Session 4: Detectors – O20

Determination of Radiation Hardness of Silicon Diodes.

Ettore Vittone
Physics Department - University of Torino (I)
Italian National Institute for Nuclear Physics

What

Object of the research

Study of the radiation hardness of a commercially available silicon photo-diode commonly used as a nuclear detector

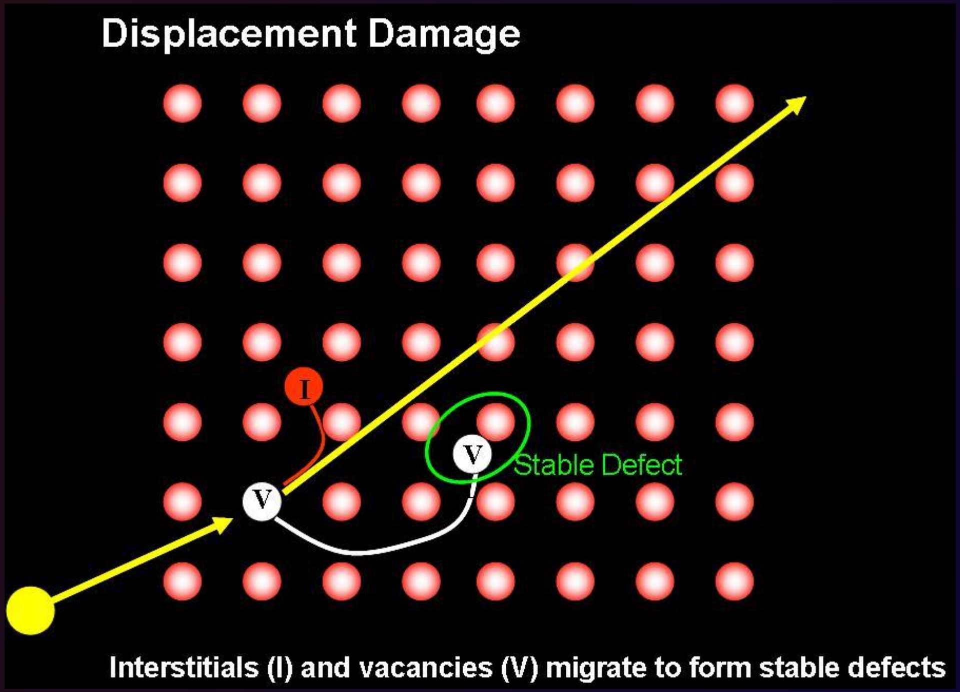
Tool

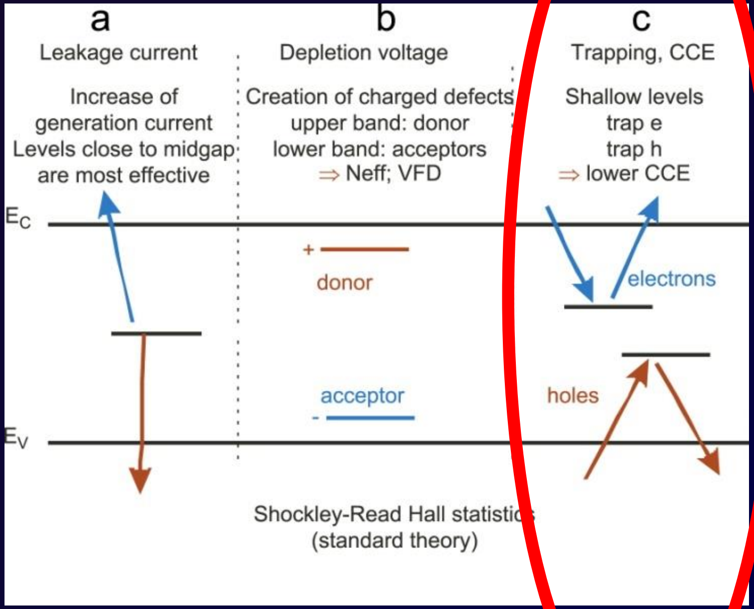
Focused MeV Ion beams

to induce the damage **to probe the damage**

Radiation damage is the general alteration of the operational properties of a semiconductor devices induced by ionizing radiation

