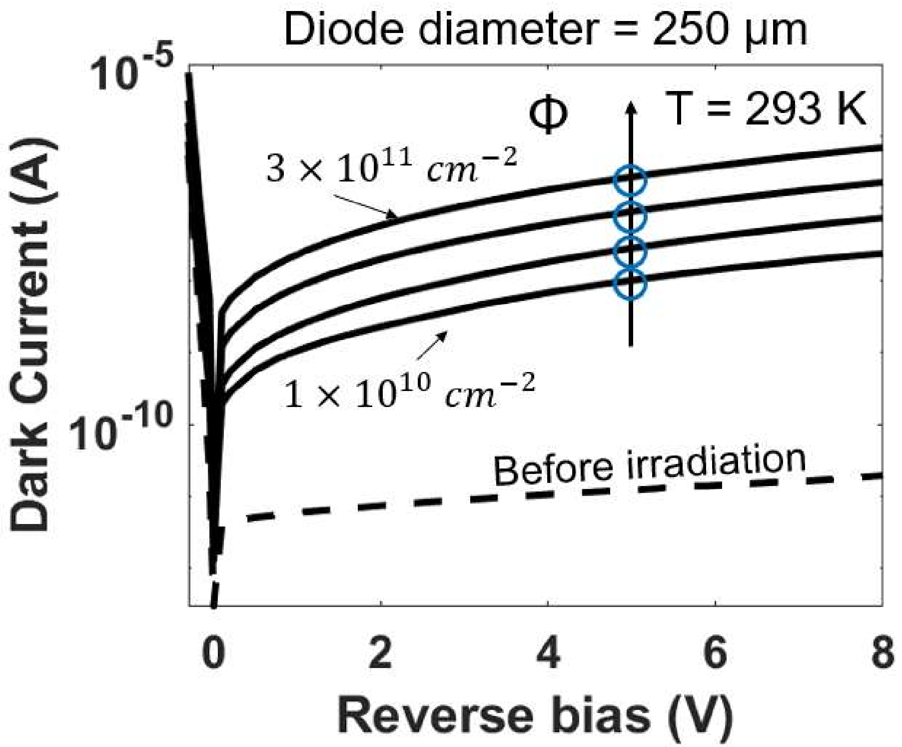
Impact on photoluminescence

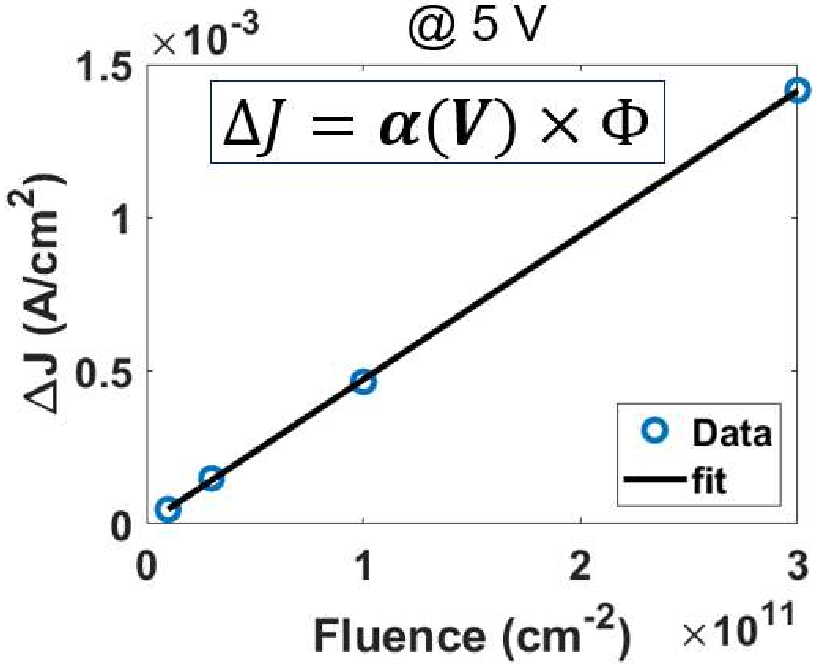
$$\text{P.L.} \propto P^{\gamma} \qquad \begin{array}{ll} \gamma = 1, & \text{Radiatif, forte injection} \\ \gamma = 2, & \text{Non-radiatif, forte injection} \\ \gamma = 2/3, & \text{Auger, forte injection} \end{array}$$



Increase of **γ** with fluence towards 2
→ Creation of non-radiative recombination centers

49,7 MeV proton radiation effects





- Dark current **increases** with fluence (# of protons)
- Dark current after irradiation depends **stronger** on bias
- Dark current **proportional** to pn junction area

Model of dark current increase?

α : Current-Related Damage Rate

Literature modeling of dark current increase

1) $K_p \equiv \Delta J_d / \Phi.$ [3]

Single value if dark current increase proportional to area and fluence ✓

2) $K_{dark} \equiv \Delta G / D_d$ ⟶ $\Delta J_d = qWD_dK_{dark}$ [8]

$$\begin{cases} \Delta J_d = qW\Delta G \\ D_d = \Phi \times NIEL \end{cases}$$

(Non-Ionizing Energy Loss)

?

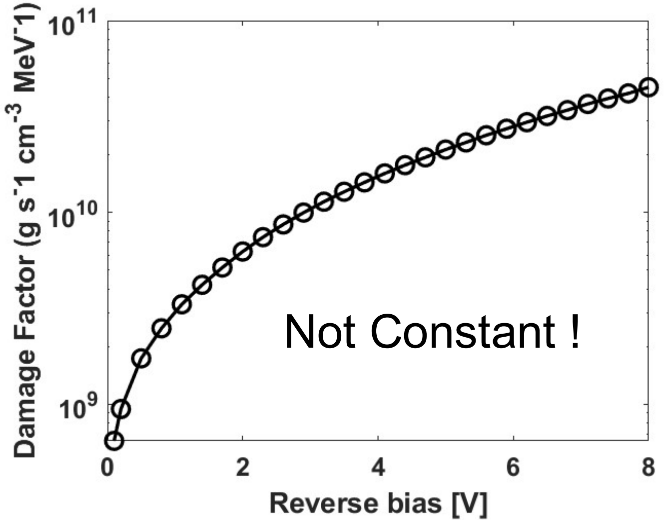
Single value if same as 1 and proportional to NIEL and W

[3] C. J. Dale, P. W. Marshall, E. A. Burke, G. P. Summers, and G. E. Bender, "The generation lifetime damage factor and its variance in silicon," *IEEE Trans. Nucl. Sci.*, vol. 36, pp. 1872–1881, Dec. 1989.

