X-ray radiation effect on colloidal quantum dot based short-wavelength infrared photodiode

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Introduction

Introduction

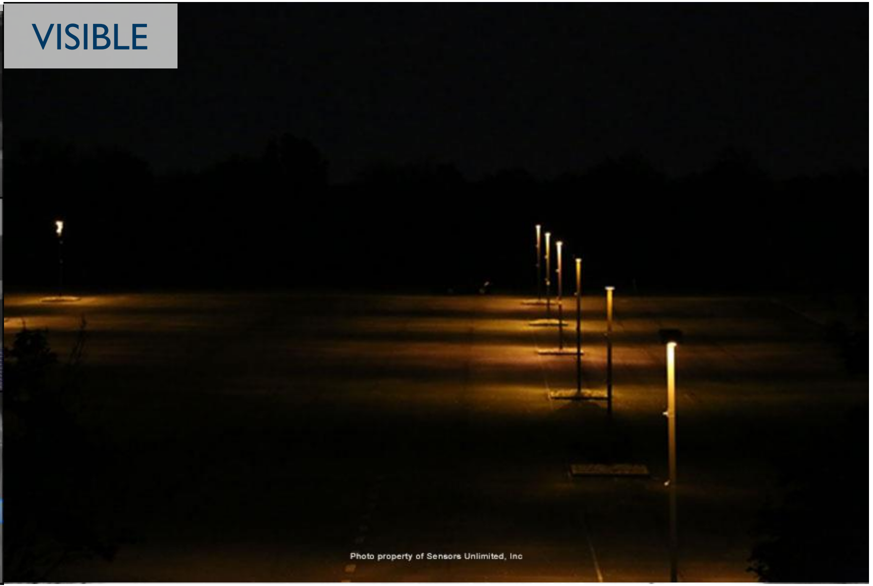
Necessity of short wavelength infrared (SWIR) detectors – Basic applications