- Displacements. Dislocations of atoms from their normal sites in the lattice, producing less ordered structures, with long term effects on semiconductor properties





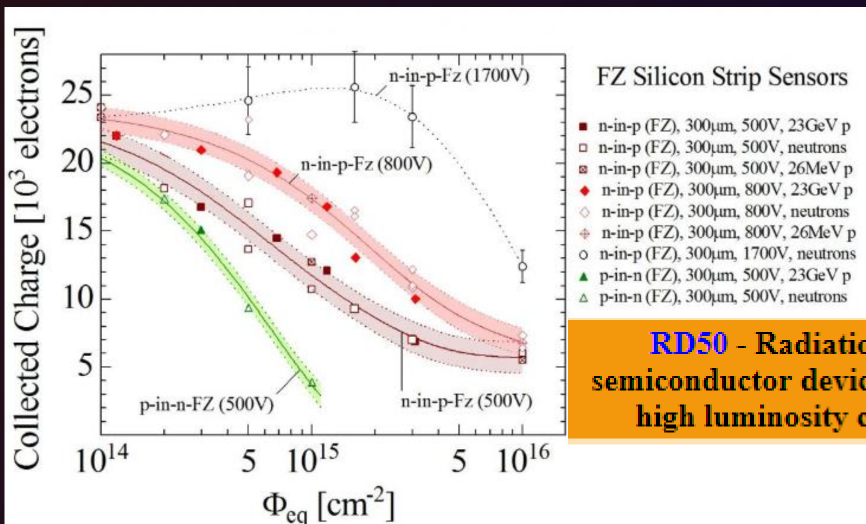
http://holbert.faculty.asu.edu/eee560/RadiationEffectsDamage.pdf

WHY

ELSEVIER
Nuclear Instruments and Methods in Physics Research A 426 (1999) 1–15
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

Radiation hardness of silicon detectors – a challenge from high-energy physics

G. Lindström*, M. Moll, E. Fretwurst



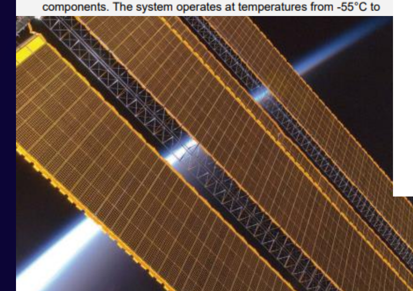
RD50 - Radiation hard semiconductor devices for very high luminosity colliders

Instrumentation

Method and Apparatus for In Situ Monitoring of Solar Cells

A novel approach to solar cell monitoring

NASA's Glenn Research Center has developed a method and apparatus for in situ health monitoring of solar cells. The innovation a novel approach to solar cell monitoring, as it is radiation-hard, consumes few system resources, and uses commercially available components. The system operates at temperatures from -55°C to



National Aeronautics and Space Administration

APPLICATIONS

The technology has several potential applications:

- Solar cell monitoring for manned and unmanned spacecraft
- Diagnostics for terrestrial solar power generation systems

PUBLICATIONS

Patent No: 8,159,238; 9,419,558

Patent Pending

WHY it is relevant to the ICNMTA community

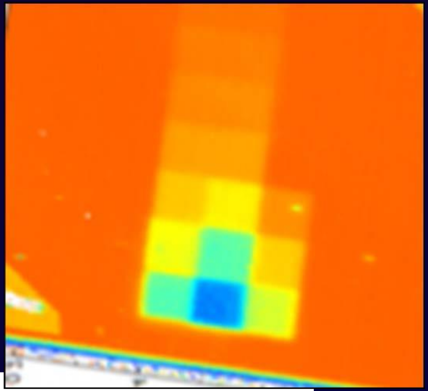
10 contributions mentioning STIM
6 contributions mentioning IBIC