[8] J. R. Srour and D. H. Lo, "Universal damage factor for radiation-induced dark current in silicon devices," *IEEE Trans. Nucl. Sci.*, vol. 47, no. 6, pp. 2451–2459, Dec. 2000.

Model of dark current increase

$$K_{dark} = \frac{\Delta J}{qW(V)NIEL \times \Phi}$$

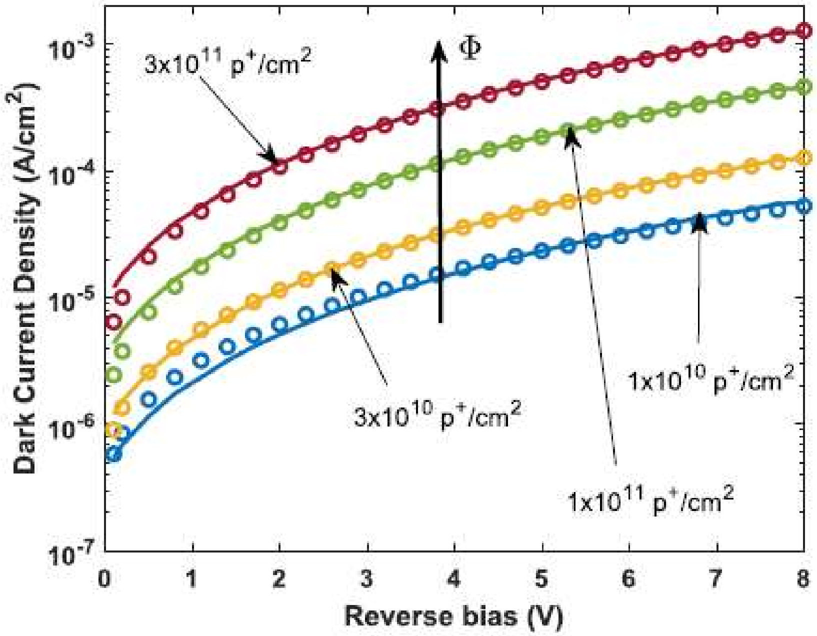


$$\Delta J(V) = [qK_{dark}W(V)NIEL] \times \Phi$$

$$\Delta J = [q \times NIEL \times W \times K_{\mathrm{dark},0} < \Gamma^{GR} >] \times \Delta\Phi$$

$$\frac{1}{qD_d}\frac{\mathrm{d}(\Delta J)}{\mathrm{d}W} = K_{\mathrm{dark},0}\Gamma^{\mathrm{GR}}(F_{\max})$$

Γ^{GR} : Generation Rate Field Enhancement Factor (GRFEF)

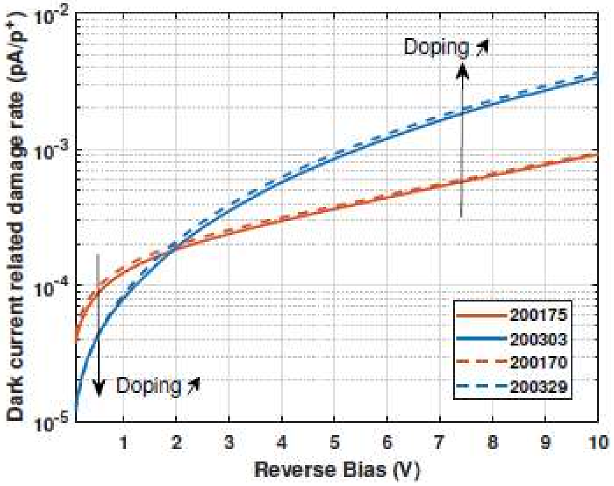


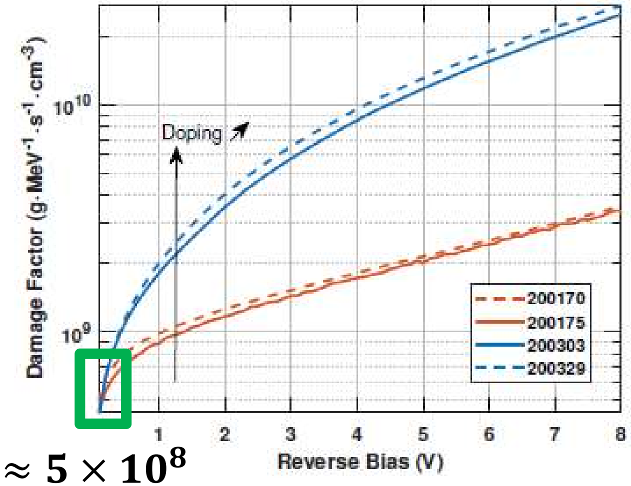
Generation current is field enhanced

Field effect: Effect of doping

- For InGaAs, there is no proportionality of dark current increase with W (because of **field enhancement effects**, confirmed by doping level impact)

$$\Delta J_d = q\boldsymbol{W}D_d K_{dark}$$





$\approx \mathbf{5 \times 10^8}$

- Damage factor K_{dark} depends on bias
- Normalization works well at low bias → Universal InGaAs damage factor?

	$K_{dark}(g \cdot s^{-1} \cdot MeV^{-1} \cdot cm^{-3})$	Comments
[20]	3.8×10^8	Low-field
[4]	1.2×10^9	Between 0 and 5 V
[24]	2.7×10^9	At 0.2 V

Electric field effect Not removed

[20] M. Benfante, J.-L. Reverchon, O. Gilard, S. Demiguel, C. Virmontois, C. Durnez, T. Dartois, and V. Goiffon, "Electric field-enhanced generation current in proton irradiated InGaAs photodiodes," *IEEE Transactions on Nuclear Science*, vol. 70, no. 4, pp. 523–531, Apr. 2023.

