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# Radiation Induced Defects in 8T-CMOS Global Shutter Image Sensor for Space Application

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- **Defects** creation mechanisms and annealing behaviors are needed for a better understanding of radiation induced dark current increase

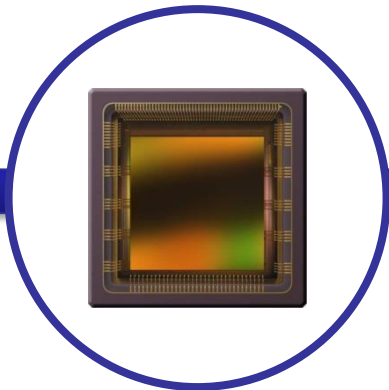
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- Displaced Si atoms create **stable defects**. Such defects act as **generation centers** and lead to a **dark current increase**.
- **Defects** creation mechanisms and annealing behaviors are needed for a better understanding of radiation induced dark current increase
- The main goal is to find a **mitigation technique**.

- DCS is used to characterize radiation induced defects throughout the **dark current distribution** of all the pixels of the matrix.

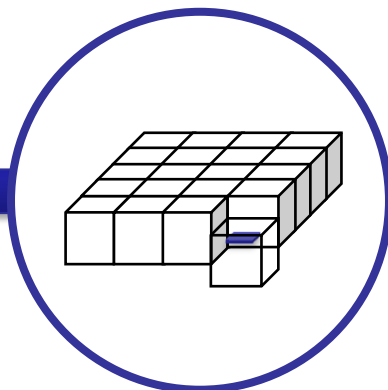
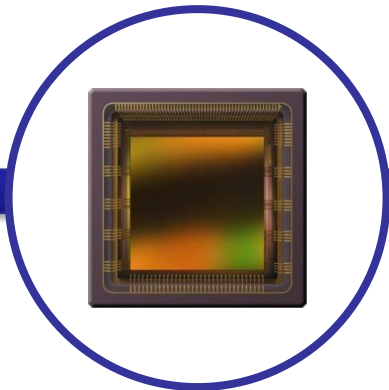


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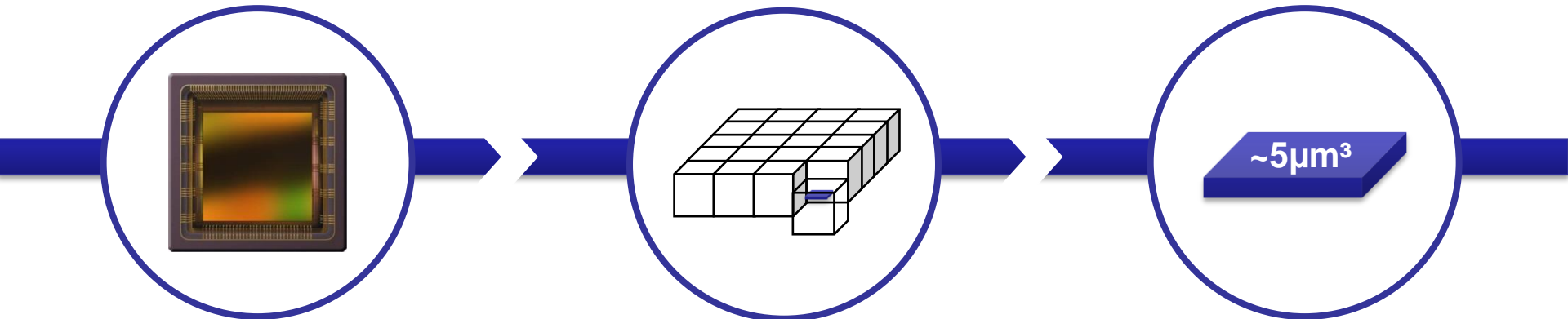
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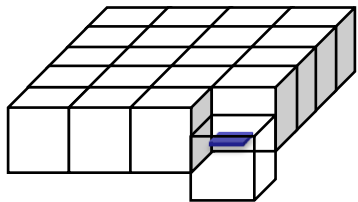
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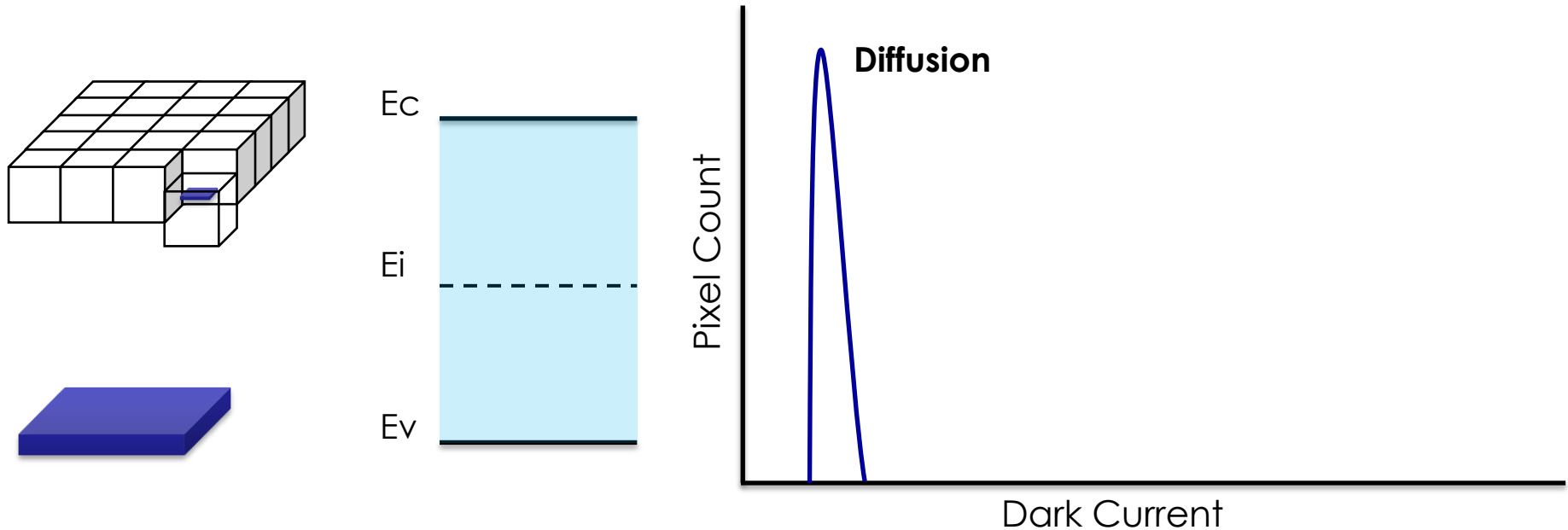
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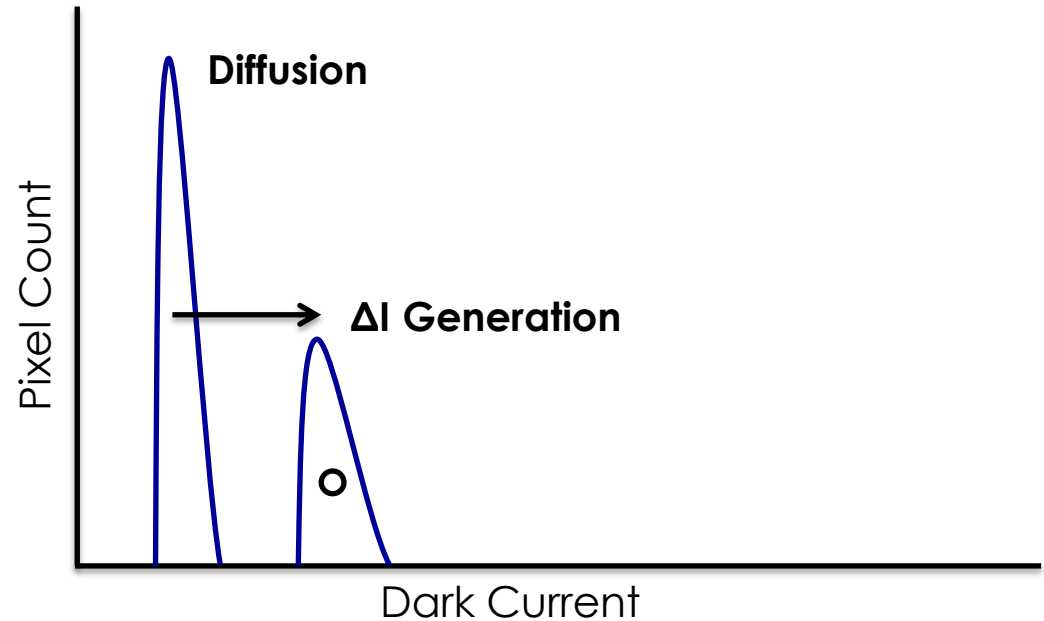
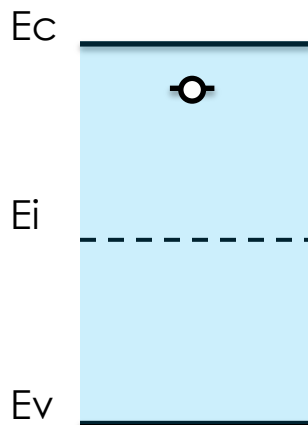
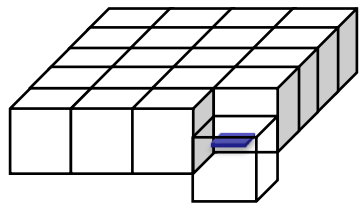
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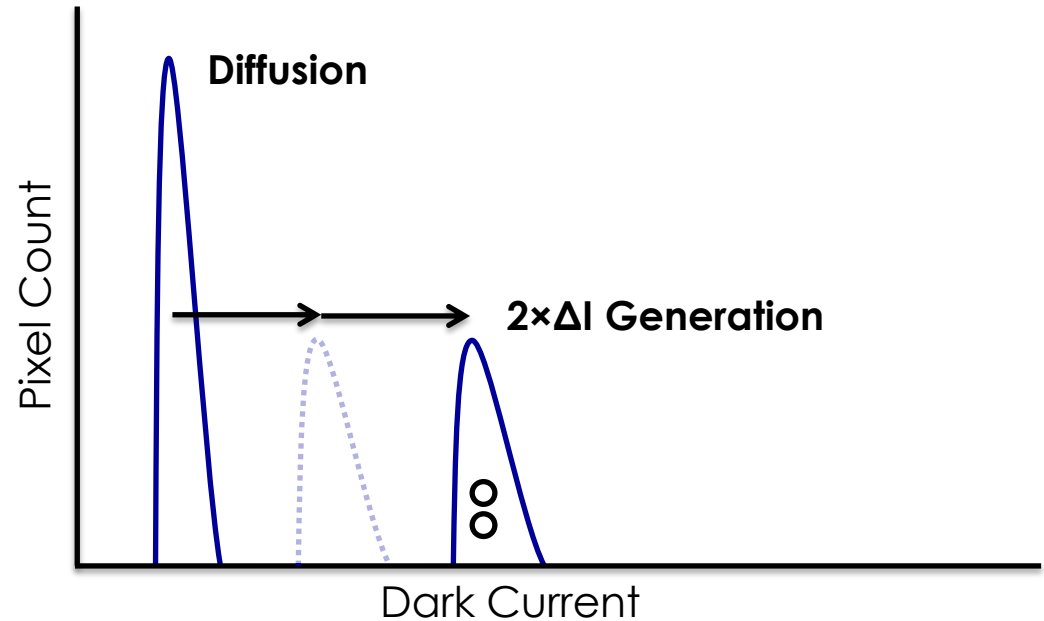
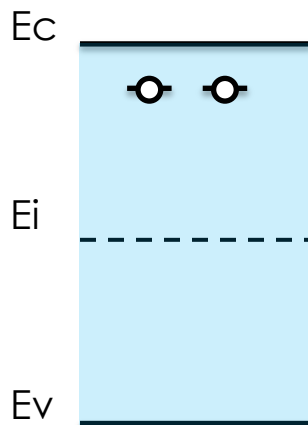
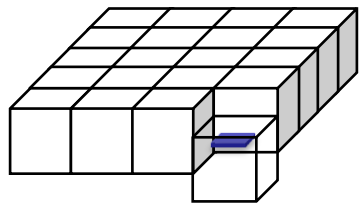
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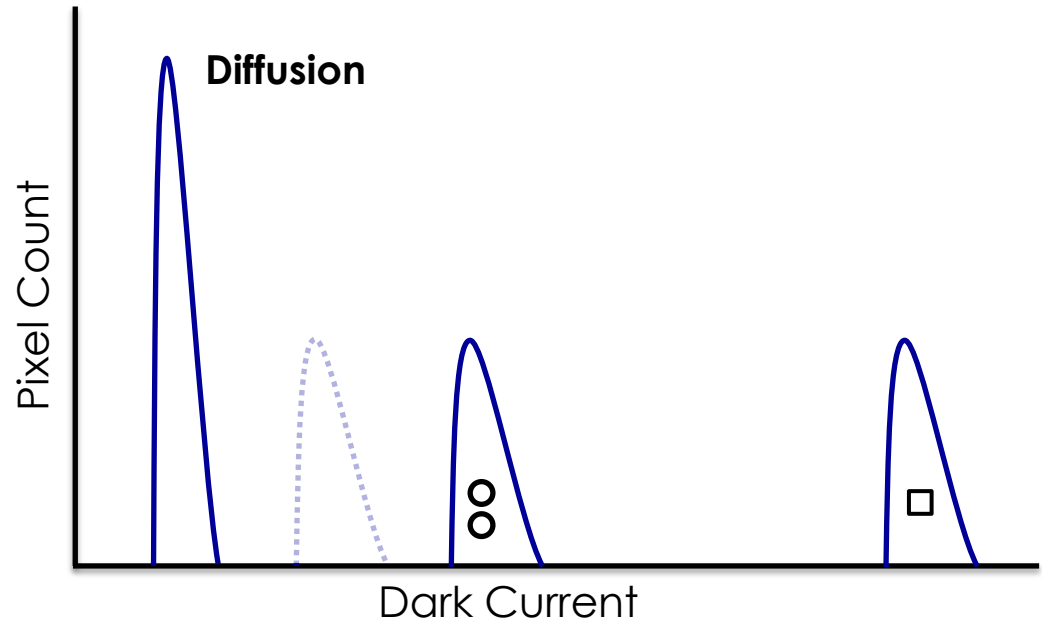
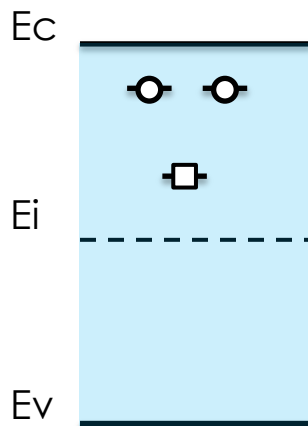
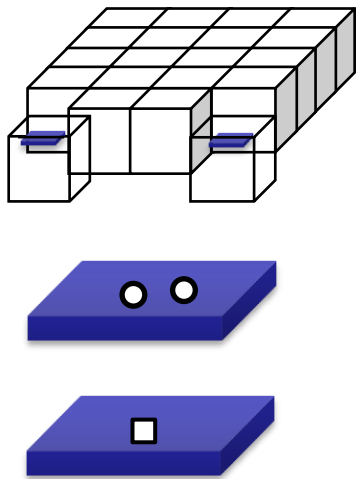