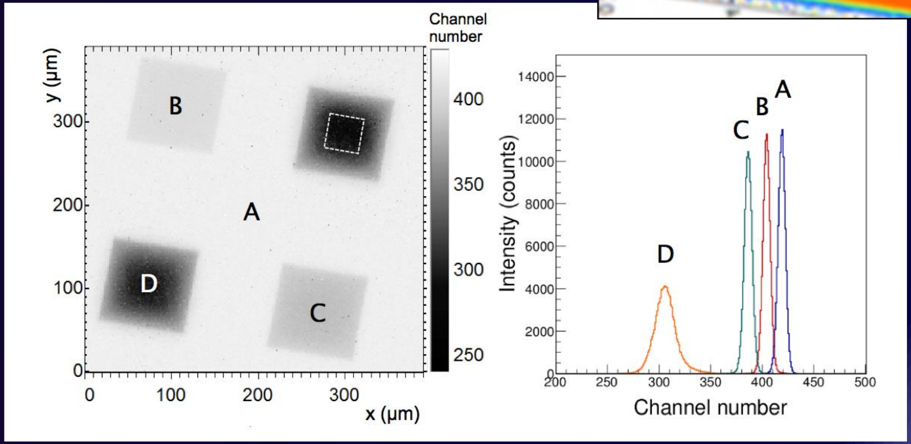
Biomedical Applications
Facilities & Techniques
Detectors
Quantum Devices

8 contributions mentioning STIM

13 contributions mentioning STIM

15 contributions mentioning STIM





Credit: Milko Jaksic

Characterization of radiation induced damage:

$$\eta = \frac{Y}{Y_0} = 1 - K \cdot \Phi = 1 - K_{ed} \cdot D_d$$

Device characteristic: Y after irradiation, Y_0 before irradiation

Particle Fluence (Φ)

Equivalent damage factor (K_{ed})

Displacement dose (D_d)

First order: proportionality, independent of the particle, between the damage factor and the particle NIEL

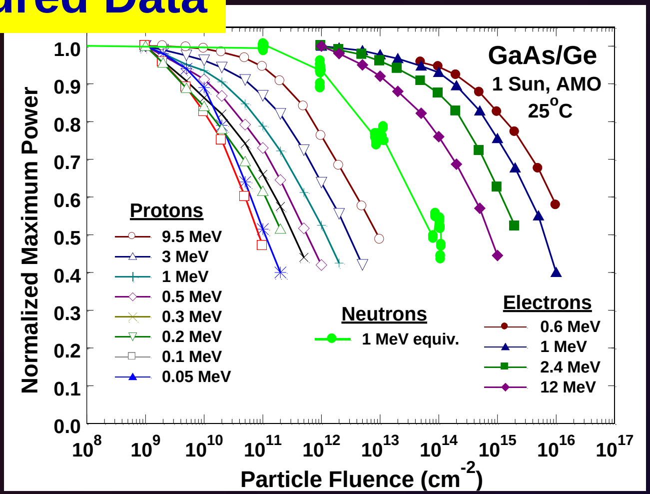
NIEL approach:

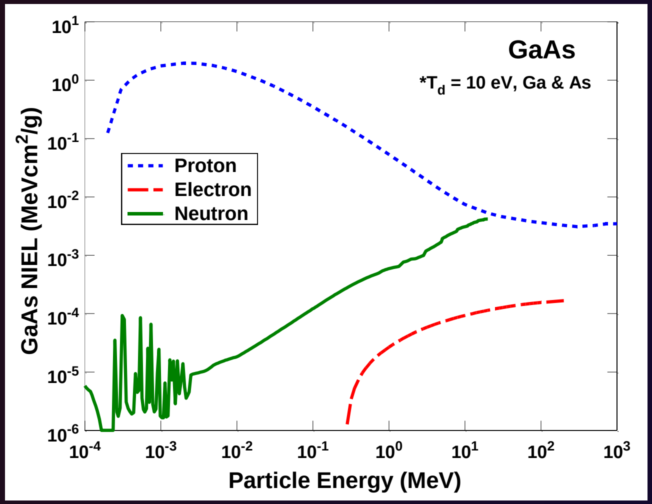
measurement of K_{ed} only for one particle (at one specific energy) → K_{ed} can be estimated for all the particles and energies