[4] O. Gilard et al., "Damage factor for radiation-induced dark current in InGaAs photodiodes," *IEEE Trans. Nucl. Sci.*, vol. 65, no. 3, pp. 884–895, Mar. 2018.

[24] G. T. Nelson et al., "In situ deep-level transient spectroscopy and dark current measurements of proton-irradiated InGaAs photodiodes," *IEEE Trans. Nucl. Sci.*, vol. 67, no. 9, pp. 2051–2061, Sep. 2020.

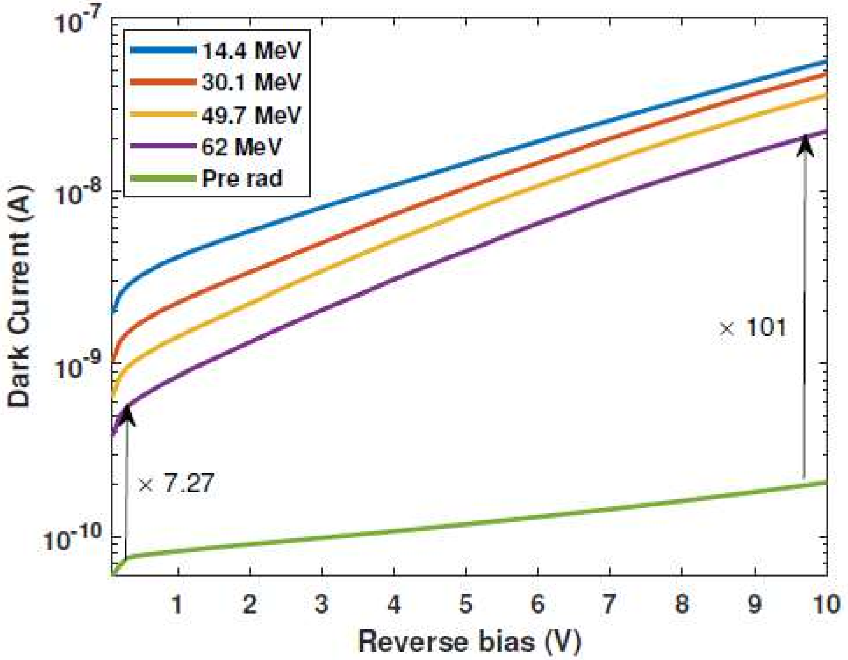
NIEL Scaling?

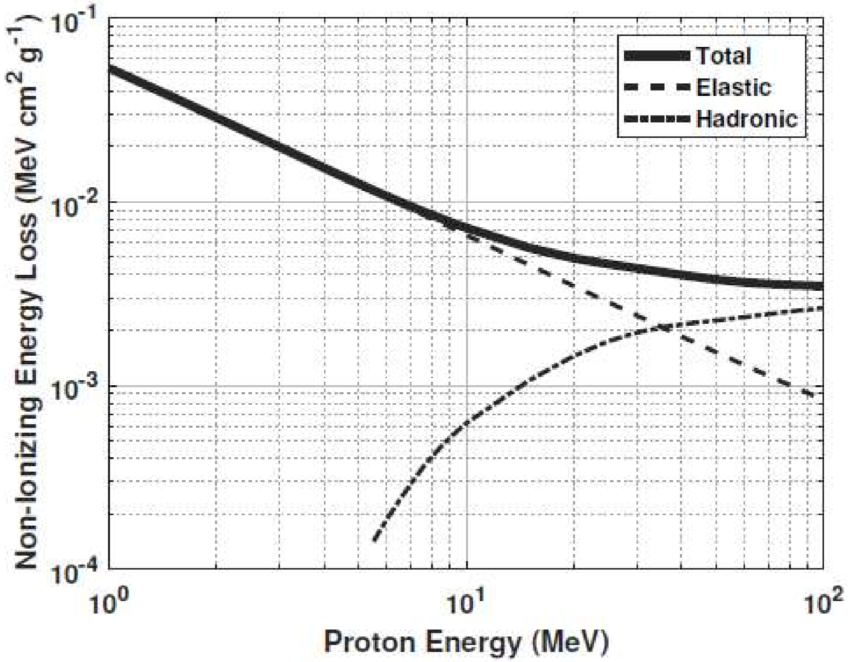
- What about proportionality with Non-Ionizing Energy Loss (NIEL)?

Irradiation steps

Step	Cumulated fluence (cm^{-2})	Proton Energy (MeV)
1	3.84×10^{10}	62
2	6.72×10^{10}	49.7
3	9.60×10^{10}	30.1
4	1.248×10^{11}	14.4

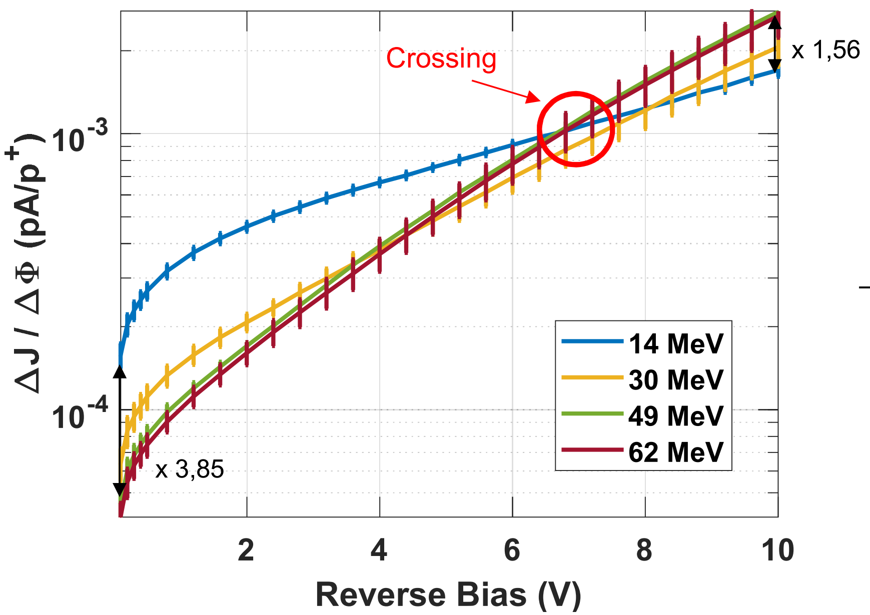
$$\Delta J_d = qWK_{dark}\Delta\Phi \times NIEL$$