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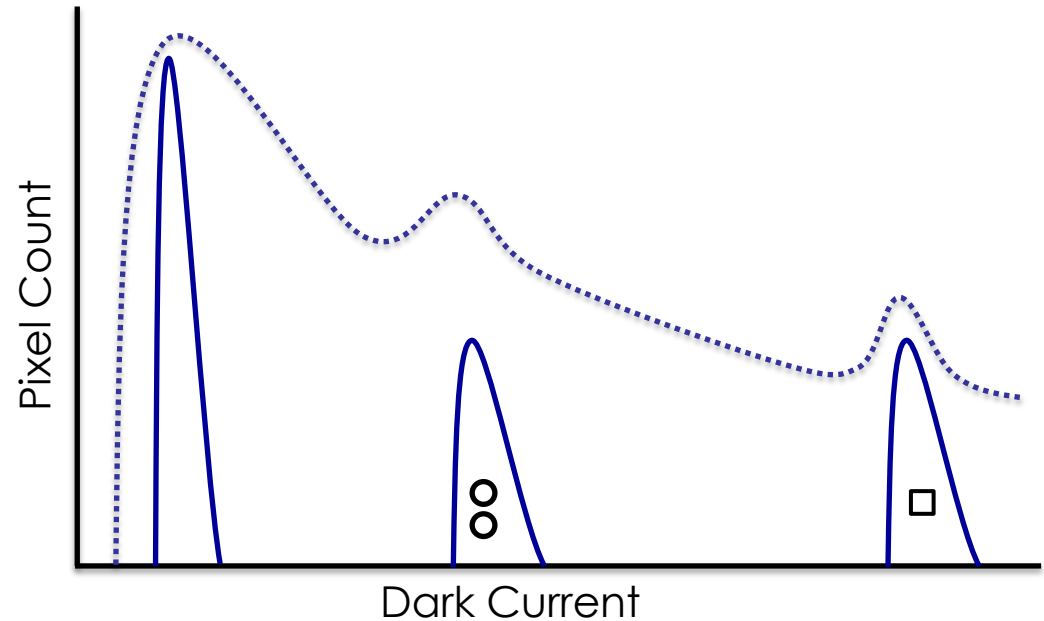
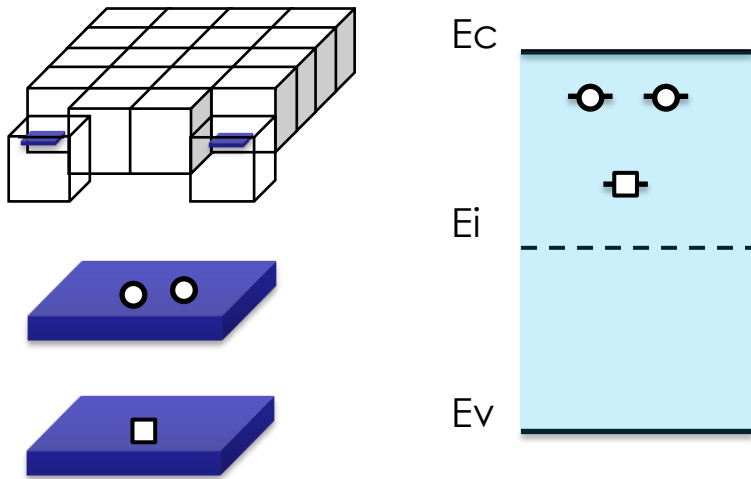




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- The generation dark current expression of a stable defect with energy level  $E_t$  is given by:

$$I_{dc} \approx A \cdot \exp\left(-\frac{\frac{E_g}{2} - |E_t - E_i|}{k_B \cdot T}\right)$$

$E_g$  Silicon band GAP

$E_t$  Defect energy level

$E_i$  Silicon mid-GAP

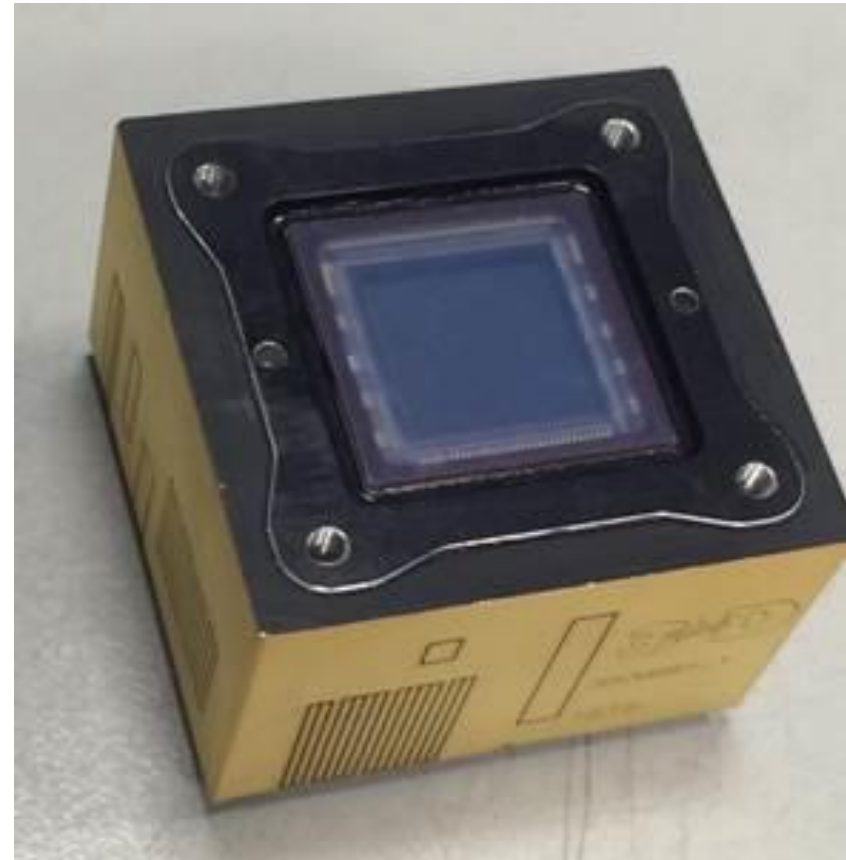
$k_B$  Boltzmann Constant

$T$  Temperature

- The dark current temperature evolution leads to defect **activation energy** estimation labeled  $E_a$  with the Arrhenius law.

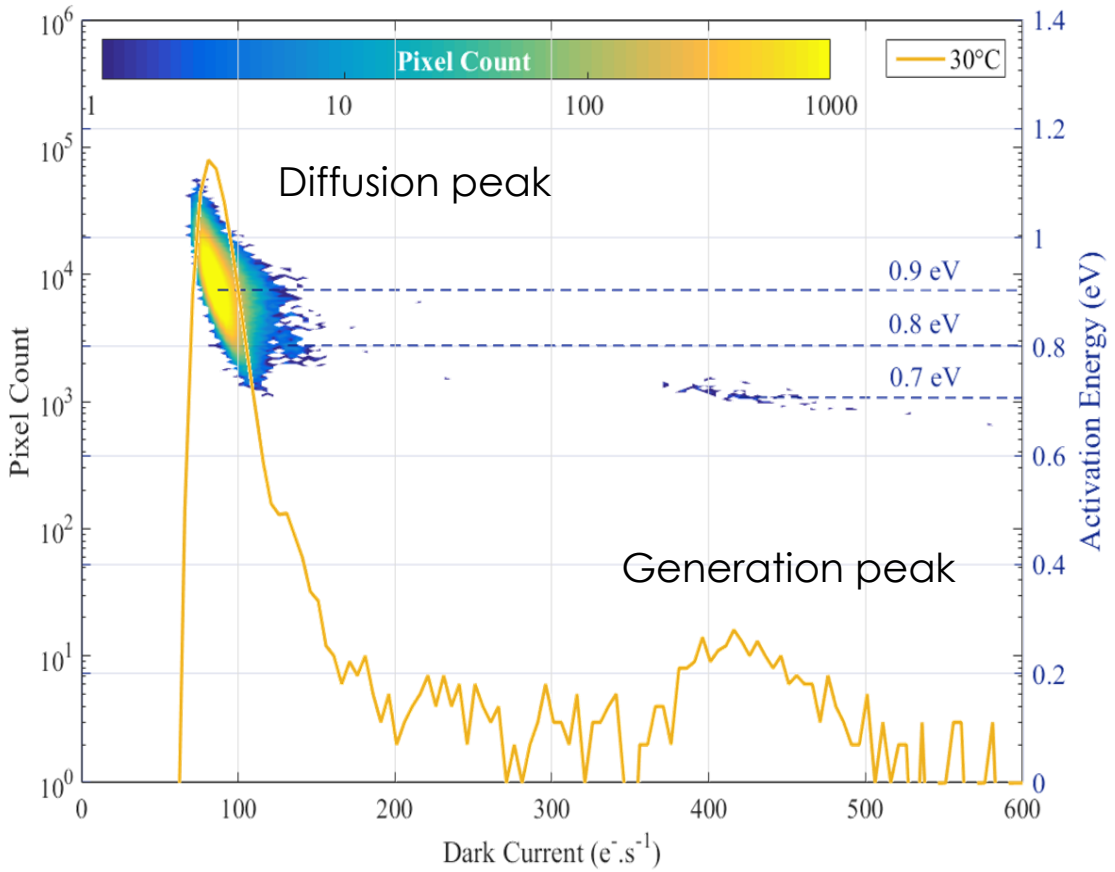
$$I_{dc} \approx A \cdot e^{\frac{-E_a}{k_B \cdot T}} \qquad E_a \approx \frac{E_g}{2} - |E_t - E_i|$$

- The CIS under test is a (Commercial Off-The-Shelf) COTS imager
  - 2048×2048 pixels
  - 0.18μm technology
  - 8T-PPD
  - Global shutter
  - 5.5 μm pitch pixels
  - PPD depleted volume of 5μm<sup>3</sup>
  
- This CIS is integrated in a microcamera for CNES space missions.



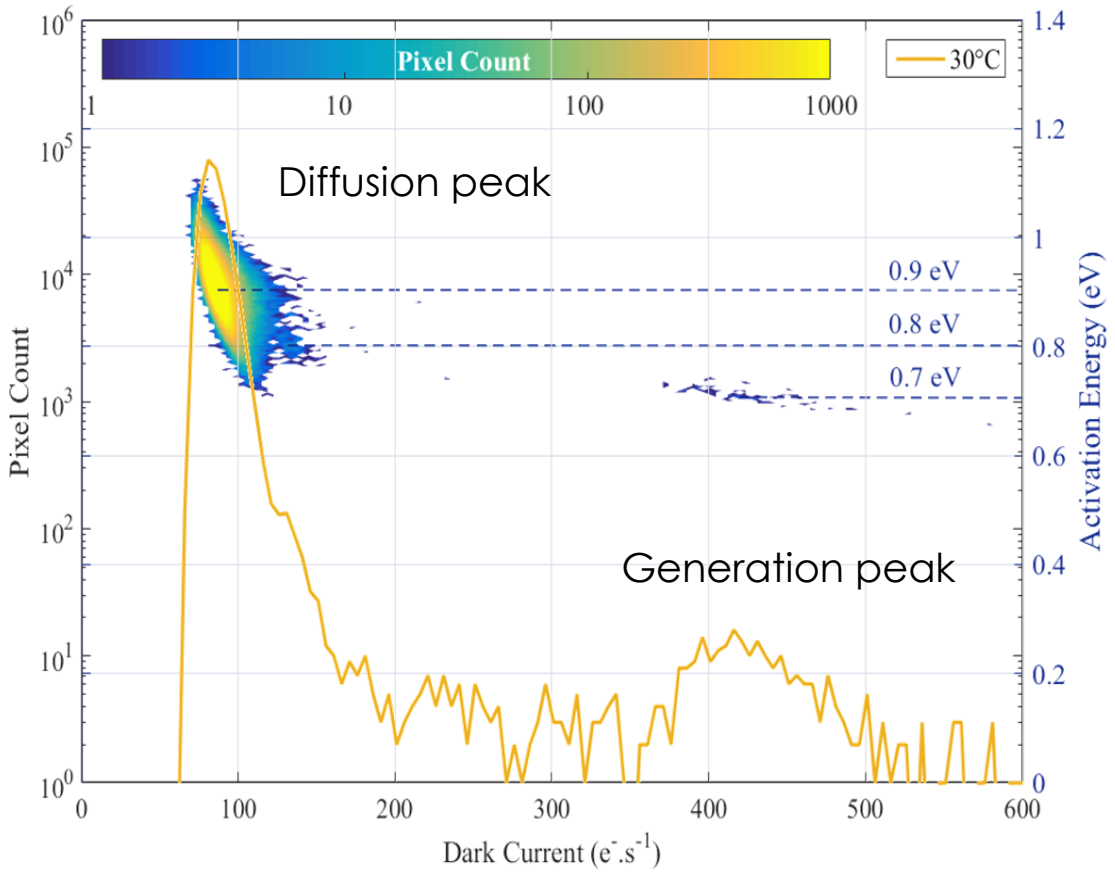
○ Dark current and activation energy distribution plotted at 20°C

- Diffusion peak containing pixels without defect in the microvolume.