Tesla's autonomous vehicle system
Using visible camera

https://www.tesla.com/autopilot

Risk of accidents at night and in bad weather

SWIR image sensor

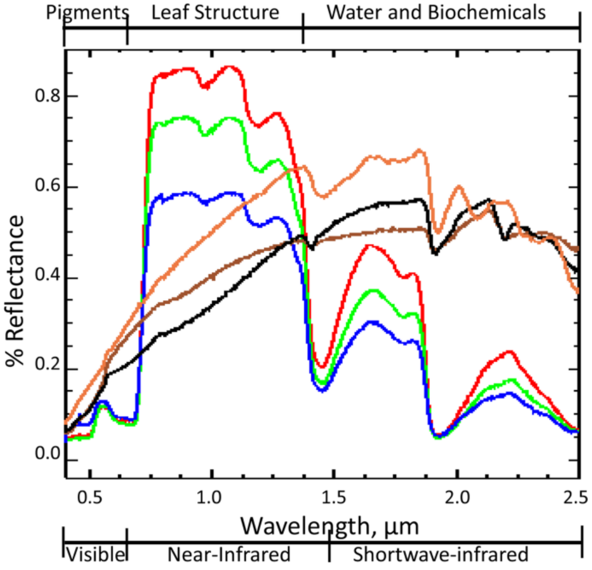


https://www.sensorsinc.com/gallery/images

Acquisition of invisible information

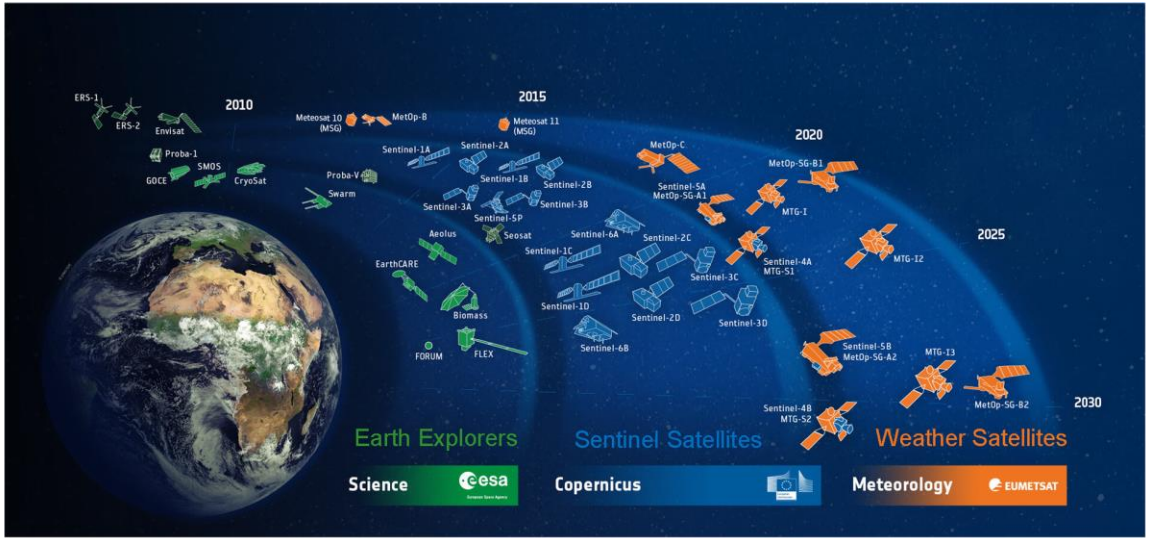
Introduction

Advantages for earth observation using SWIR imager



Low-reflectance in 1420 nm wavelength

Ecological Processes 10, 1, 2021

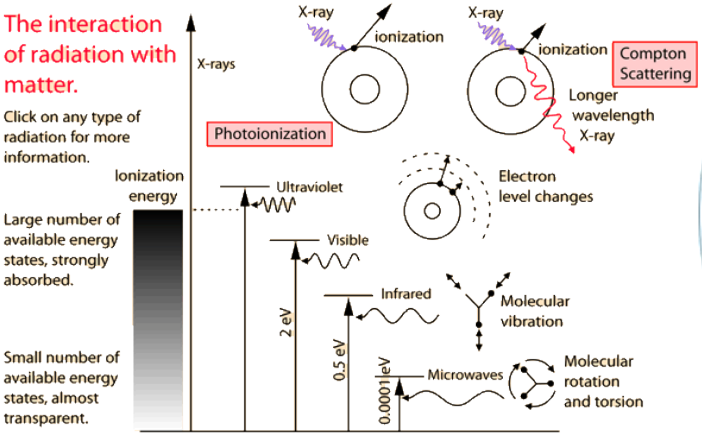


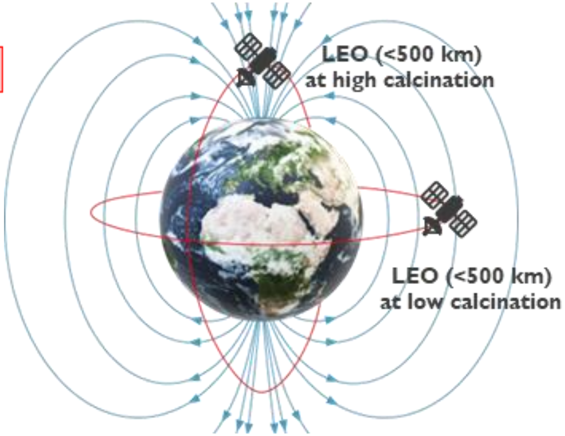
ESA's earth observation program from 2010 to 2023

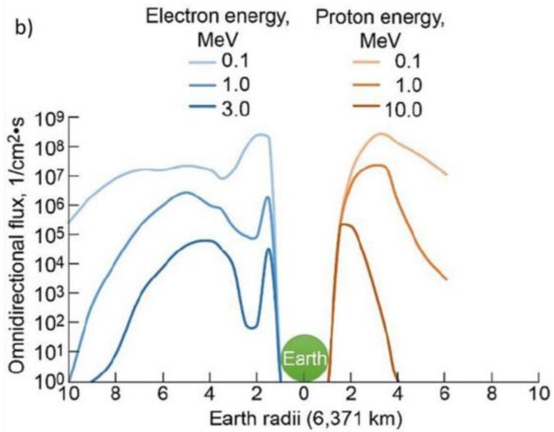
- We believe that the monolithic CQD-based SWIR imager is a promising candidate for a cost-competitive observation system for earth observation