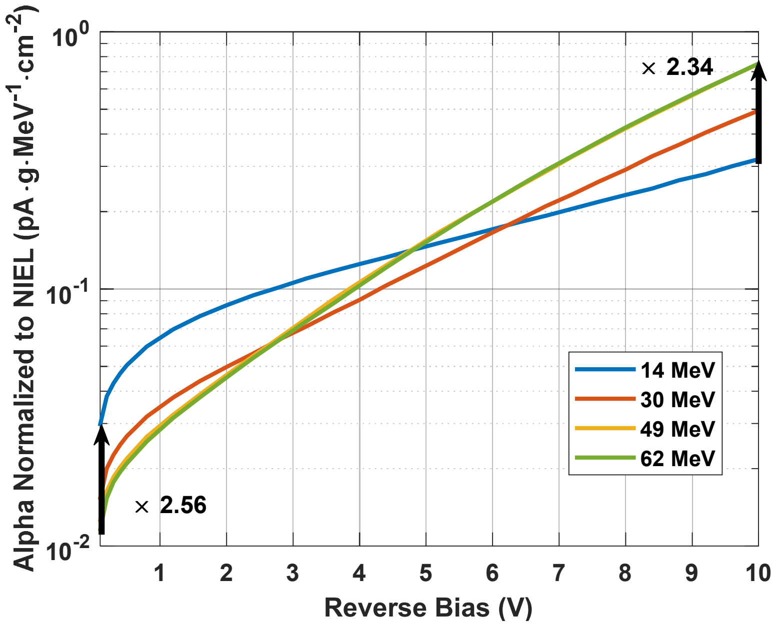


NIEL Scaling?

$$\Delta J_d = qWK_{dark}\Delta\Phi \times \boxed{NIEL}$$



$$\longrightarrow \frac{\Delta J_d}{\Delta\Phi \times NIEL}$$



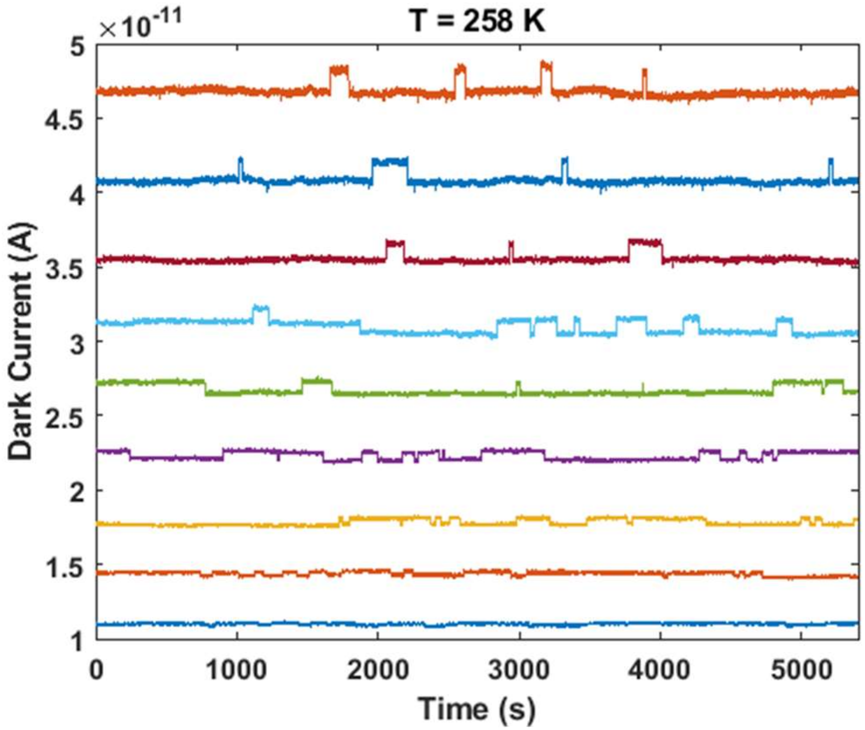
Lower proton energy has:

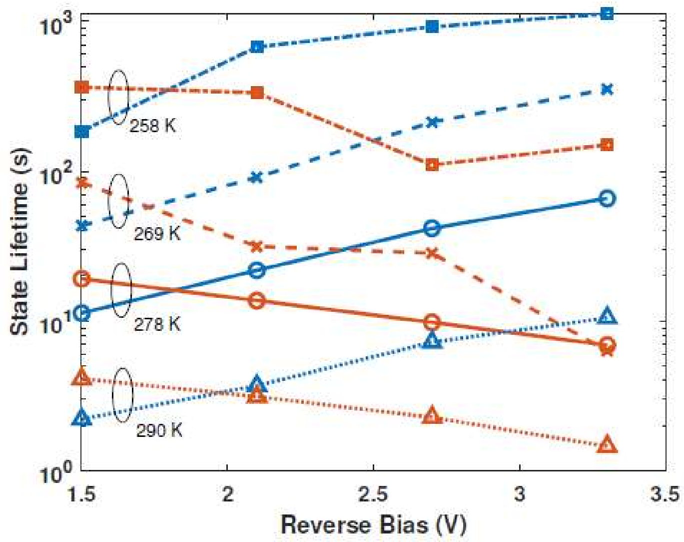
- **Higher** damage rate at **low bias**
- **Lower** damage rate at **high bias**

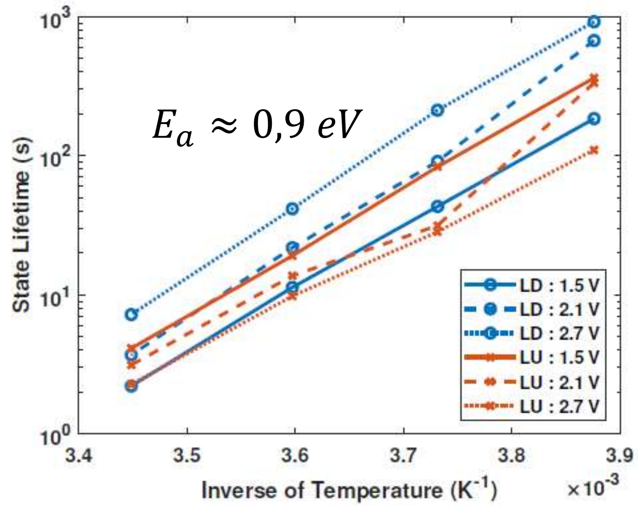
→ NIEL scaling depends on bias!