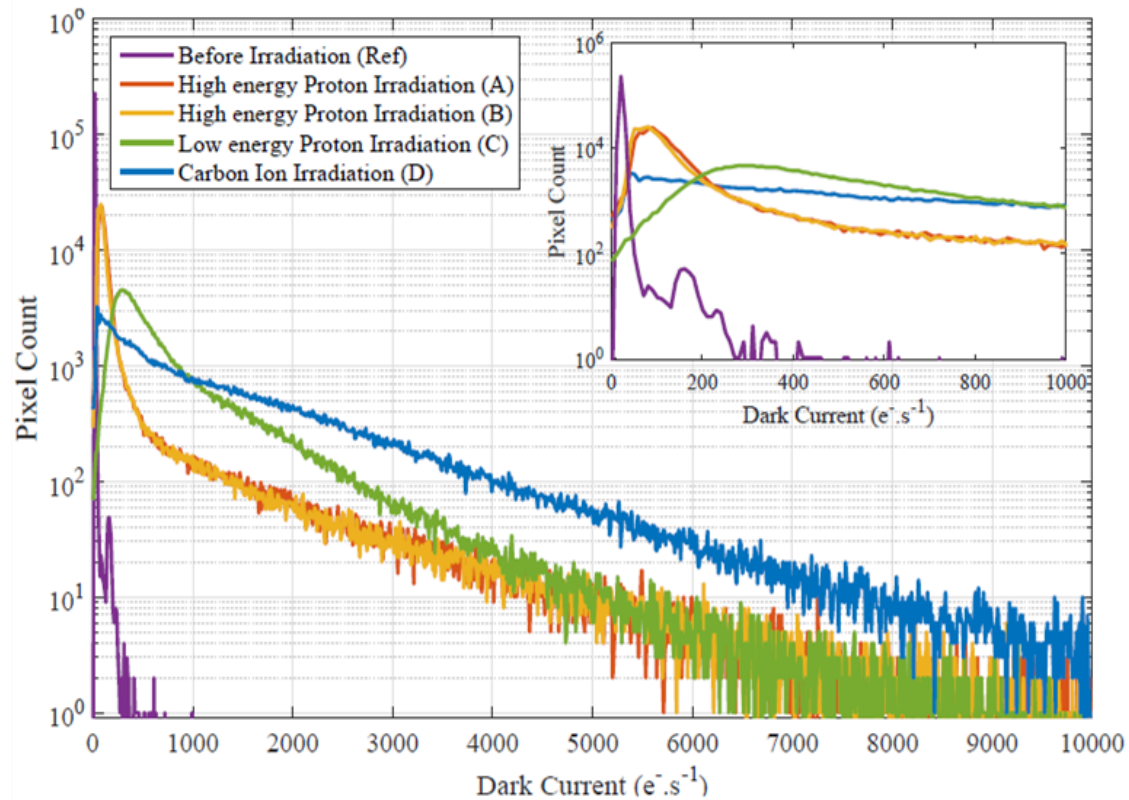


○ Dark current and activation energy distribution plotted at 20°C

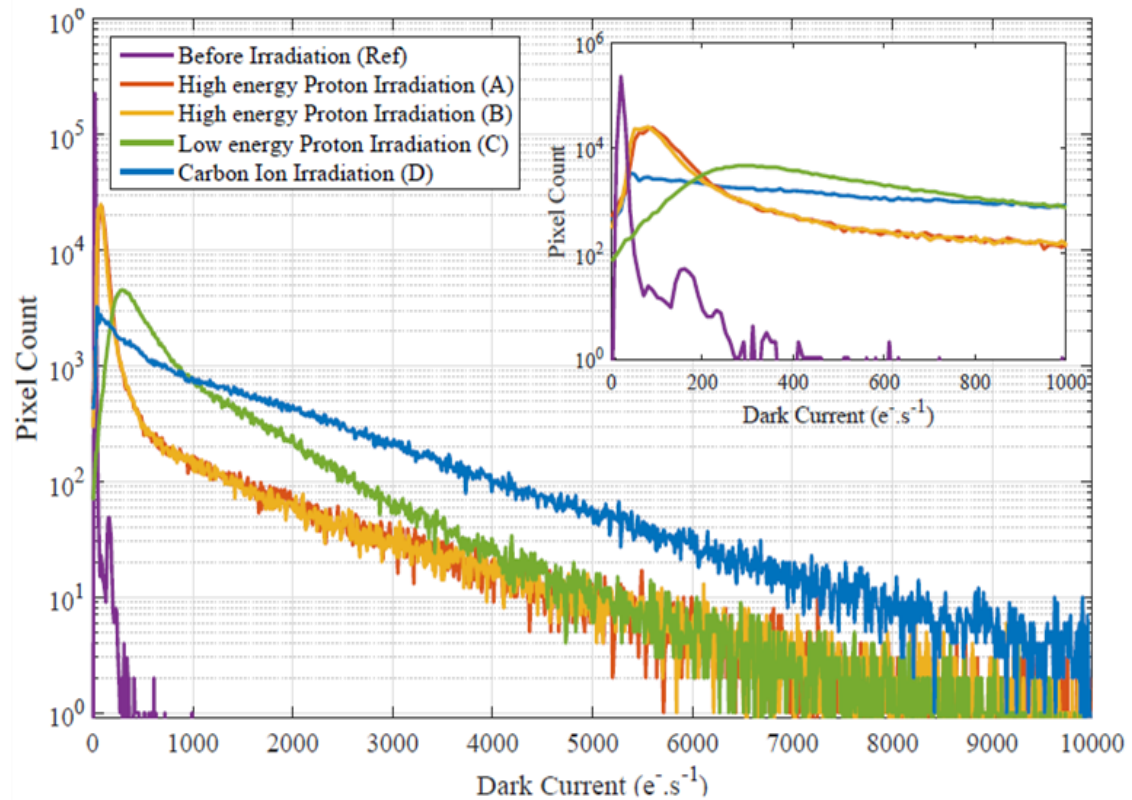
- Diffusion peak containing pixels without defect in the microvolume.
- Generation peak due to CMOS foundry process.



- High energy proton (A-50MeV B-150 MeV)
  - Nuclear chocs
  - **Cascade of defects**



- High energy proton (A-50MeV B-150 MeV)
  - Nuclear chocs
  - **Cascade of defects**
  
- Carbon ion (D-10 MeV)
  - Nuclear chocs and Coulombic interaction
  - **Cascade of defects and Point defects**





- High energy proton (A-50MeV B-150 MeV)

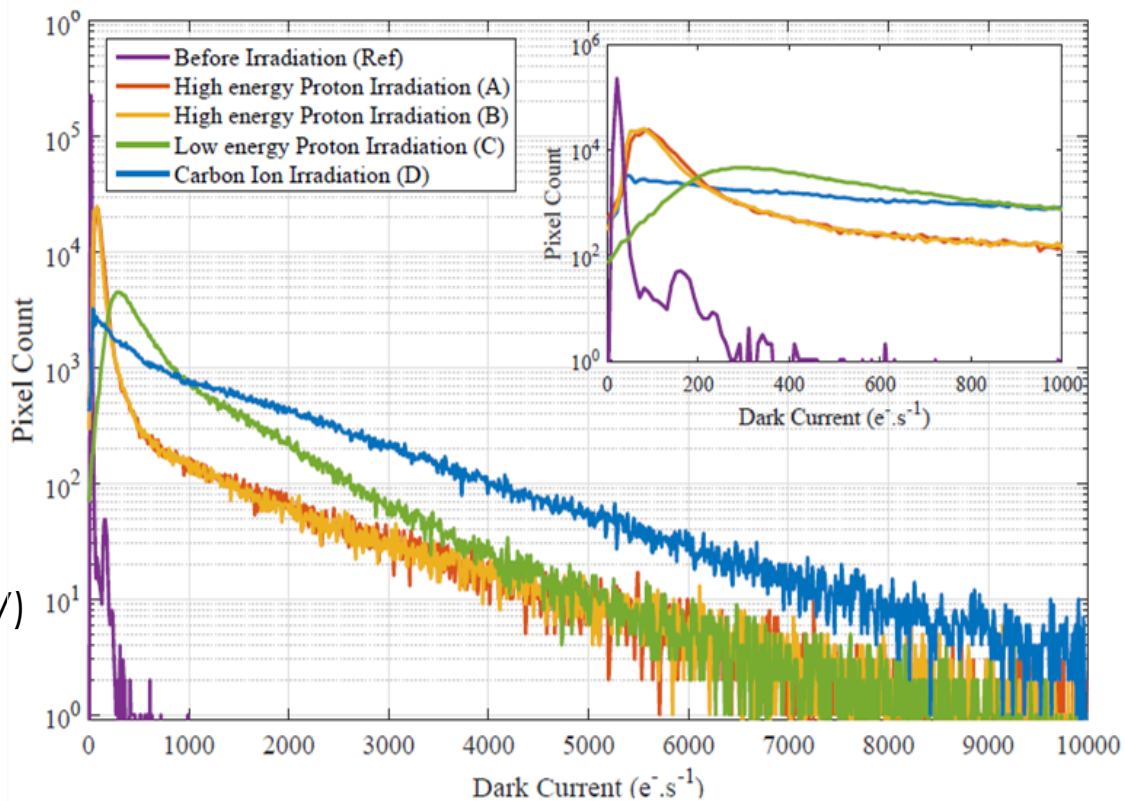
- Nuclear chocs
- **Cascade of defects**

- Carbon ion (D-10 MeV)

- Nuclear chocs and Coulombic interaction
- **Cascade of defects and Point defects**

- Low energy proton (C-1 MeV)

- Coulombic interaction
- **Point defects**
- **Best case for the Dark Current Spectroscopy technique**