US Naval Research Laboratory (NRL)

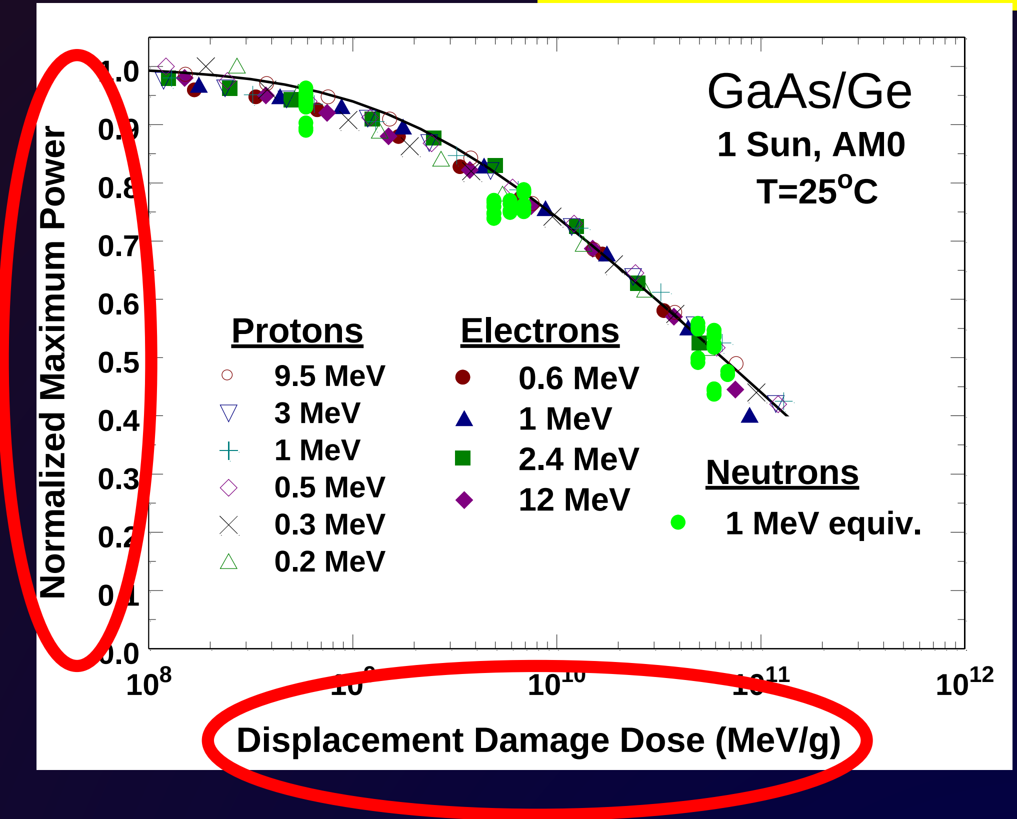
Displacement Damage Dose Method

Measured Data





Characteristic Curve

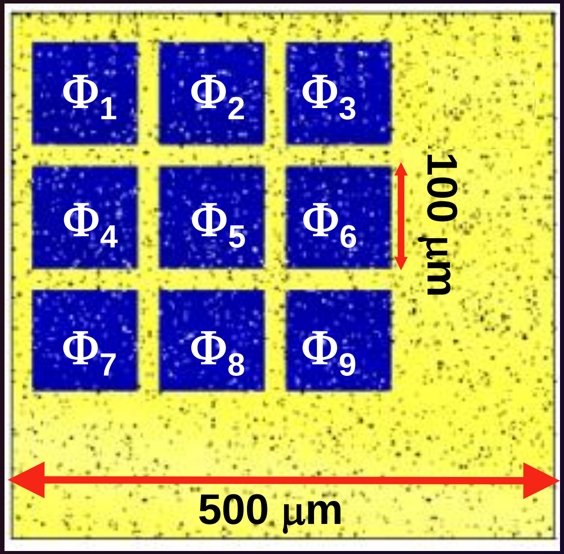


- Characteristic curve is independent of particle
- Calculated NIEL gives energy dependence of damage coefficients