DC-RTS

- Irradiation induces appearance of dark current random telegraph signal (**DC-RTS**)







Conclusion

- InGaAs photodiodes strongly affected by proton irradiation
  - Introduction of generation-recombination centers
  - Increase of dark current
  - Appearance of Dark Current Random Telegraph Signal (DC-RTS)
    - Similar behavior with MOSFET → charging/decharging mechanisms?
- Modeling of dark current **after irradiation**
  - Generation current is field enhanced → reduce (increase) doping for high(low) bias operation
- **NIEL Scaling**
  - For low (high) bias operation reduce the low (high) proton energy spectrum
    - For imaging application (shielding would help)

Thank you !

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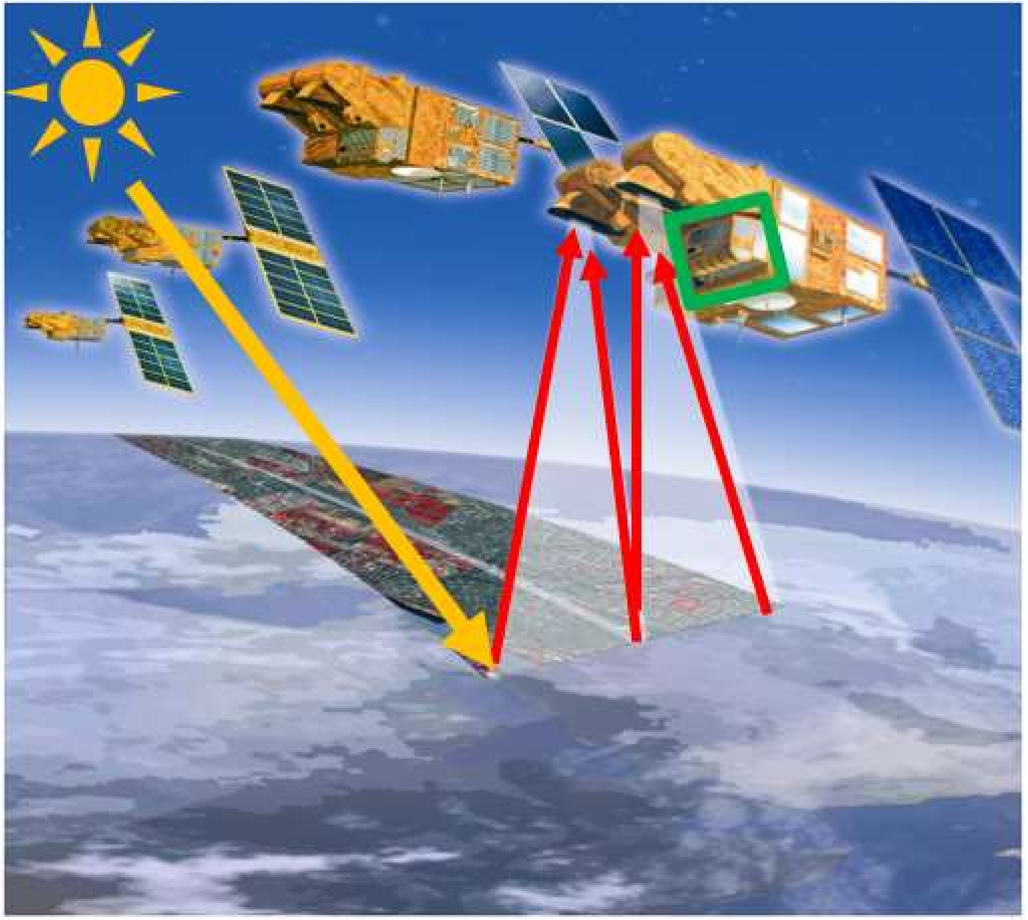
Electric Field-Enhanced Generation Current in Proton Irradiated InGaAs Photodiodes

Marco Benfante, Jean-Luc Reverchon, Olivier Gilard, Stéphane Demiguel, Cédric Virmontois, *Senior Member, IEEE*, Clémentine Durnez, Thierry Dartois, and Vincent Goiffon, ~~*Student*~~ *Member, IEEE*
Senior

Space application example

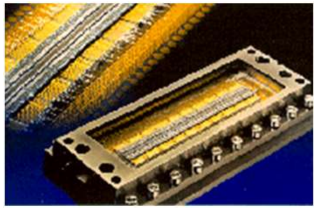


https://www.intelligence-airbusds.com/files/pmedia/public/r329_9_spotsatellitetechnicaldata_en_sept2010.pdf