1

○ Dark current distribution evolution with annealings plotted at 20°C

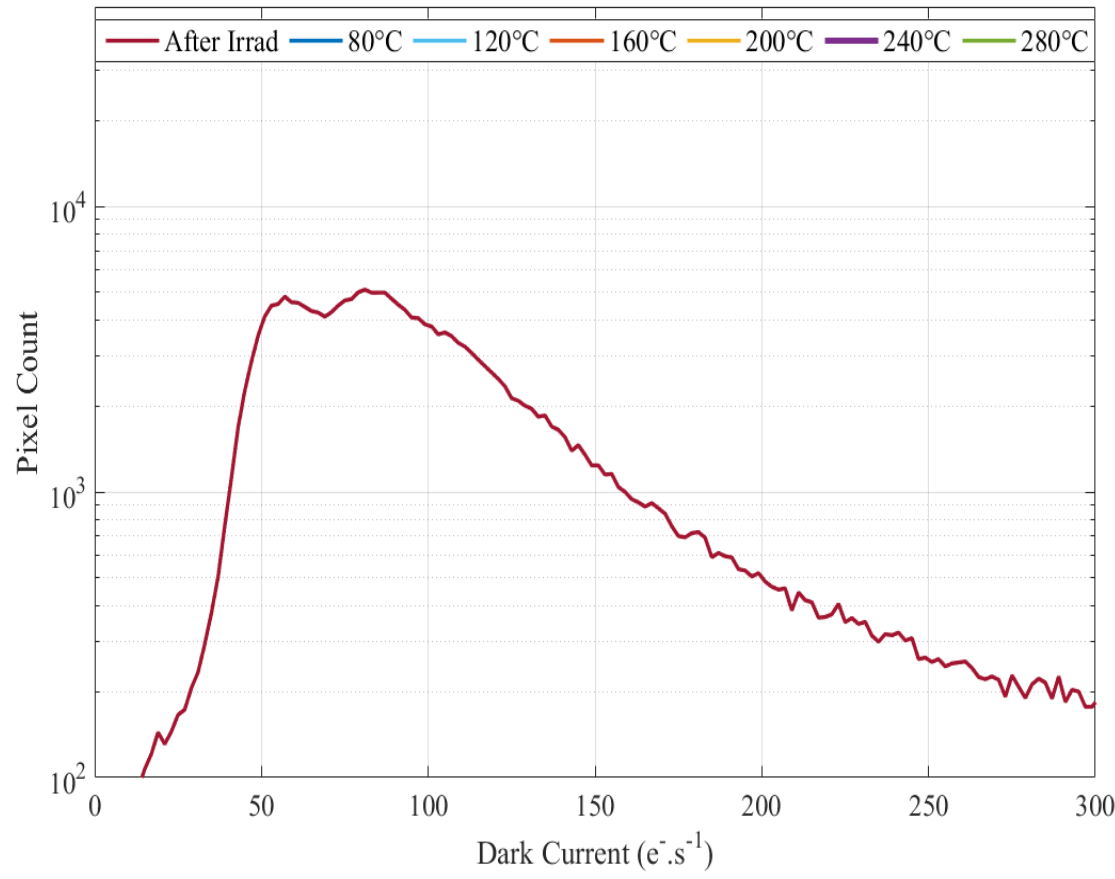
High-energy proton

2

Carbon ion

3

Low energy proton



1

○ Dark current distribution evolution with annealings plotted at 20°C

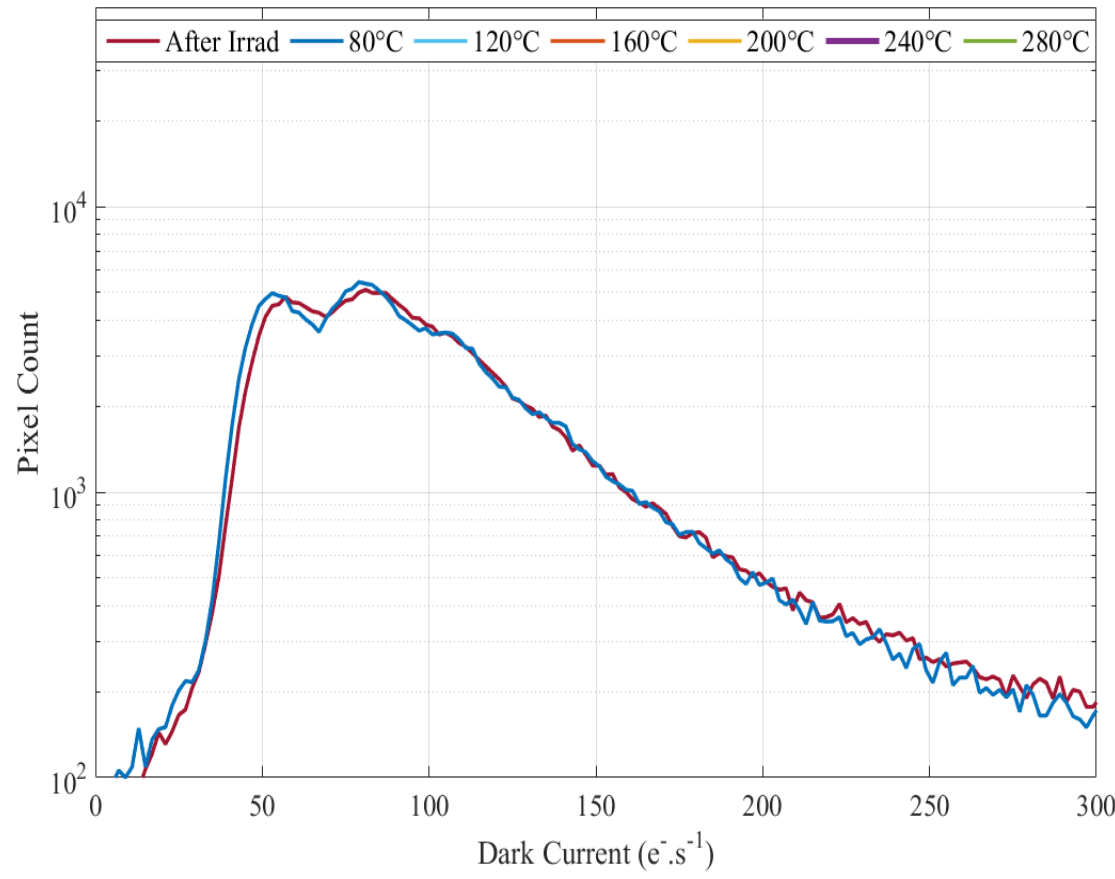
High-energy proton

2

Carbon ion

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1

○ Dark current distribution evolution with annealings plotted at 20°C

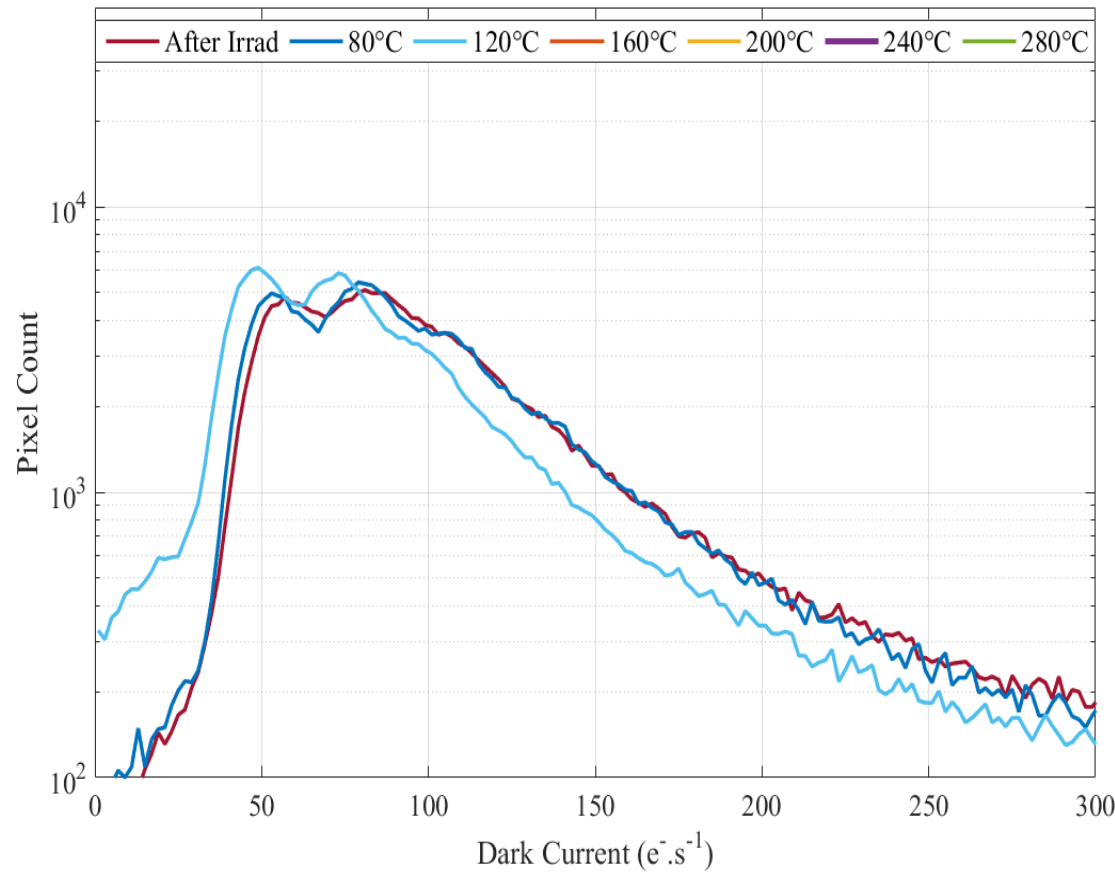
High-energy proton

2

Carbon ion

3

Low energy proton



1

○ Dark current distribution evolution with annealings plotted at 20°C

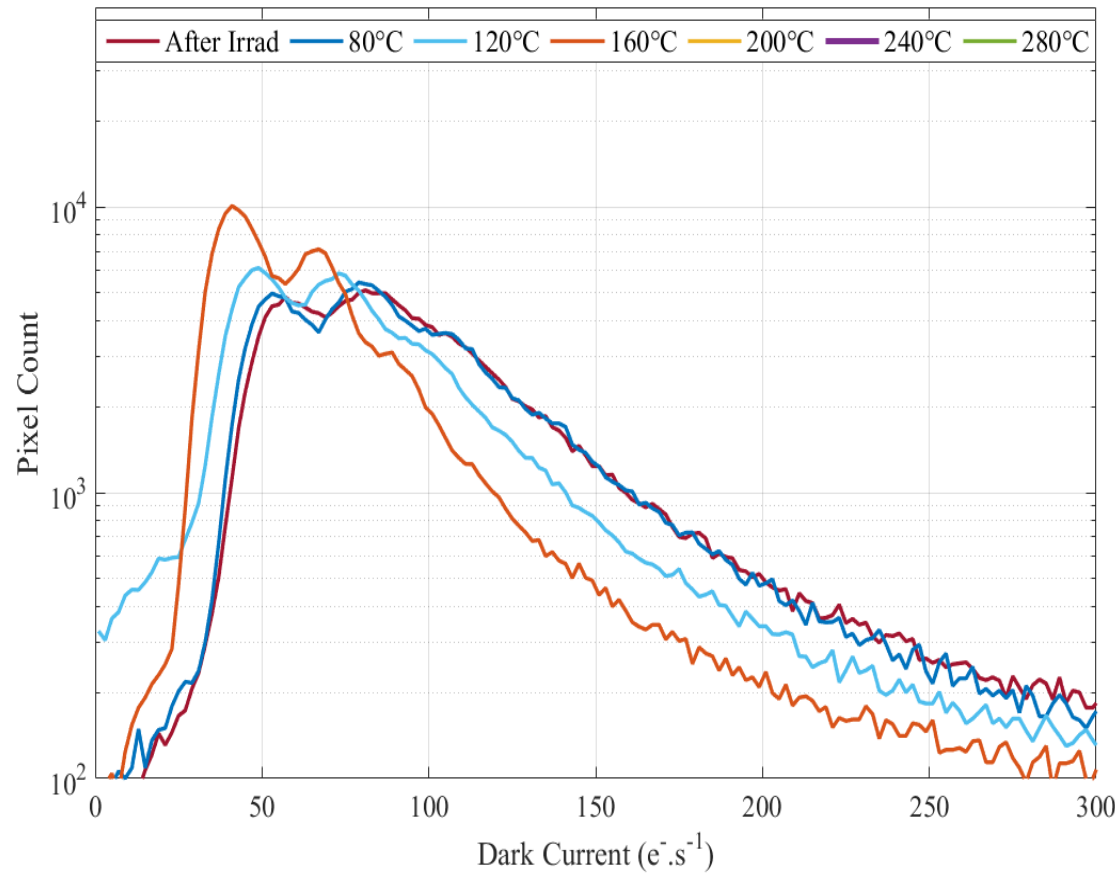
High-energy proton

2

Carbon ion

3

Low energy proton



1

○ Dark current distribution evolution with annealings plotted at 20°C

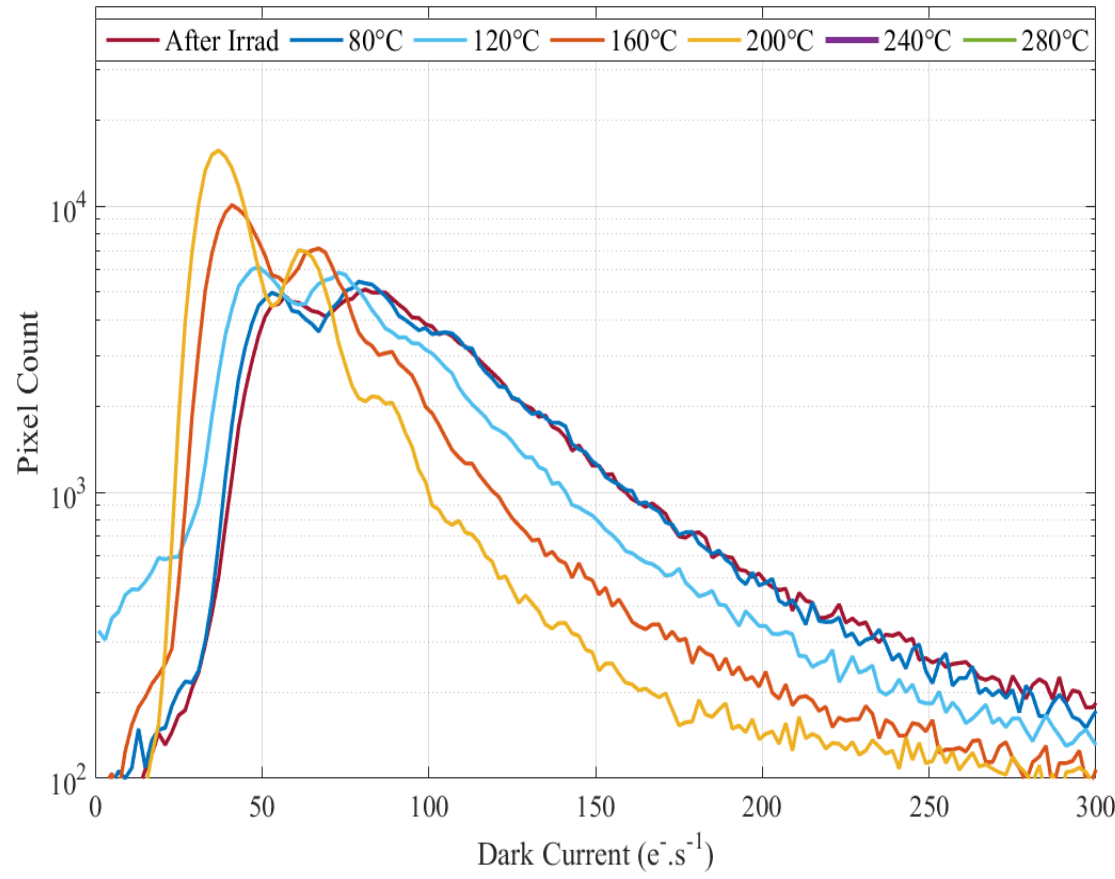
High-energy proton

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Carbon ion

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Low energy proton



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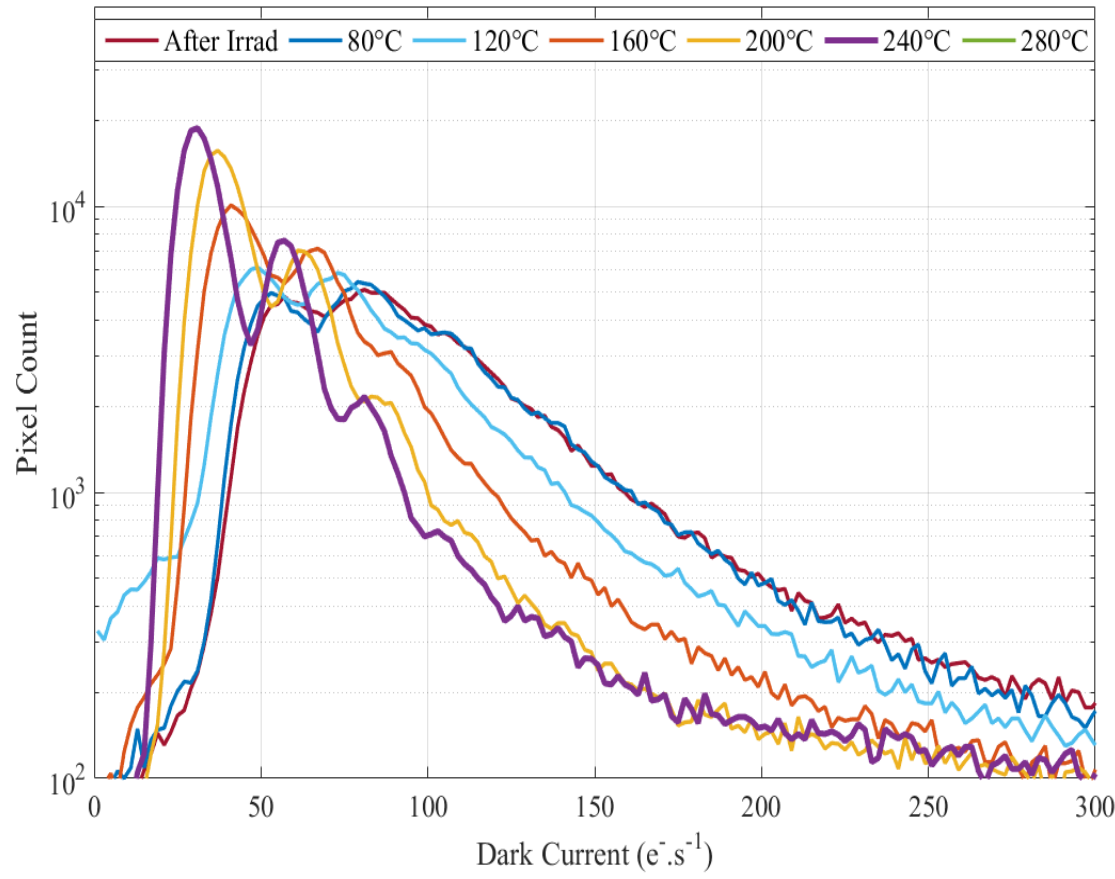
High-energy proton

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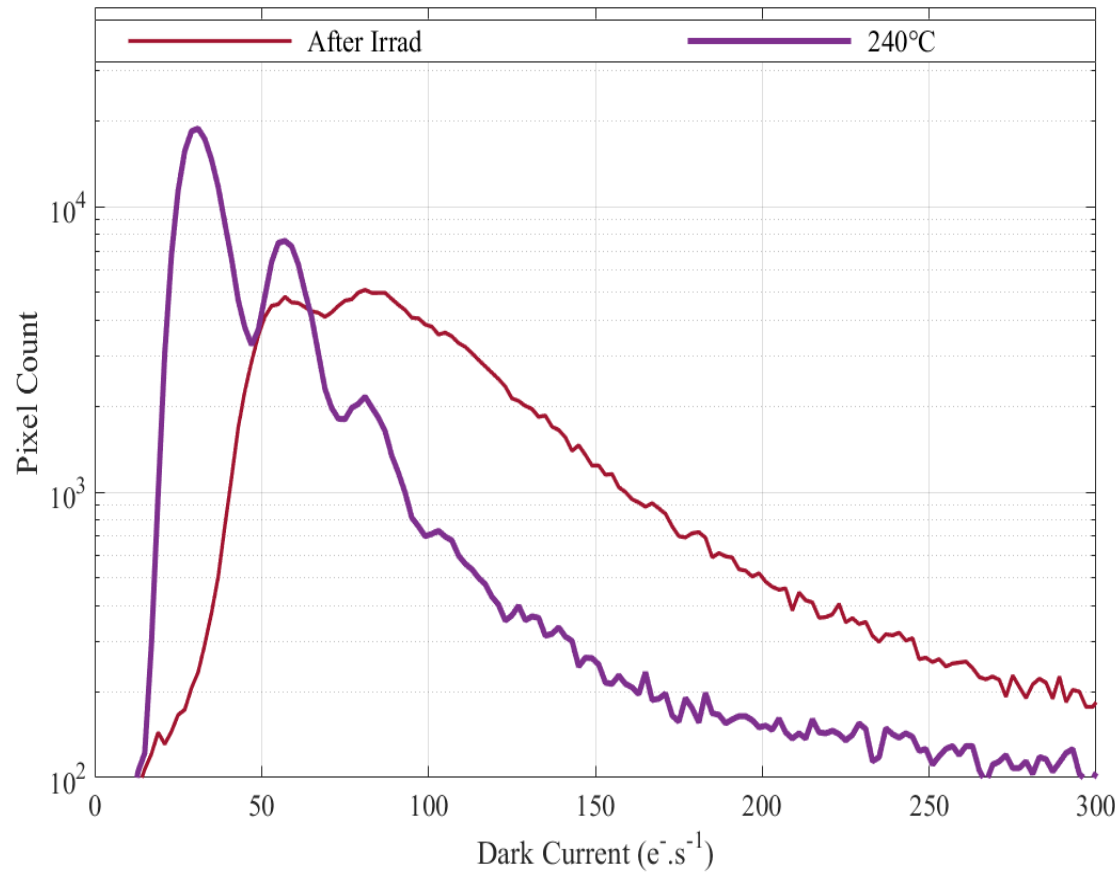
High-energy proton