Introduction

Radiation effects on near-Earth orbit





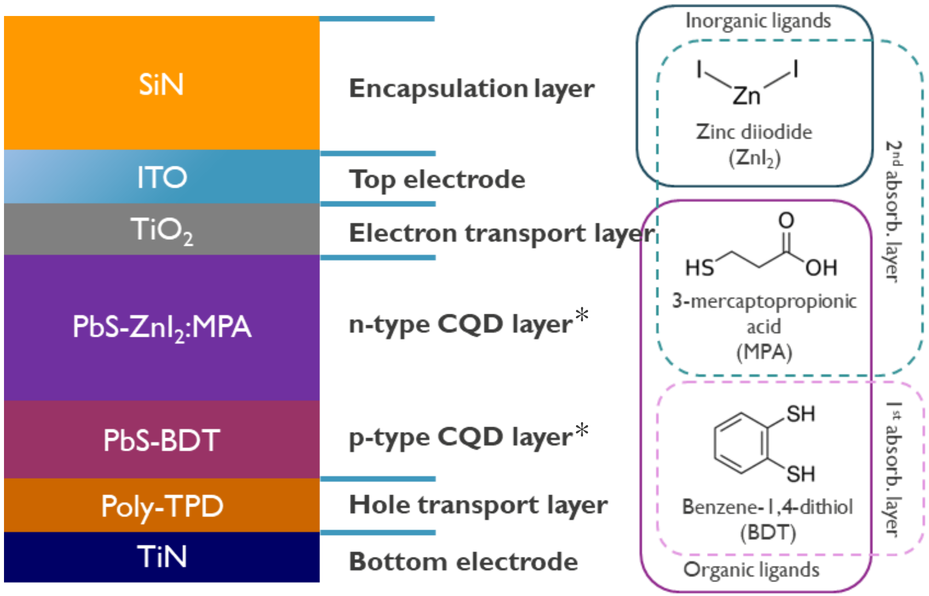


- X-rays have a high ionization energy, which is a suitable to test radiation effects.
- In near-Earth orbit (<500 km), the artificial satellites are exposed to 0.1-1 krad(Si)/year on low inclination and 1-10 krad(Si) on higher inclinations

Our approaches

Device structure (TFPD)

Key issues under X-ray irradiation



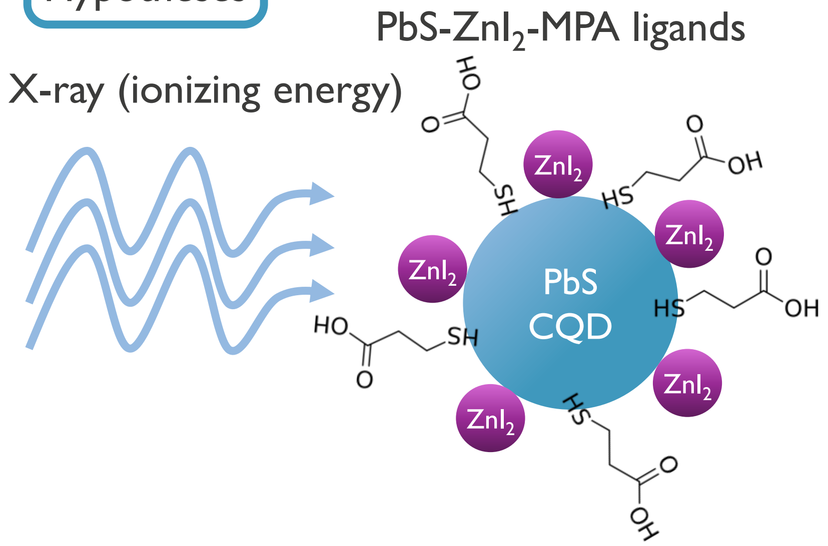
*CQDs are selected for 1420 nm detection

- Issue
  - How much is affected under X-ray (ionizing energy) radiation?
    - 220 krad(Si) is enough to understand the robustness of X-ray radiation in near-Earth space for 10 yrs.
  - Which layer is a dominant layer in determining device performance?
    - Interface between ETL and CQD
    - Interface between HTL and CQD
    - Interface between n-type and p-type CQDs

Hypotheses – Materials(I)