Sunlight

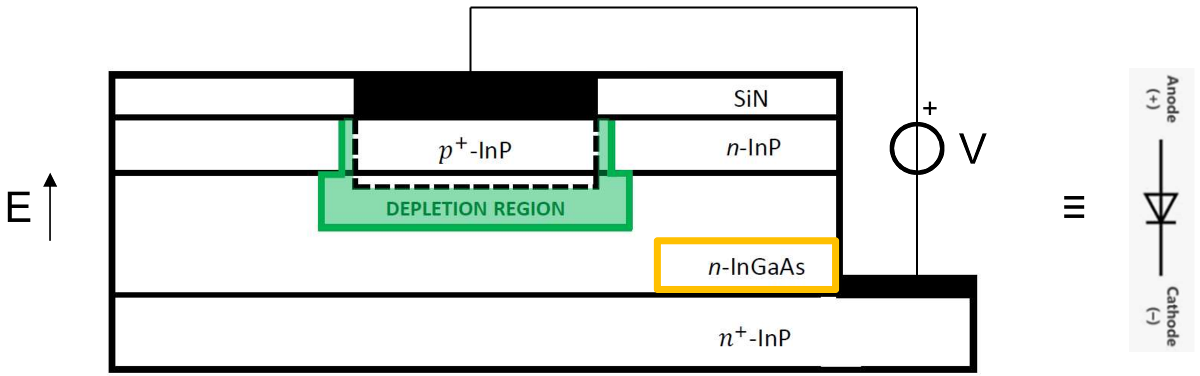
Reflected light

Partie dédié à la détection

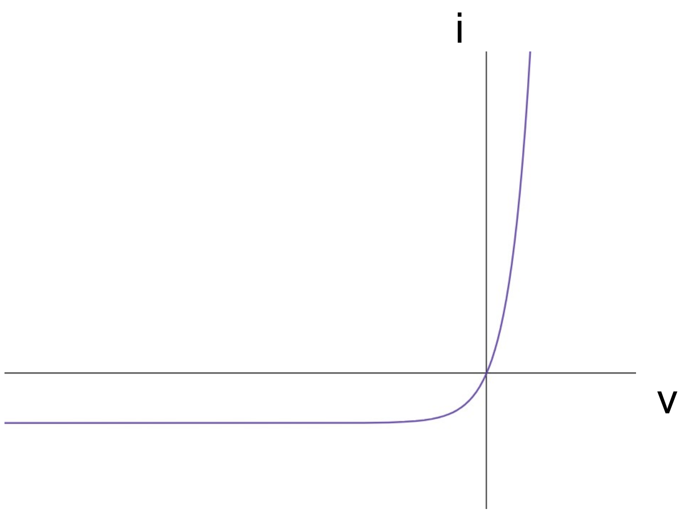


Working principle

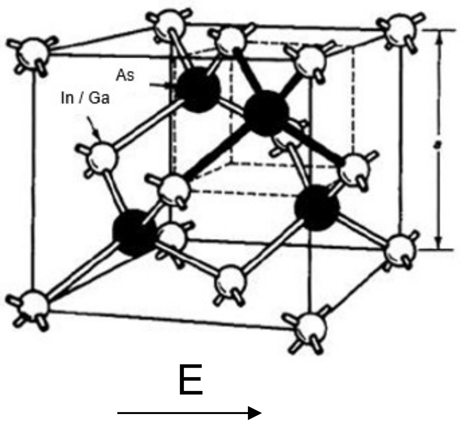
Photodiode ≡ p – n junction



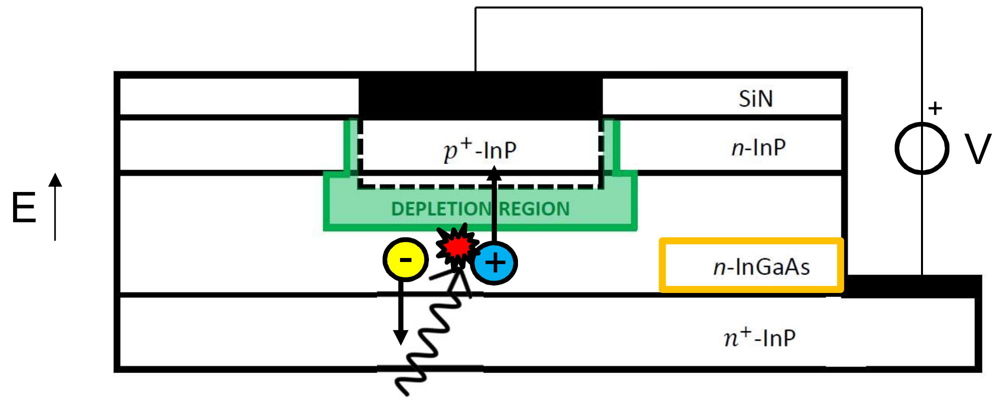
Dark current characteristics



Structure crystalline

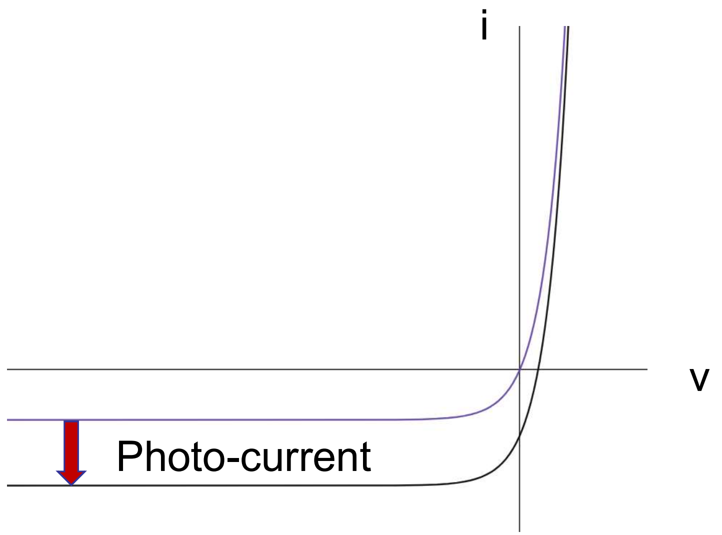


Photodiode

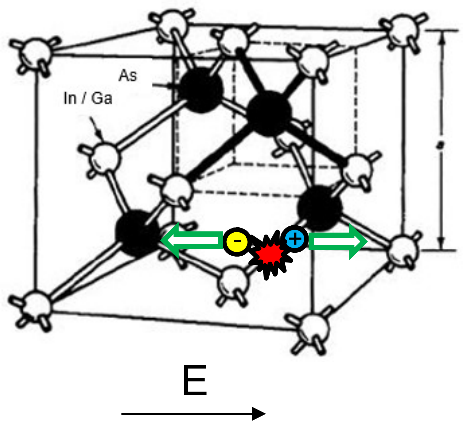


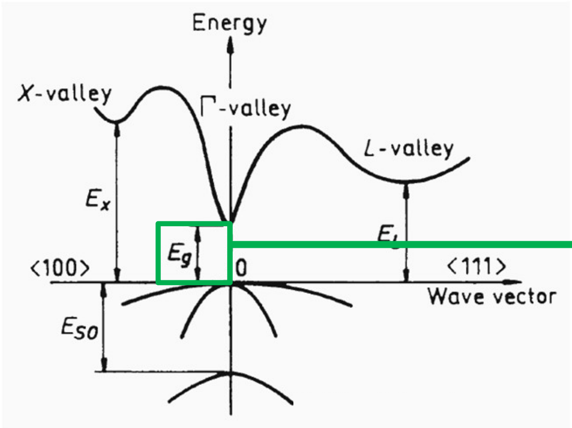
≡