2

Carbon ion

3

Low energy proton

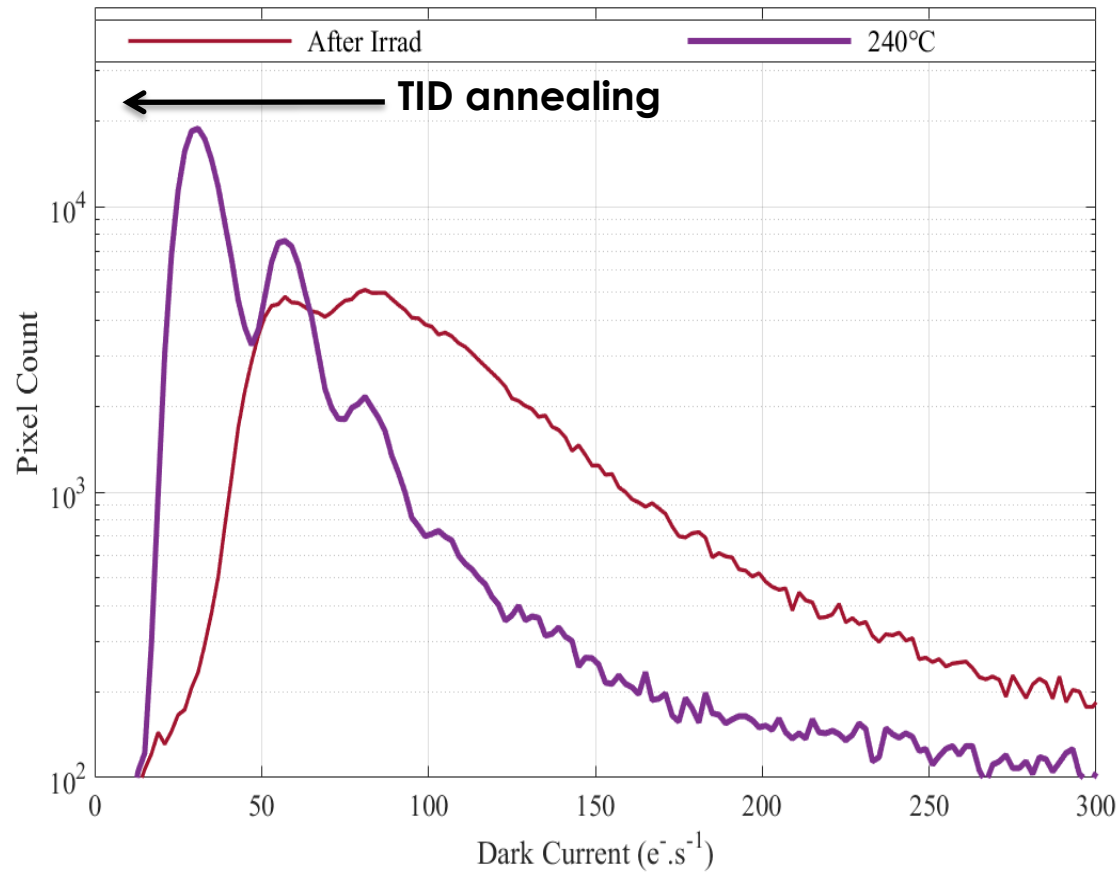




- 1 ○ Dark current distribution evolution with annealings plotted at 20°C
  - TID annealing

2  
Carbon ion

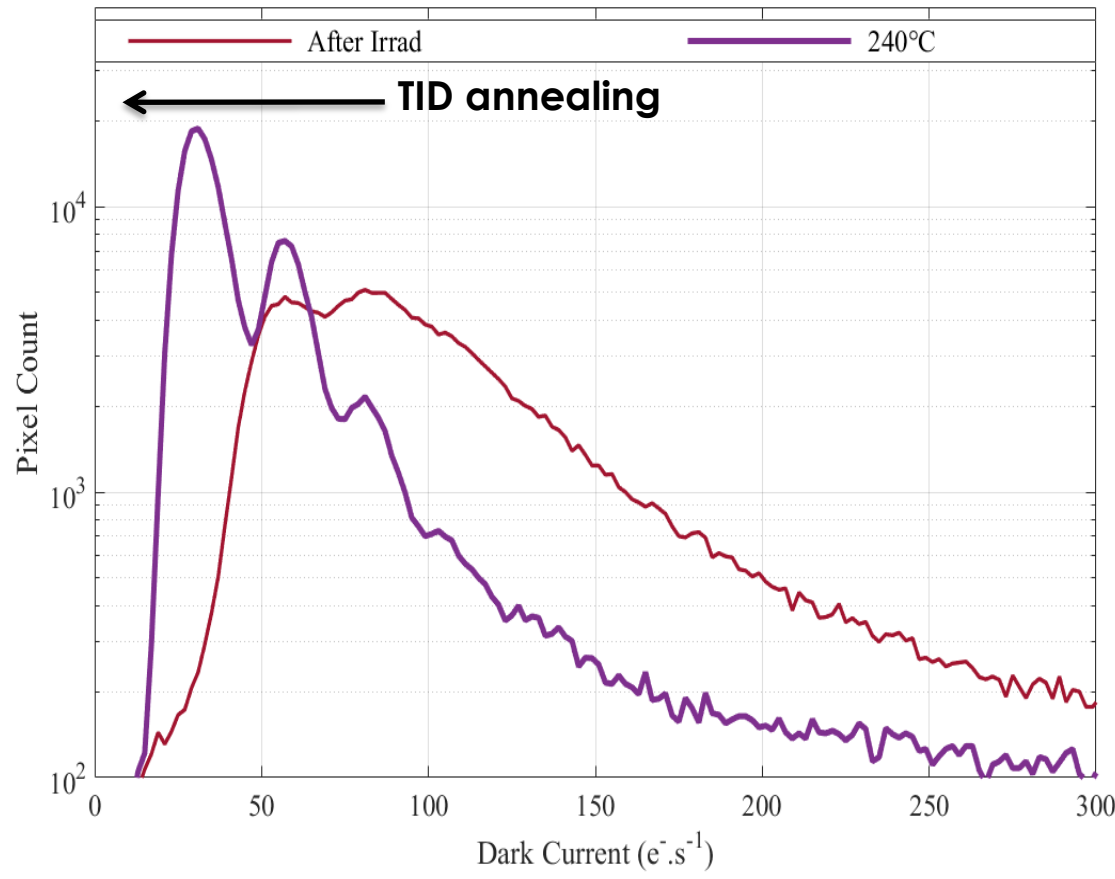
3  
Low energy proton



1

○ Dark current distribution evolution with annealings plotted at 20°C

- TID annealing
- Increase of the diffusion peak.



2

Carbon ion

3

Low energy proton

1

High-energy proton

2

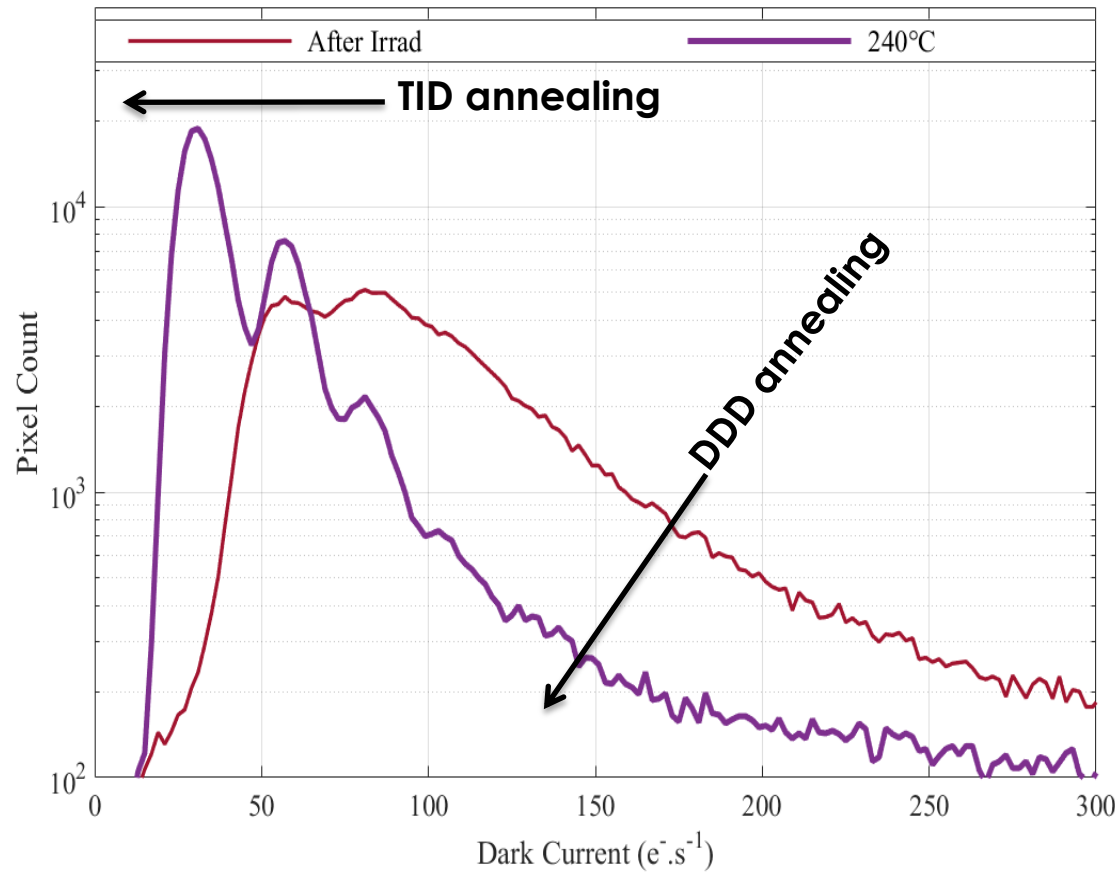
Carbon ion

3

Low energy proton

○ Dark current distribution evolution with annealings plotted at 20°C

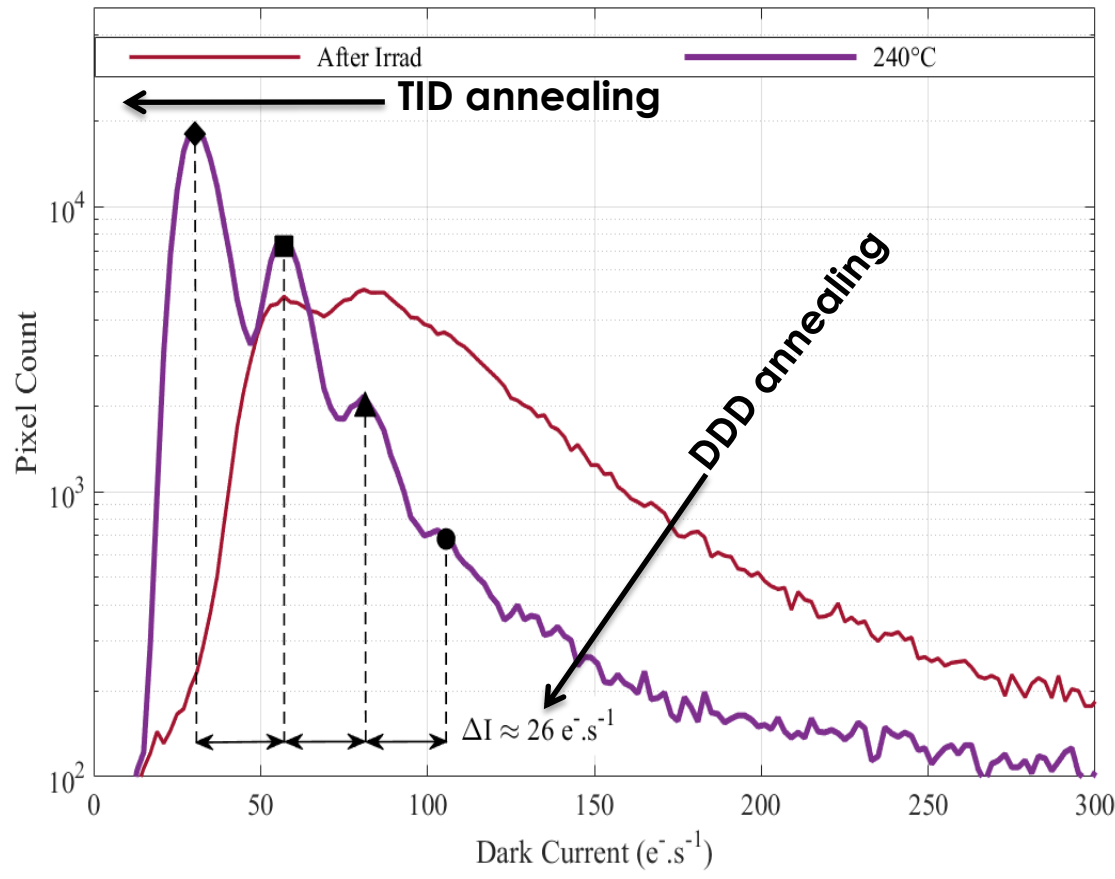
- TID annealing
- Increase of the diffusion peak.
- Decrease of the dark current tail.