Investigation of influence under X-ray irradiation

Hypotheses

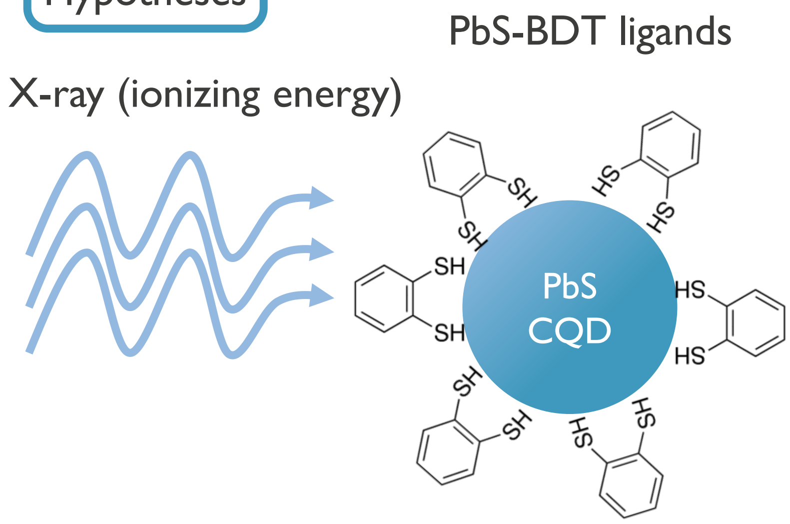


1. Ionizing radiation generates electron from PbS CQDs to ligands
   1. PbS CQD loses the electrons (loss electron)
   2. ZnI_2 becomes ZnI_3^-
2. Ionizing radiation generates electron from ligands
   1. ZnI_2 loses electrons and separates as ZnI^+ and the oxidized iodide
   2. Hydroxyl group in MPA loose electron and Hydrogen becomes free

Hypotheses – Materials(II)

Investigation of influence under X-ray irradiation

Hypotheses



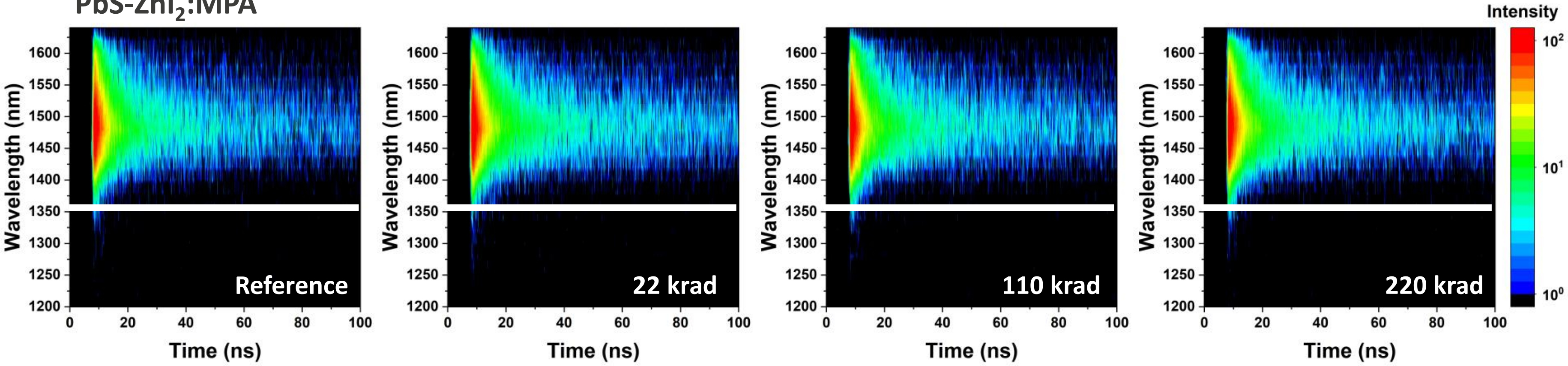
1. Ionizing radiation generates electron from ligands
   1. BDT loses electrons and separates as BDT^+
   2. And BDT will be delaminated from PbS CQD layer

Results - Materials characterization

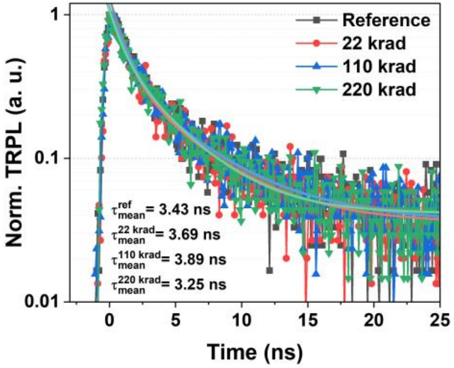
Materials characterisation - 1

Time-resolved photoluminescence (TRPL)