S. Messenger, SPENVIS Workshop 2005

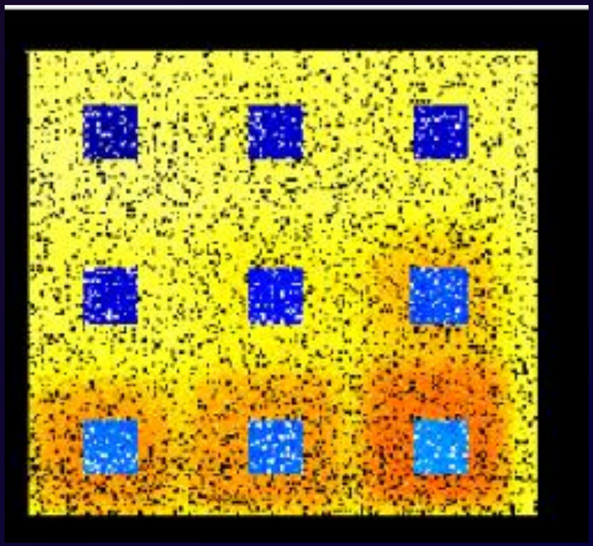
Physical Observable
Charge Collection Efficiency
Focused MeV Ion beams

to induce the damage



DIB
damaging ion beam

to probe the damage



PIB
probing ion beam