1

○ Dark current distribution evolution with annealings plotted at 20°C

- TID annealing
- Increase of the diffusion peak.
- Decrease of the dark current tail.
- Multiple generation peaks  $\Delta I = 26 \text{ e}^-/\text{s}$  (20°C)



2

Carbon ion

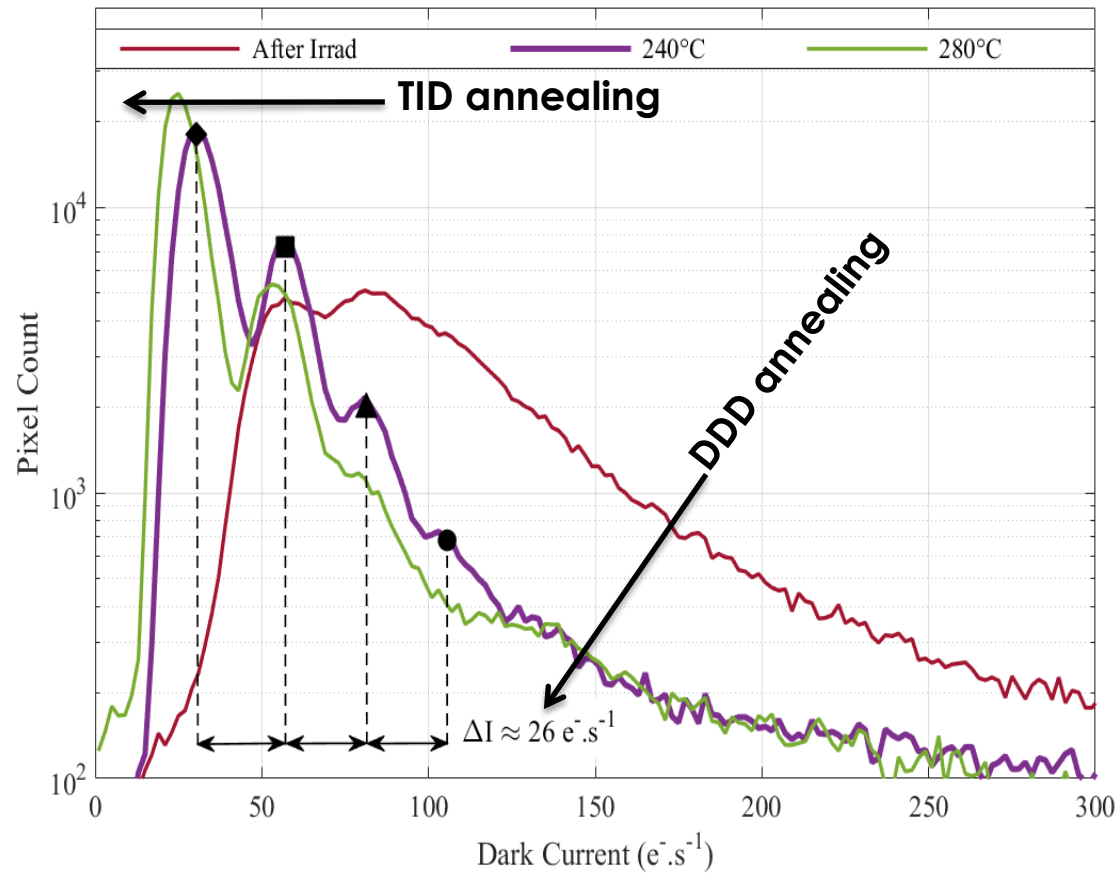
3

Low energy proton

1

Dark current distribution evolution with annealings plotted at 20°C

- TID annealing
- Increase of the diffusion peak.
- Decrease of the dark current tail.
- Multiple generation peaks  $\Delta I = 26 \text{ e}^-/\text{s}$  (20°C)
- Defect annealing between 240°C and 280°C.



2

Carbon ion

3

Low energy proton

1

High-energy proton

- Activation energy evolution with annealings (240°C and 280°C)
  - Dark current  $\Delta I = 26 \text{ e-}/s$  (20°C)
  - Activation energy  $E_a = 0,83\text{eV}$
  - Annealing temperature [240°C – 280°C]

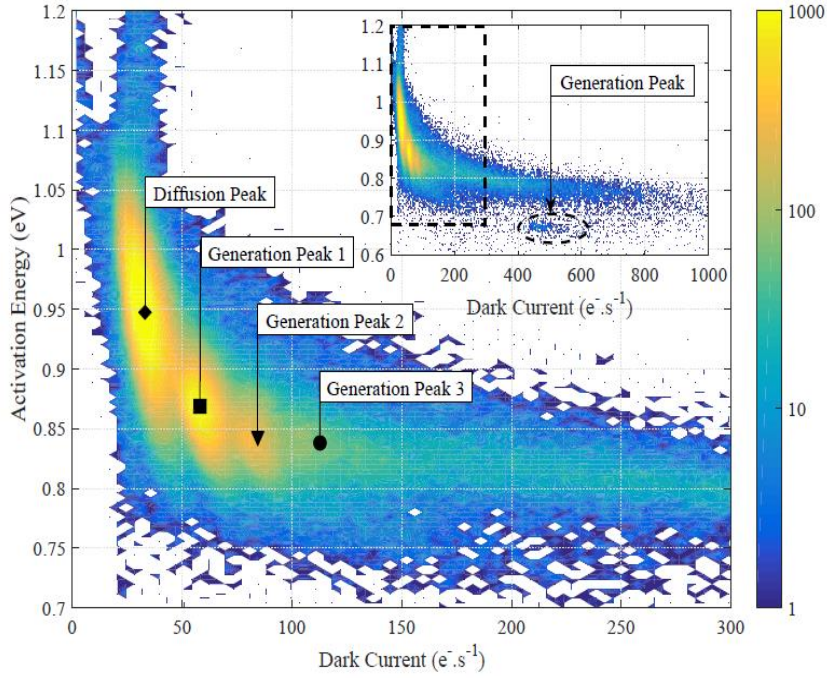
2

Carbon ion

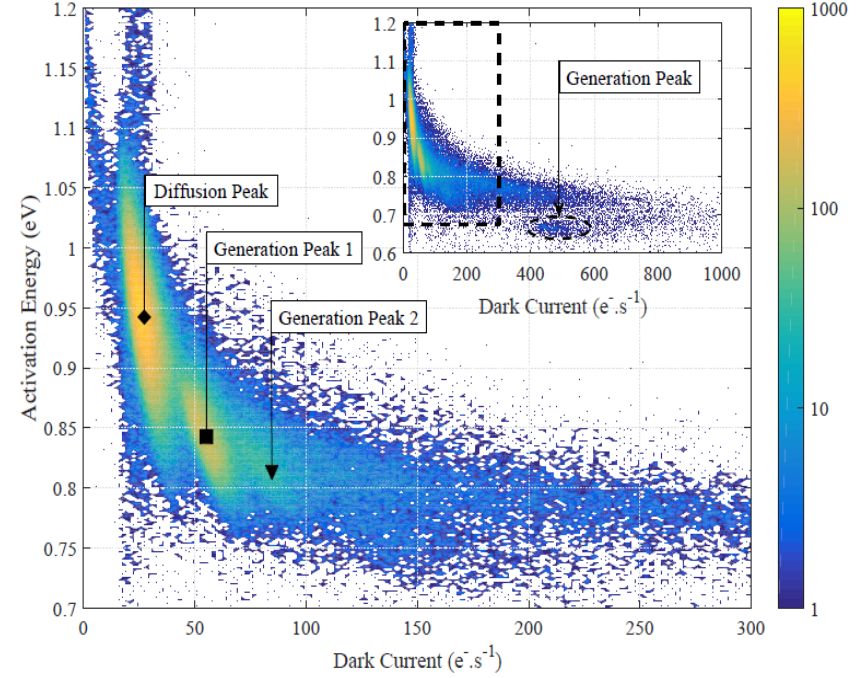
3

Low energy proton

240°C annealing



280°C annealing





1

High-energy proton

- Activation energy evolution with annealings (240°C and 280°C)
  - Dark current  $\Delta I = 30 \text{ e-}/s$  (20°C)
  - Activation energy  $E_a = 0,83\text{eV}$
  - Annealing temperature [240°C – 280°C]

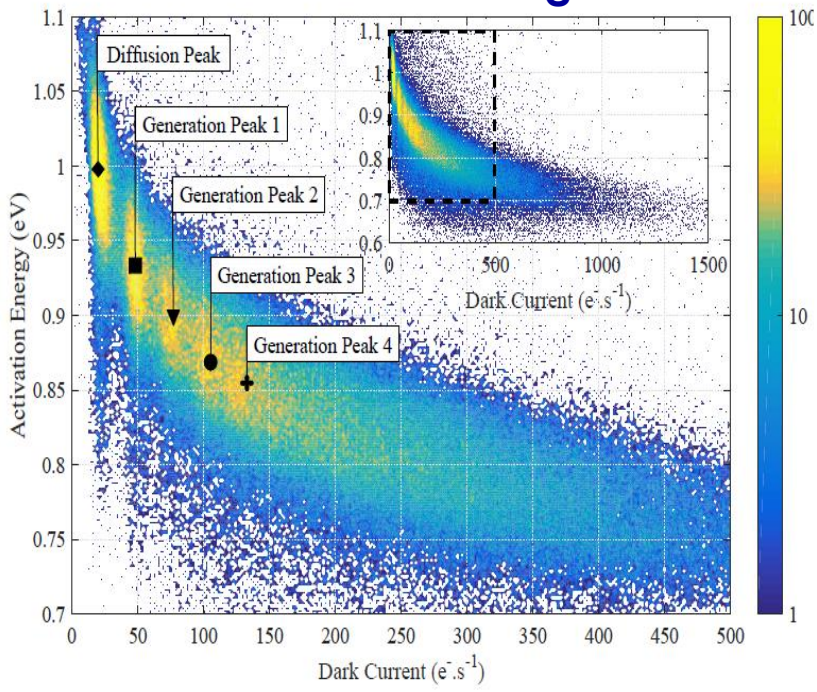
2

Carbon ion

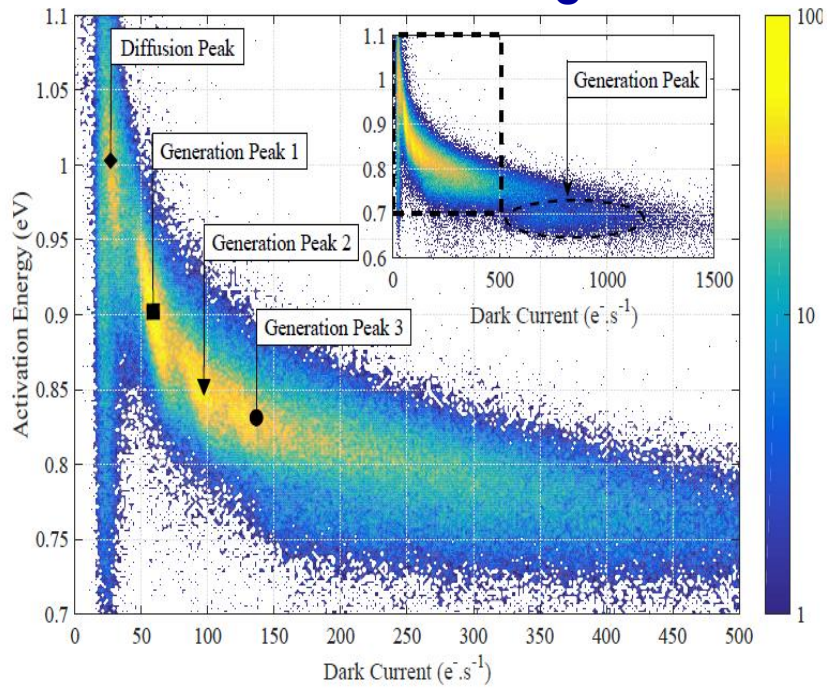
3

Low energy proton

240°C annealing



280°C annealing



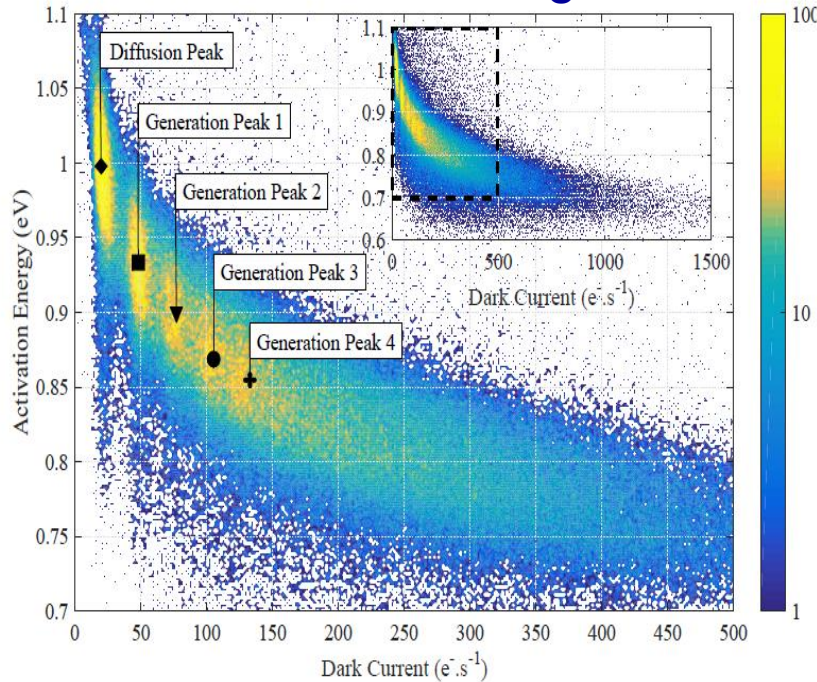
1  
High-energy proton

- Activation energy evolution with annealings (240°C and 280°C)
    - Dark current  $\Delta I = 30 \text{ e-}/s$  (20°C)
    - Activation energy  $E_a = 0,83\text{eV}$
    - Annealing temperature [240°C – 280°C]
- } Same defects identification after high energy proton