$PbS\text{-}ZnI_2$:MPA



Pump wavelength: 1460 nm

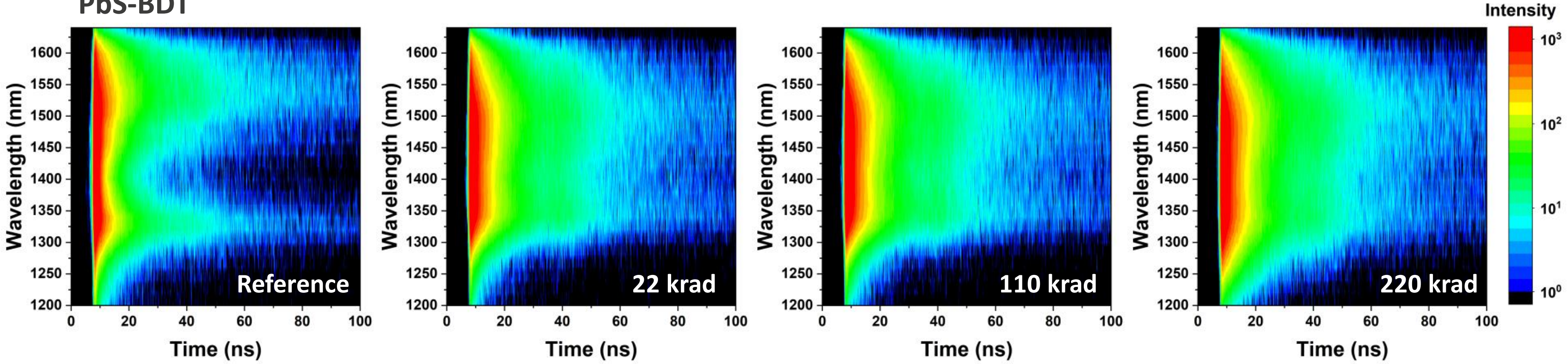


- Biexponential treatment to extract the mean carrier lifetime
  - $I_{PL}(t) = A_{\text{fast}} \exp(-t/\tau_{\text{fast}}) + A_{\text{slow}} \exp(-t/\tau_{\text{slow}})$
  - $\tau_{\text{mean}} = [A_{\text{fast}}\ \tau_{\text{fast}}^2/(A_{\text{fast}}\ \tau_{\text{fast}} + A_{\text{slow}}\ \tau_{\text{slow}})] + [A_{\text{slow}}\ \tau_{\text{slow}}^2/(A_{\text{fast}}\ \tau_{\text{fast}} + A_{\text{slow}}\ \tau_{\text{slow}})]$
  - $\tau_{\text{mean}}^{\text{ref}}$=3.43 ns, $\tau_{\text{mean}}^{22\ \text{krad}}$= 3.69 ns, $\tau_{\text{mean}}^{110\ \text{krad}}$= 3.89 ns, $\tau_{\text{mean}}^{220\ \text{krad}}$= 3.25 ns

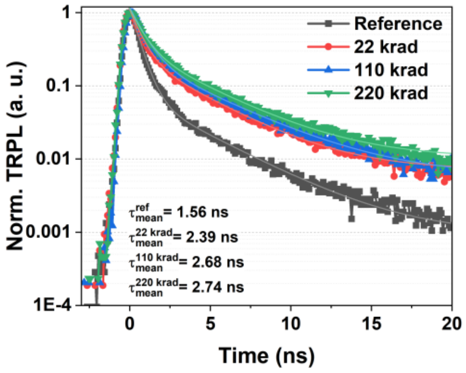
Materials characterisation - 1

Time-resolved photoluminescence (TRPL)

PbS-BDT



Pump wavelength: 1460 nm



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  - $\tau_{\text{mean}}^{\text{ref}}$=1.56 ns, $\tau_{\text{mean}}^{22\text{ krad}}$= 2.39 ns, $\tau_{\text{mean}}^{110\text{ krad}}$= 2.68 ns, $\tau_{\text{mean}}^{220\text{ krad}}$= 2.74 ns

Hypotheses – Materials(I)