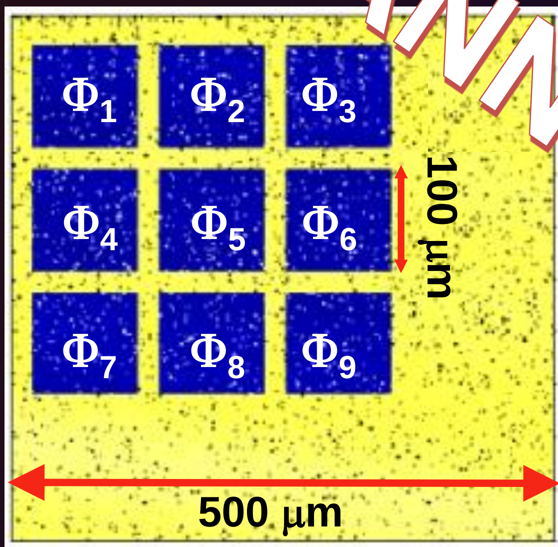
Physical Observable

Charge Collection Efficiency

Focused MeV Ion beams

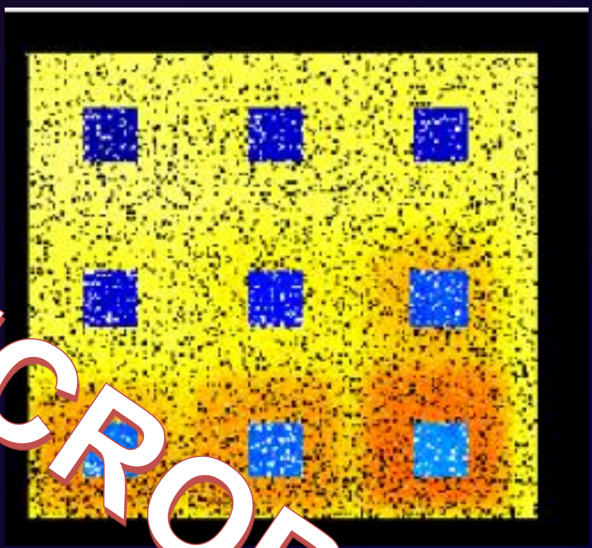
SCANNING MICROBEAM

to induce the damage



DIB
damaging ion beam

to probe the damage

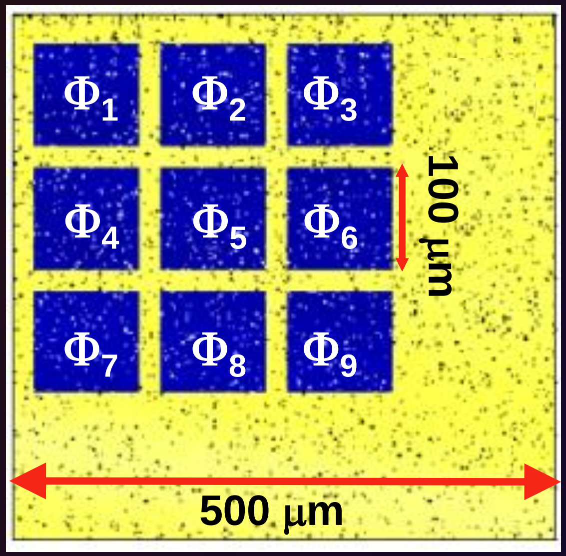