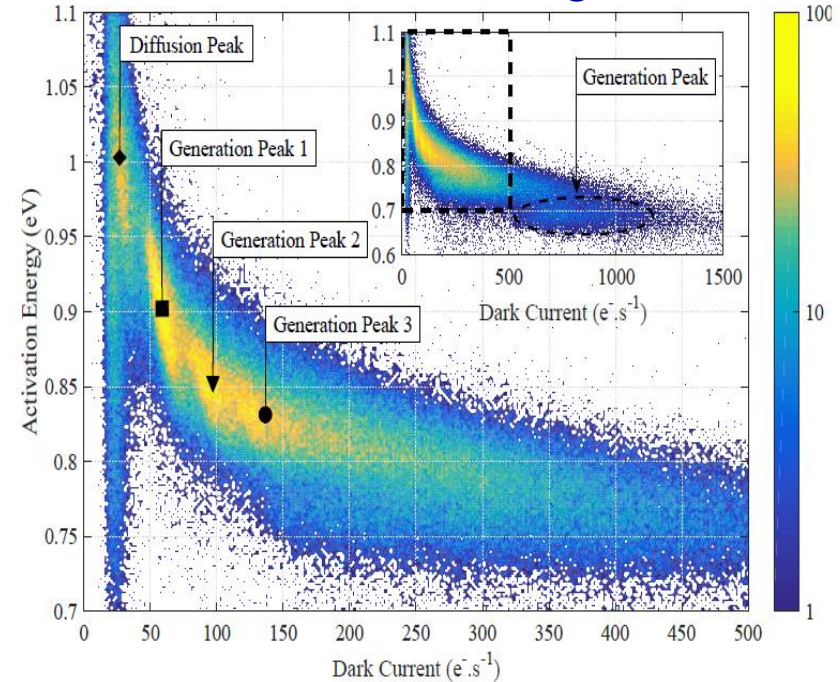
2  
Carbon ion

3  
Low energy proton

240°C annealing



280°C annealing





1

High-energy proton

2

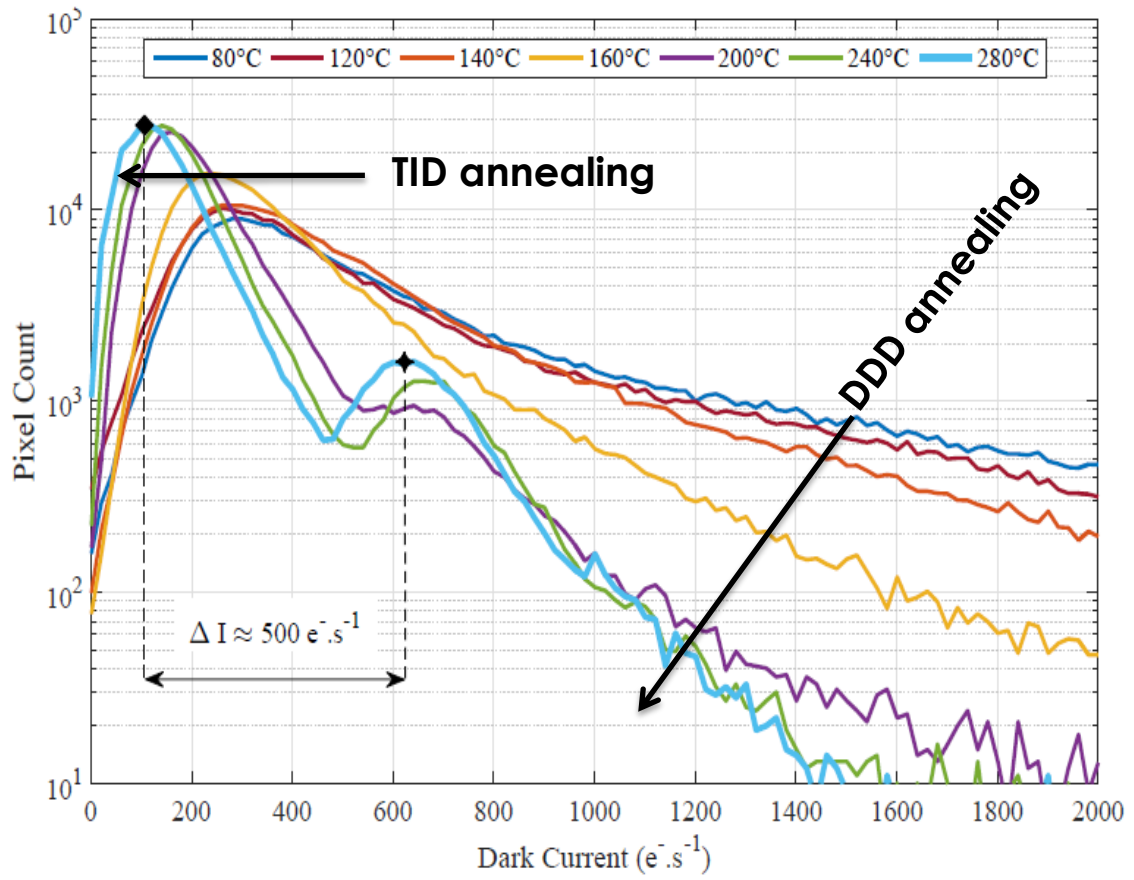
Carbon ion

3

Low energy proton

○ Dark current distribution evolution with annealings plotted at 20°C

- TID annealing
- Increase of the diffusion peak.
- Decrease of The dark current tail.
- Generation peaks  $\Delta I = 500 \text{ e}^-/\text{s}$  (20°C)
- No annealing between 240°C and 280°C.

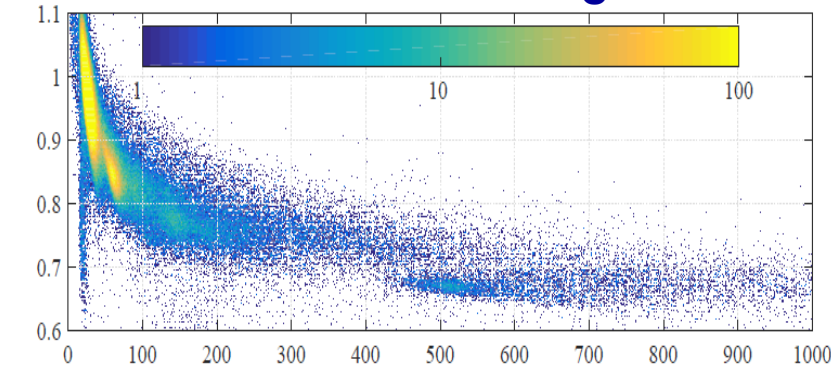


300°C annealing

Last annealing at 300°C

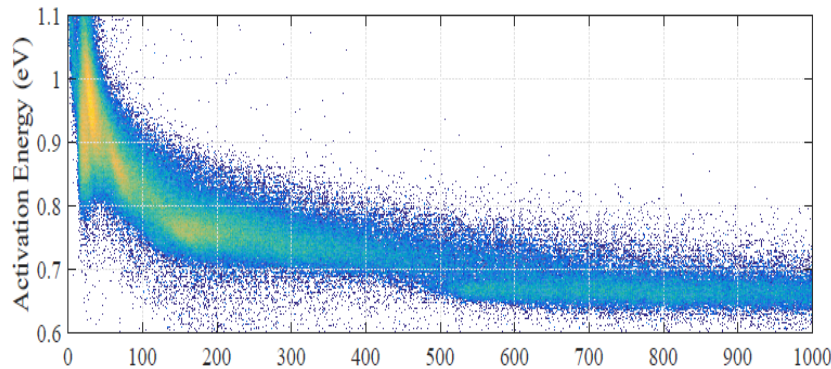
1

High-energy proton



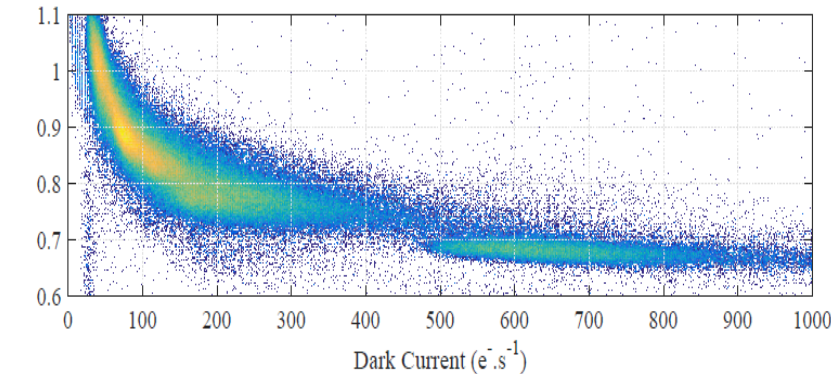
2

Carbon ion



3

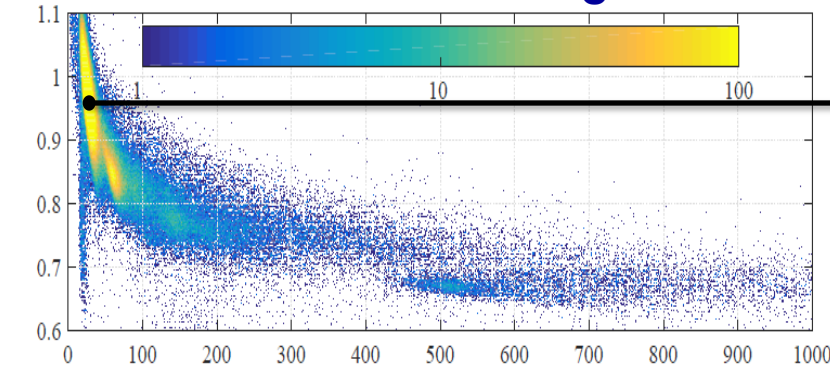
Low energy proton



300°C annealing

Last annealing at 300°C

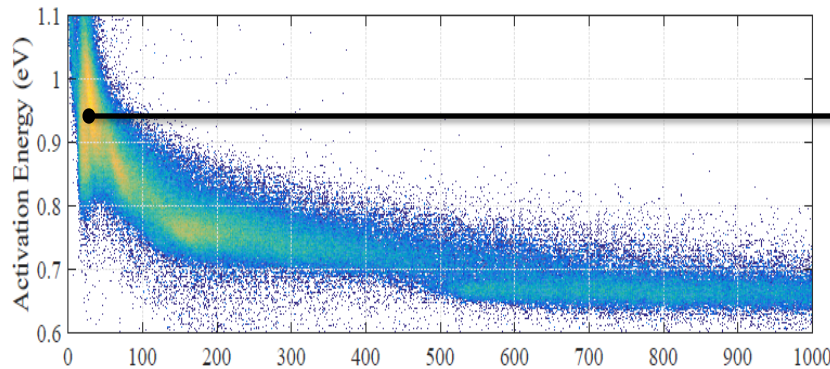
1  
High-energy proton



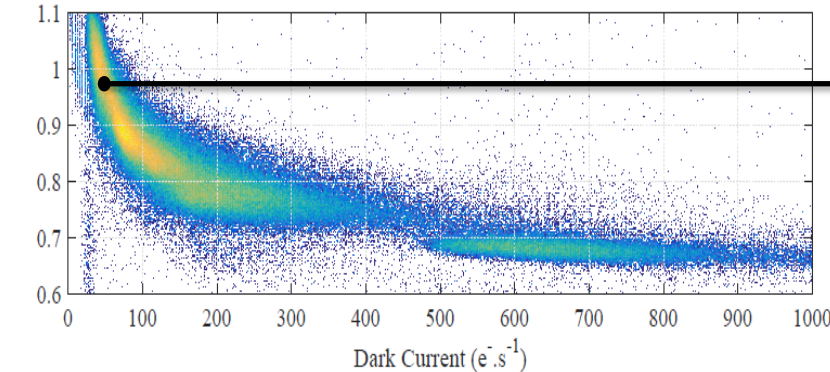
○ Diffusion peak

- $I_{dc} \sim 30 e^-/s$  (20°C)
- $E_a \sim 0,95 eV$

2  
Carbon ion



3  
Low energy proton

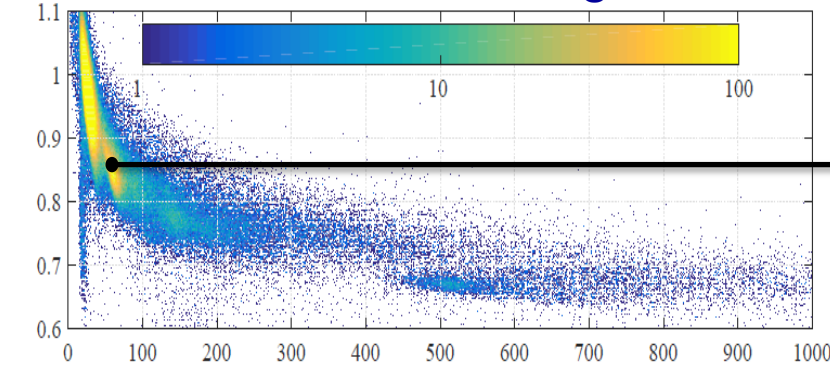


Dark Current ( $e^- \cdot s^{-1}$ )

## 300°C annealing

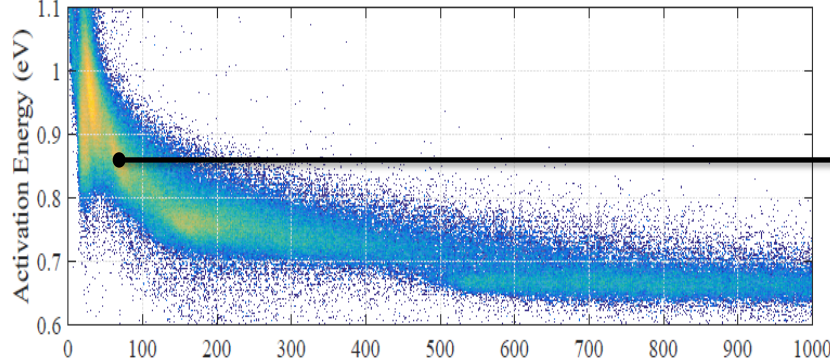
Last annealing at 300°C

**1**  
High-energy proton



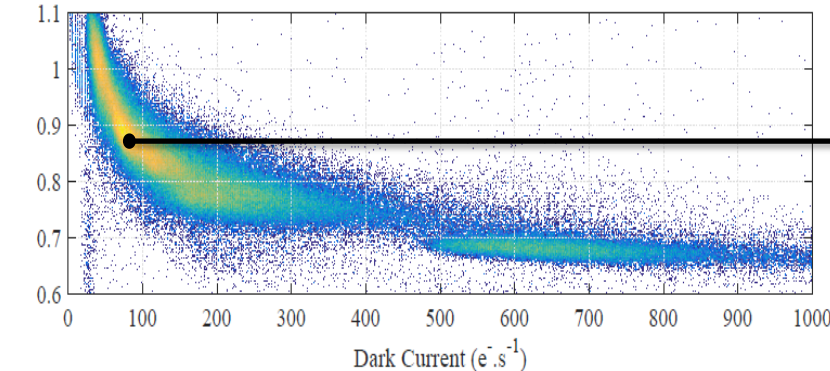
- Diffusion peak
  - $I_{dc} \sim 30 e^-/s$  (20°C)
  - $E_a \sim 0,95 eV$

**2**  
Carbon ion



- First generation peak (remaining)
  - $\Delta I_{dc} \sim 30 e^-/s$  (20°C)
  - $E_a \sim 0,83 eV$