Investigation of influence under X-ray irradiation

Hypotheses

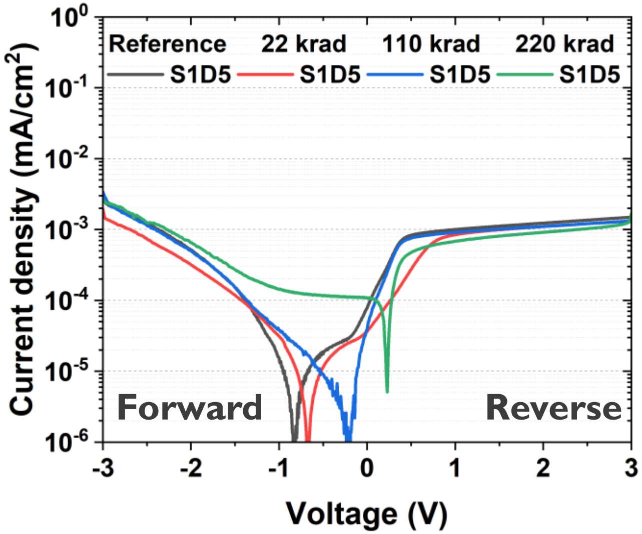
$PbS-ZnI_2$-MPA ligands

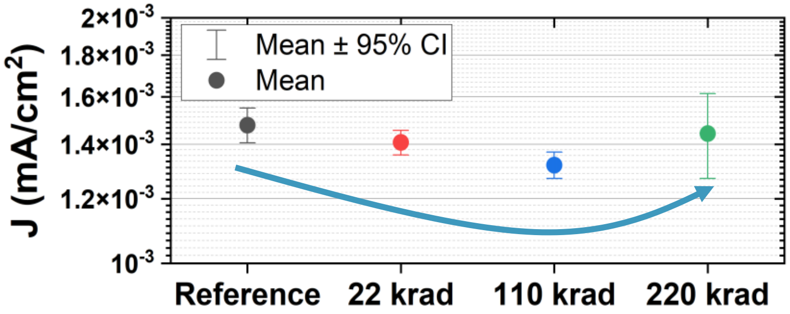
$PbS-ZnI_2$:MPA has a robustness under X-ray radiation

Results - Device characterization

J-V measurement

TFPD

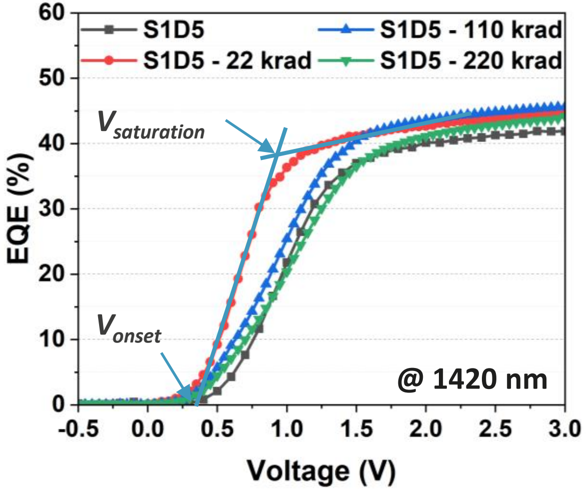


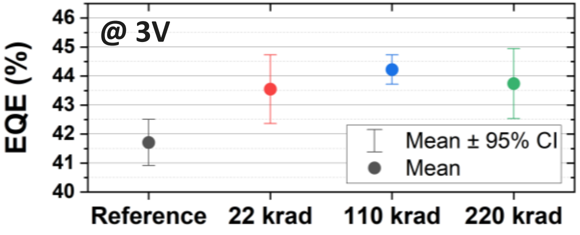


- According to the increase in X-ray radiation dose (Total ionizing dose, TID), the leakage current was decreased slightly until 110 krad, after that was recovered.