PIB
probing ion beam

Physical Observable
Charge Collection Efficiency

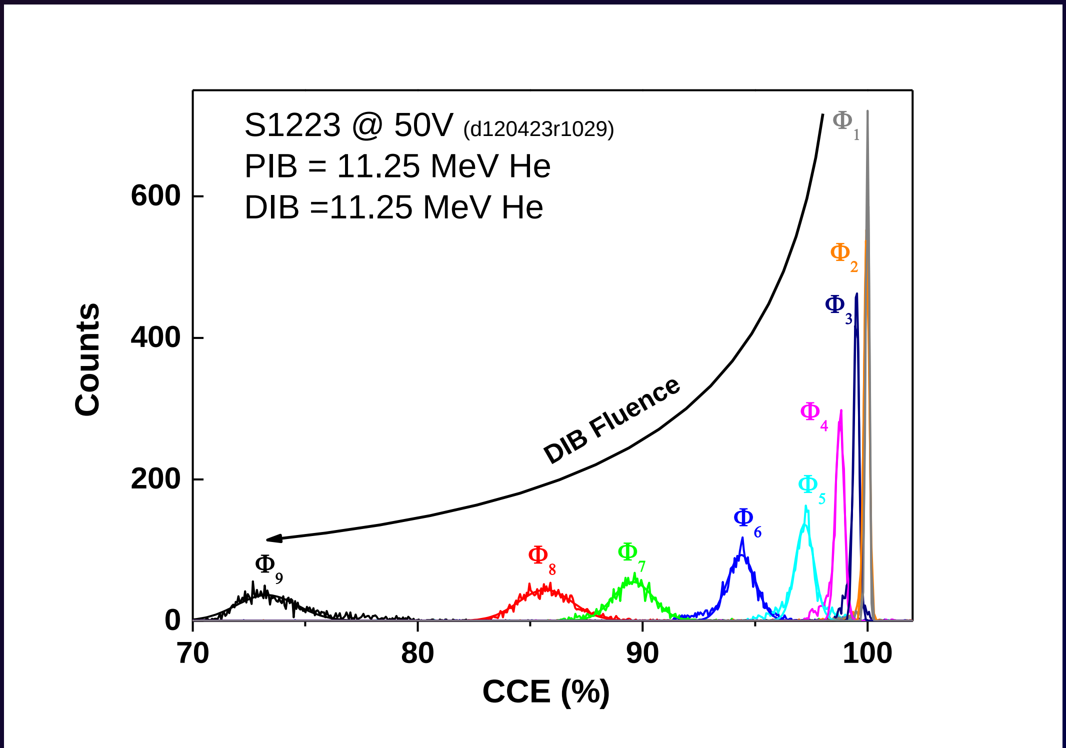
Focused MeV Ion beams

to induce the damage



DIB
damaging ion beam

to probe the damage

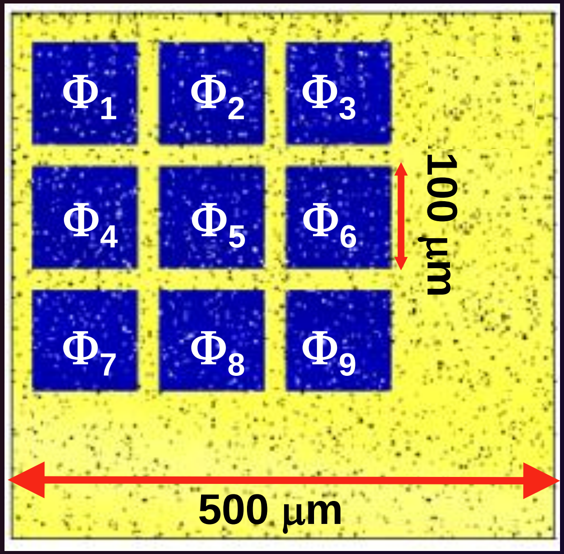