**3**  
Low energy proton





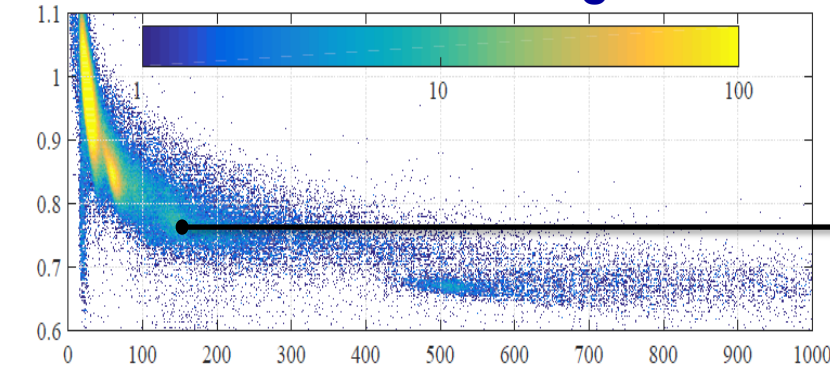
## 300°C annealing

Last annealing at 300°C

- Diffusion peak
  - $I_{dc} \sim 30 e^-/s$  (20°C)
  - $E_a \sim 0,95 eV$
- First generation peak (remaining)
  - $\Delta I_{dc} \sim 30 e^-/s$  (20°C)
  - $E_a \sim 0,83 eV$
- Second generation peak ?
  - $\Delta I_{dc} \sim 150 e^-/s$  (20°C)
  - $E_a \sim 0,75 eV$

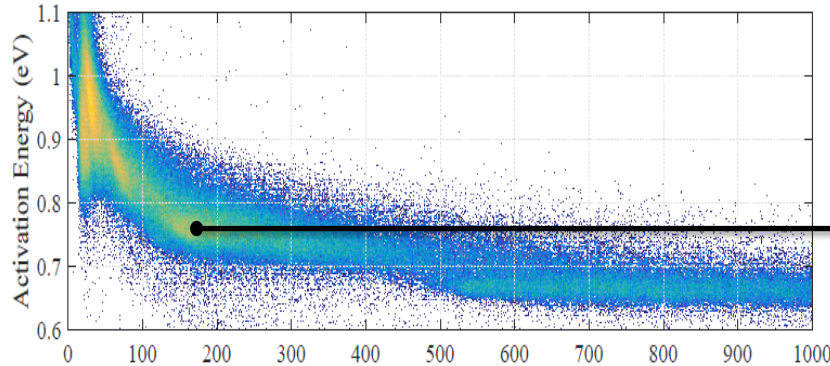
1

High-energy proton



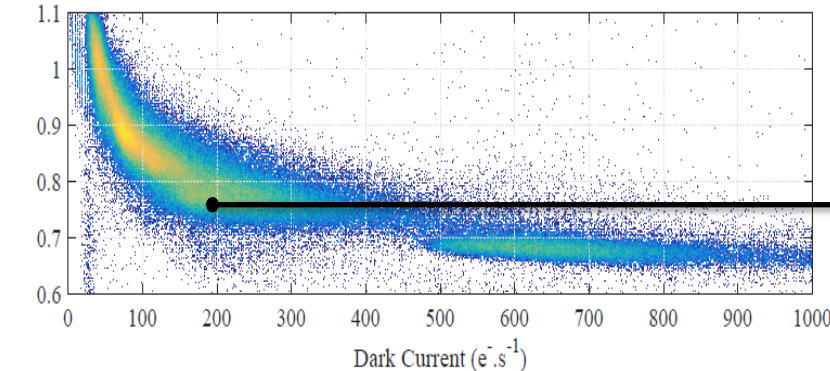
2

Carbon ion



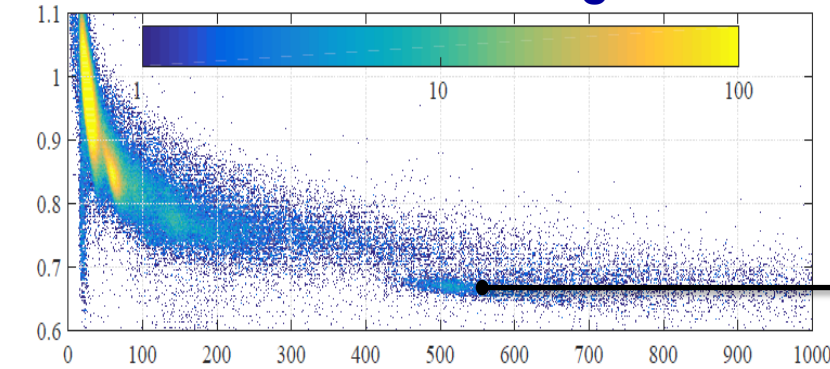
3

Low energy proton

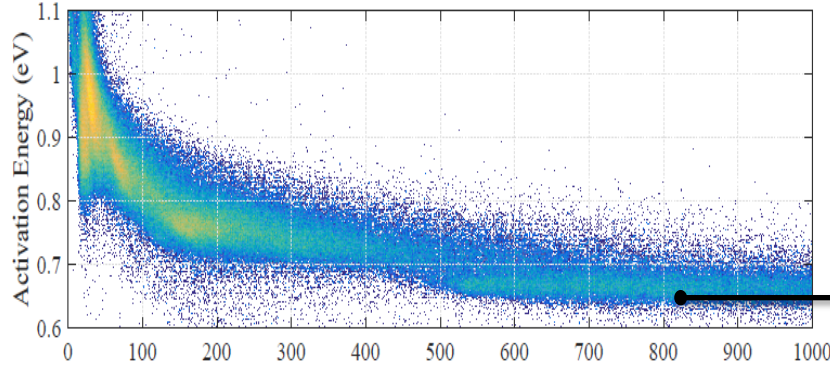


## 300°C annealing

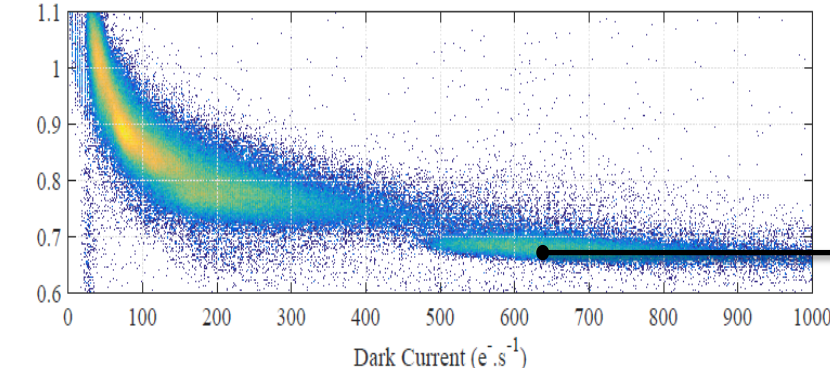
**1**  
High-energy proton



**2**  
Carbon ion



**3**  
Low energy proton

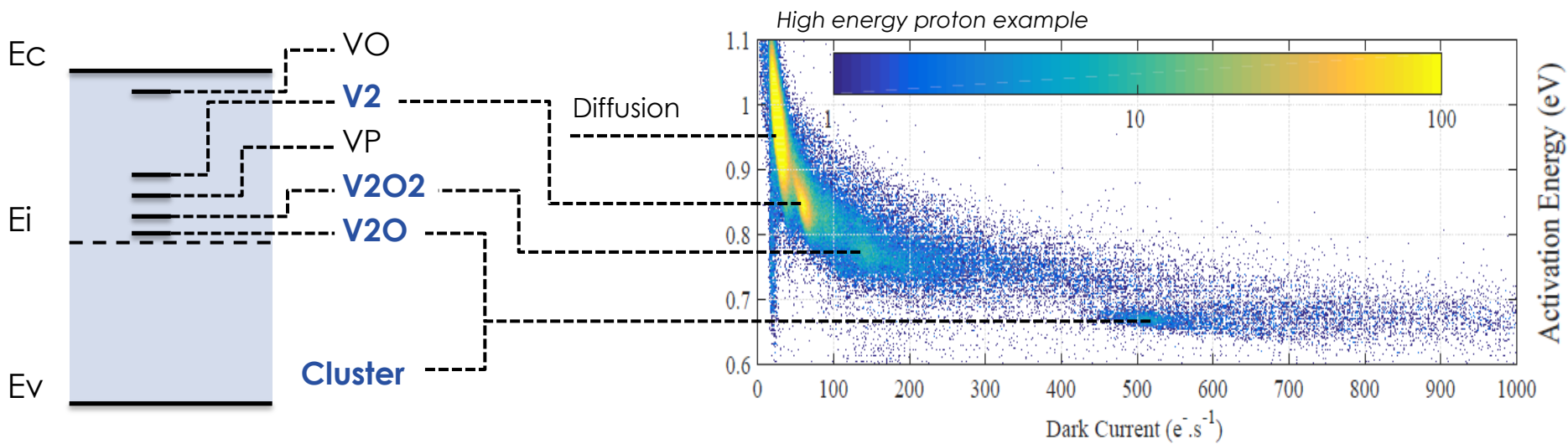


Last annealing at 300°C

- Diffusion peak
  - $I_{dc} \sim 30 e^-/s$  (20°C)
  - $E_a \sim 0,95 eV$
- First generation peak (remaining)
  - $\Delta I_{dc} \sim 30 e^-/s$  (20°C)
  - $E_a \sim 0,83 eV$
- Second generation peak ?
  - $\Delta I_{dc} \sim 150 e^-/s$  (20°C)
  - $E_a \sim 0,75 eV$
- Third generation peak
  - $\Delta I_{dc} \sim 600 e^-/s$  (20°C)
  - $E_a \sim 0,67 eV$

Defect	20°C Dark Current (e-/s)		Et-Ei  (eV)		Annealing Temperature	
Vacancy-Oxygen <b>VO</b>		-		~0,39		> 300°C
Divacancy <b>V2</b>	<b>~[26-30]</b>	~30	<b>~0,18</b>	~0,17	<b>[240°C-280°C]</b>	260°C
Divacancy-Dioxygen <b>V2O2</b>	<b>150</b>	-	<b>~0,11</b>	~0,16	<b>&gt; 300°C</b>	> 300°C
Vacancy-Phosphorus <b>VP</b>		~35		~0,13		150°C
Divacancy-Oxygen <b>V2O</b>	<b>~[500-600]</b>	-	<b>~0,01</b>	~0,06	<b>&gt; 300°C</b>	> 330°C

**Experimental Datas**



- 4 COTS imagers have been irradiated with:
  - High energy proton / Carbon ion / Low energy proton



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- The hypothetical existence of oxygen based defects such as  $V_2O$  and  $V_2O_2$  have been pointed out.
  - The role of oxygen impurities in the dark current rise after irradiation.

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Oxygen concentration



Minimum impurity concentration in pure Si

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Oxygen concentration



Minimum impurity concentration in pure Si

- The DCS measurements suggest that similar divacancy based defects are involved in all the irradiations.



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Thanks for your attention

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## IRRADIATION PARAMETERS

Sensor Ref	A	B	# (for UDF)	C	D
Particles	Proton	Proton	Proton	Proton	Carbon
Energy (Mev)	50	150	50	1	10
Fluence (cm-2)	1,30 E+11	3,00 E+11	2,00 E+11	3.00 E+8	1.00 E+10
DDD (Tev.g-1)	504,4	645	776	+	++
TID (KradSi)	20,49	21,02	315,2	-	-

### High energy proton

- Good NIEL estimation
- DDD Nuclear chocs
- Cluster of defects

### Low energy proton

- Huge NIEL at End Of Range (EOR)
- Huge DDD
- Coulombic interactions
- Point defects

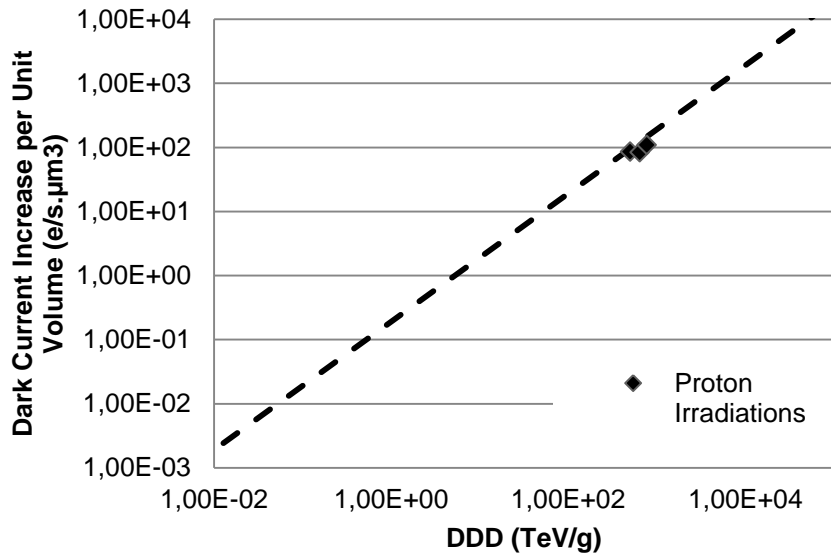
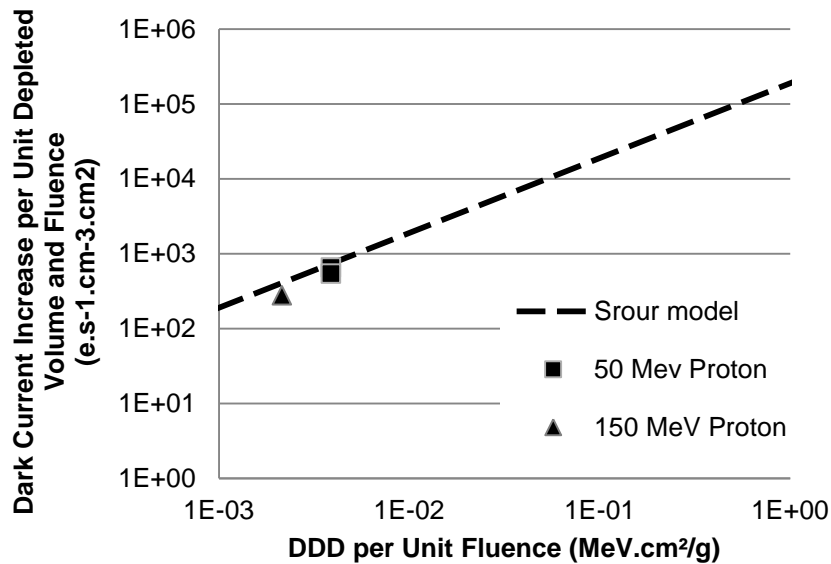
### Carbon ion

- Huge cross section and mass
- DDD Nuclear chocs
- Cluster of defects

Sensor Ref	A	B	C
Particles	Proton	Proton	Proton
Energy (Mev)	50	150	50
Fluence (cm-2)	1,30 E+11	3,00 E+11	2,00 E+11
DDD (TeV.g-1)	504,4	645	776
TID (KradSi)	20,49	21,02	315,2
$\Delta I$ (e-/s)	415	424	542

$$V_{dep} = 5\mu m^3$$

$$K_{dark} = 1.9 \times 10^5 (e/cm^3.s)/(MeV/g)$$



## IRRADIATION PARAMETERS

Sensor Ref	A	B	C	D
Particles	Proton	Proton	Proton	Carbon
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