Dark + photo current characteristics



Structure crystalline

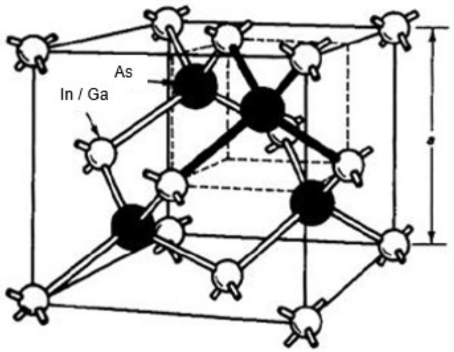


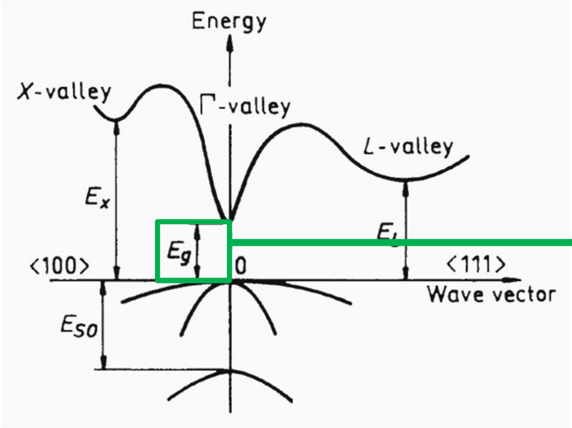


$\lambda_c = 1,67$ μm

SWIR
(Short Wavelength **InfraRed**)

Working spectral region





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SWIR
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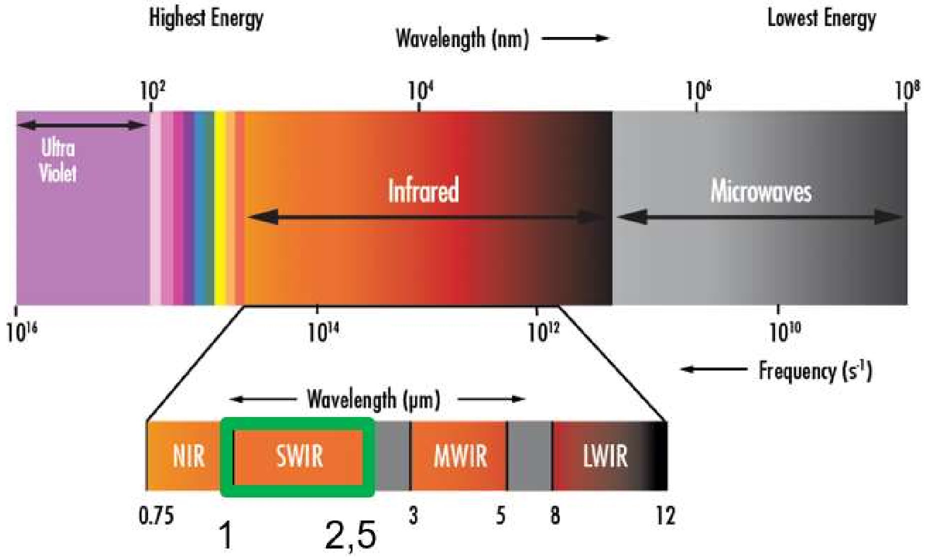
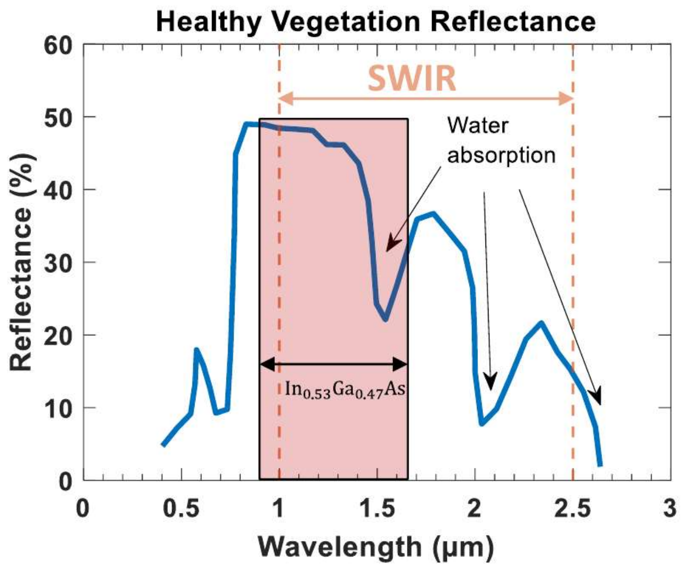
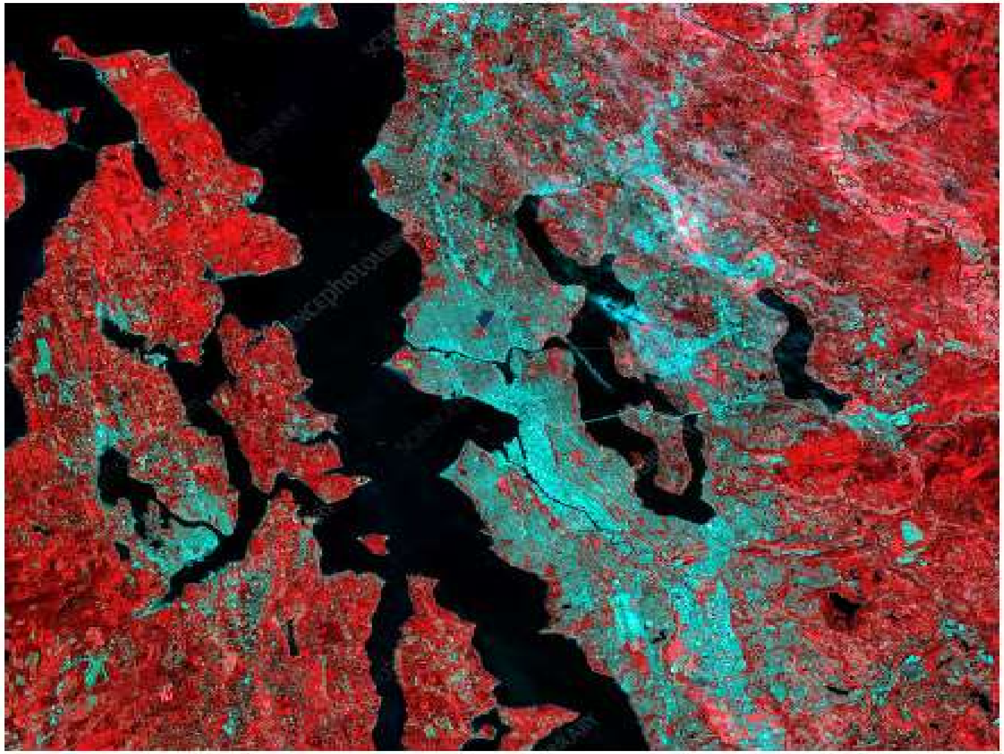