EQE measurement

EQE vs Voltage / EQE vs Wavelength



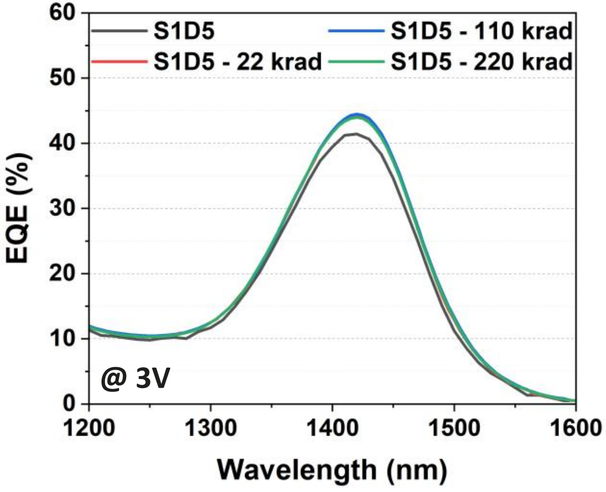


$V_{onset}^{Ref} = 0.522\ V$ $V_{sat}^{Ref} = 1.374\ V$

$V_{onset}^{22\ krad} = 0.399\ V$ $V_{sat}^{22\ krad} = 0.951\ V$

$V_{onset}^{110\ krad} = 0.416\ V$ $V_{sat}^{110\ krad} = 1.405\ V$

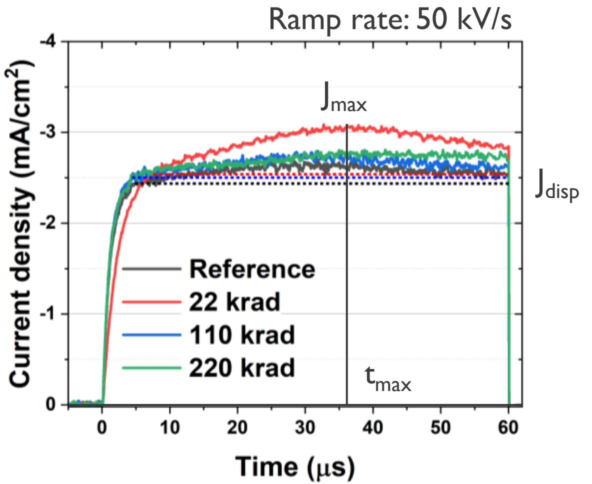
$V_{onset}^{220\ krad} = 0.382\ V$ $V_{sat}^{220\ krad} = 1.590\ V$

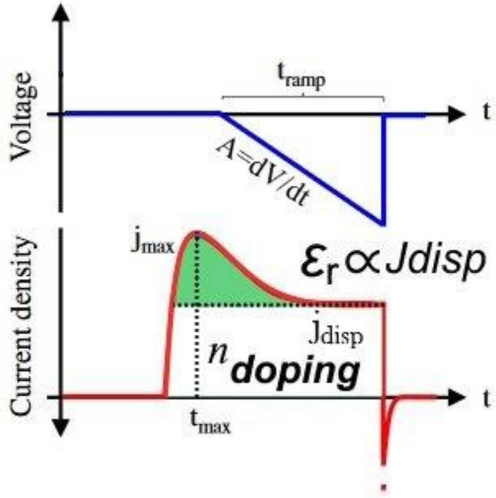


- In EQE vs Voltage graph, the initial X-ray dose (22 krad) helped to enhance of onset voltage.
  - thereafter, it tends to return to its initial performance. That is, performance decreased.
- In EQE vs Wavelength graph, X-ray radiation seemed to affect the enhancement of EQE performance

Data physics - 1

Dark Charge Extraction by Linearly Increasing Voltage (Dark-CELIV)





ramp rate — relative permittivity — thickness

$$j_{disp} = \frac{A\varepsilon_0\varepsilon_r}{d}$$

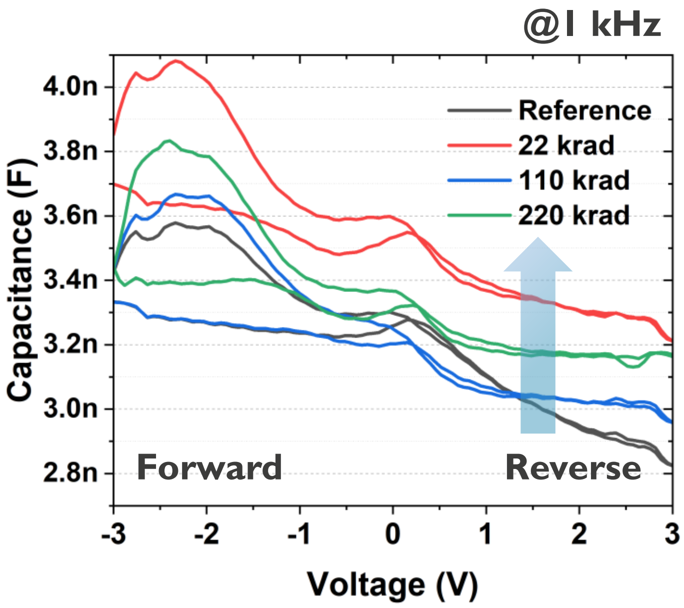
$$\mu = \frac{2d^2}{3At_{max}^2\left[1+0.36\frac{\Delta j}{j(0)}\right]} \quad \text{if } \Delta j \leqslant j(0). \qquad (1)$$

$$n_{doping} = \frac{1}{dq}\left(-\int_0^{t_{ramp}} j(t)dt - \frac{C_{geom}V(t_{ramp})}{S}\right)$$

	J_{disp} (mA/cm²)	J_{max} (mA/cm²)	t_{max} (μs)	μ (cm²/V*s)	n (1/cm³)
Reference	2.434	2.700	31.901	3.151e-5	2.068e+15
22 krad	2.545	3.086	32.704	2.895e-5	2.267e+15
110 krad	2.502	2.803	38.767	2.128e-5	2.136e+15
220 krad	2.502	2.808	50.324	1.261e-5	2.163e+15