Remote Sensing

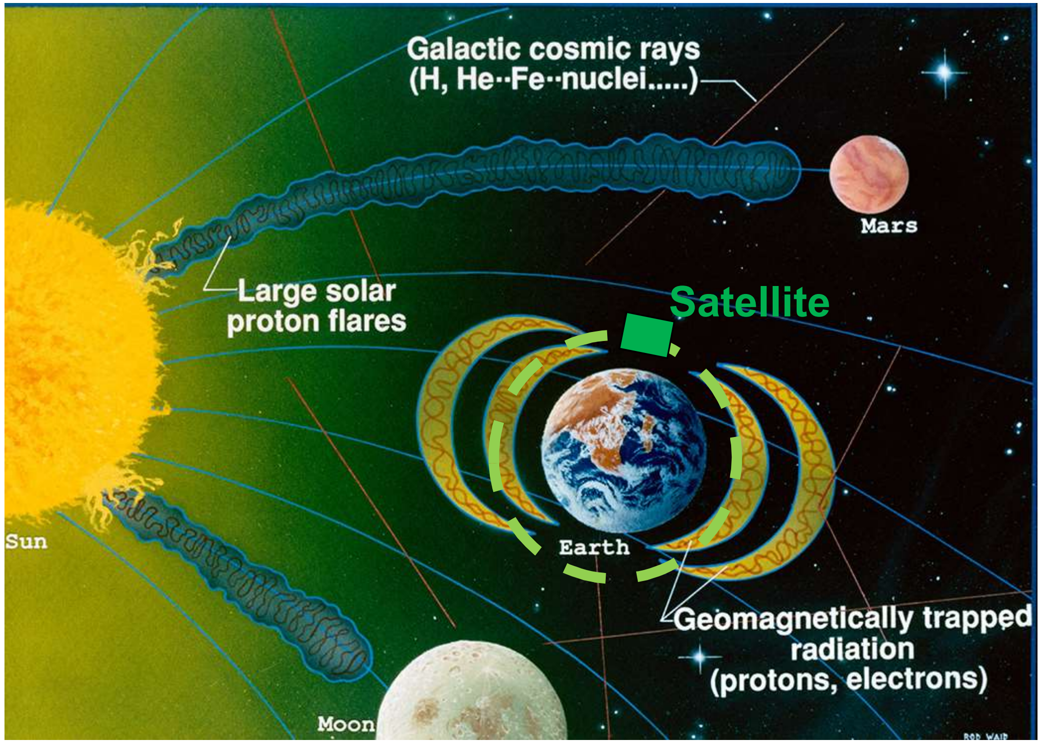


Remote Sensing
(e.g. **Earth Vegetation**)

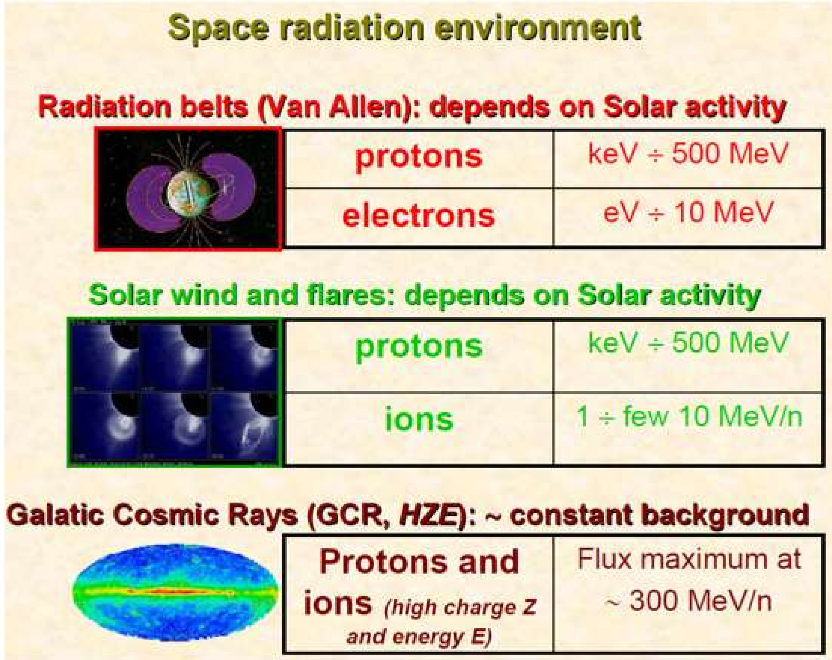
False color SWIR image

Red : Healthy
Blue : Unhealthy

Space radiation environment



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



Space radiation environment

Radiation belts (Van Allen): depends on Solar activity

protons	keV ÷ 500 MeV
electrons	eV ÷ 10 MeV

Solar wind and flares: depends on Solar activity

protons	keV ÷ 500 MeV
ions	1 ÷ few 10 MeV/n

Galatic Cosmic Rays (GCR, *HZE*): ~ constant background

Protons and ions *(high charge Z and energy E)*	Flux maximum at ~ 300 MeV/n

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

Space radiation **degrade** the InGaAs Photodiodes