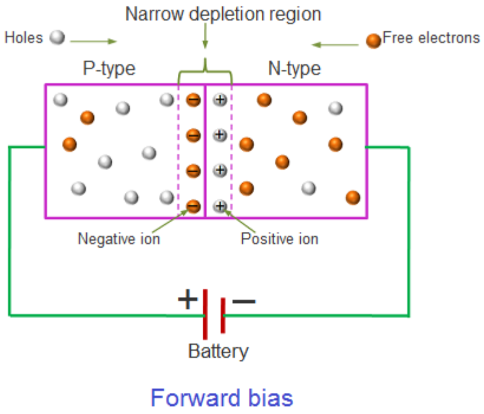
Device physics - 2

Capacitance – Voltage measurement



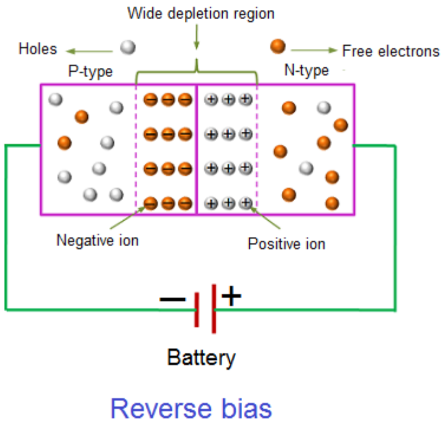
- In p-n junction diode, two types of capacitance take place

Diffusion capacitance (C_D)



$$C_D = dQ / dV$$

Transition capacitance (C_T)



$$C_T = \varepsilon A / W$$

Comparing single device to imager

Future work plan - SWIR image sensor

Experimental plan

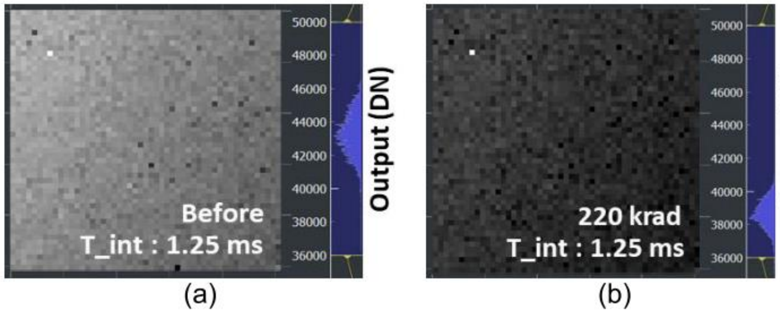


Fig. 11. Comparison of images (a) before and (b) after irradiation under dark conditions taken with QD-CIS.

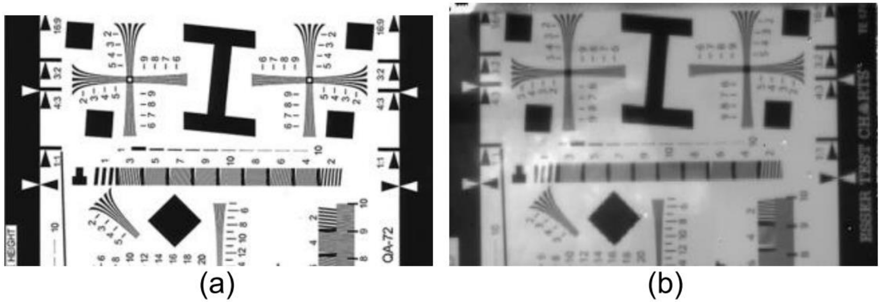


Fig. 12. Image quality test chart of (a) original image and (b) image captured using QD-CIS after 220 krad TID.

- I suspect how the thin film photodetector can protect Si-ROIC under X-ray radiation?
- We need more investigation of imager under X-ray radiation

Conclusion

X-ray radiation effects on CQD thin-film photodiode

Summary

- Materials characterization
  - we recognized the organic ligands were detortion points under X-ray radiation.
  - The degradation of BDT ligands induced the oxidation of CQD surface.
  - This red shift phenomenon of PL spectra.
  - However, we covered the encapsulation layer in the actual device. Thus, the oxidation may not happen at the device level.
- Device characterization
  - Dark current and EQE are enhanced until TID of 22 krad(Si) and slightly degraded upon the TID.
  - X-ray radiation generates the increased doping concentration in TFPDs
    - From the C-V curves, the depletion region has a rigid (reducing trap states) than un-irradiated samples
  - Through the imager demonstration, we prove that this phenomenon is reliable.

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