PIB
probing ion beam

Physical Observable
Charge Collection Efficiency

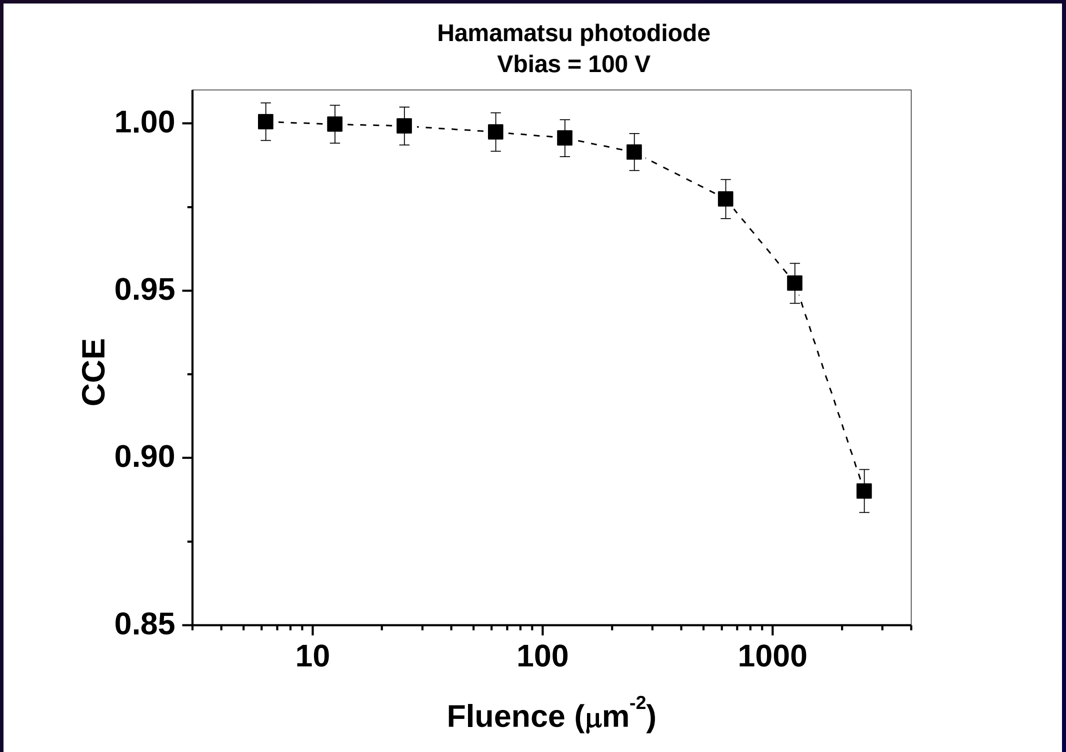
Focused MeV Ion beams

to induce the damage

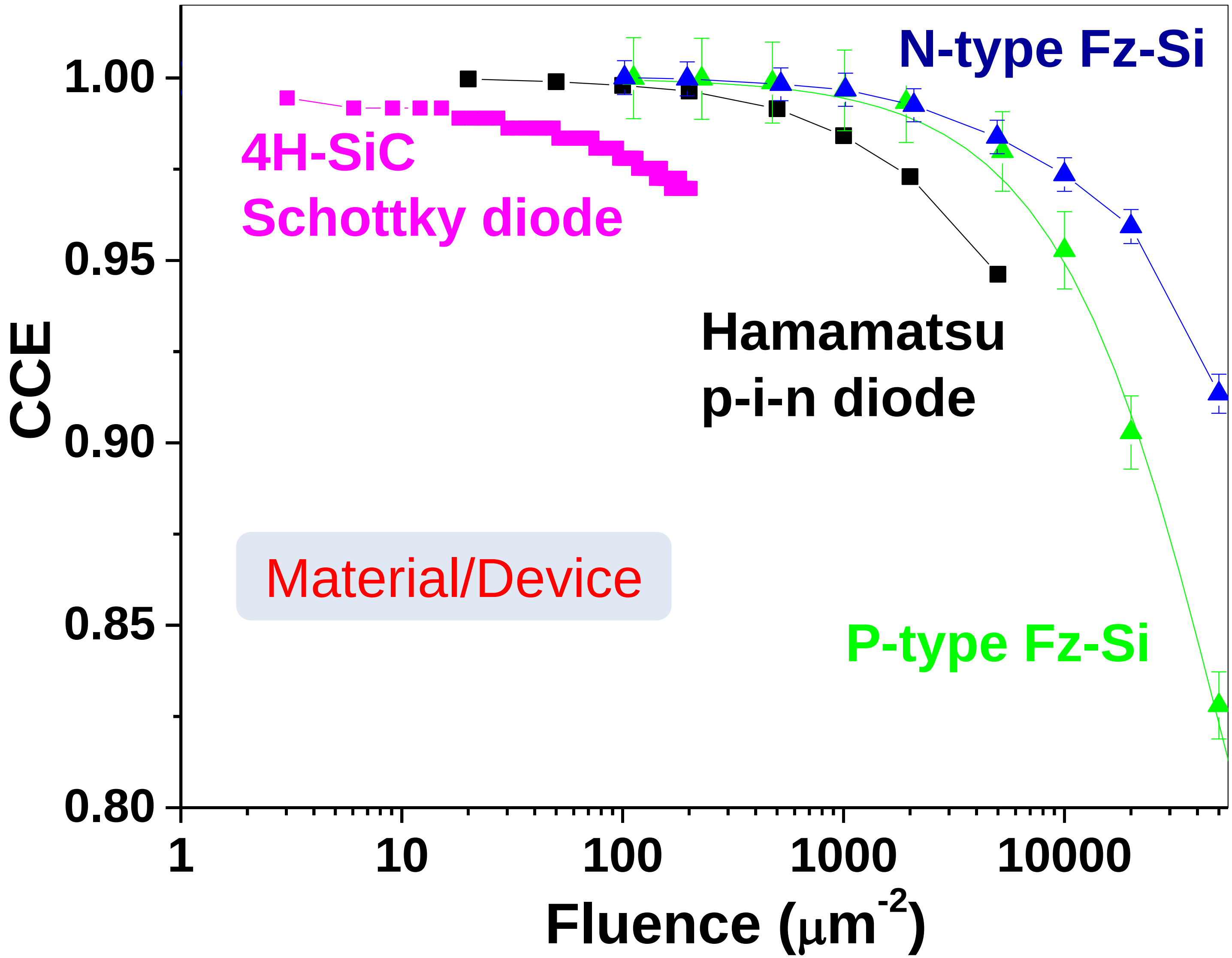


DIB = 2.15 MeV Li damaging ion beam

to probe the damage

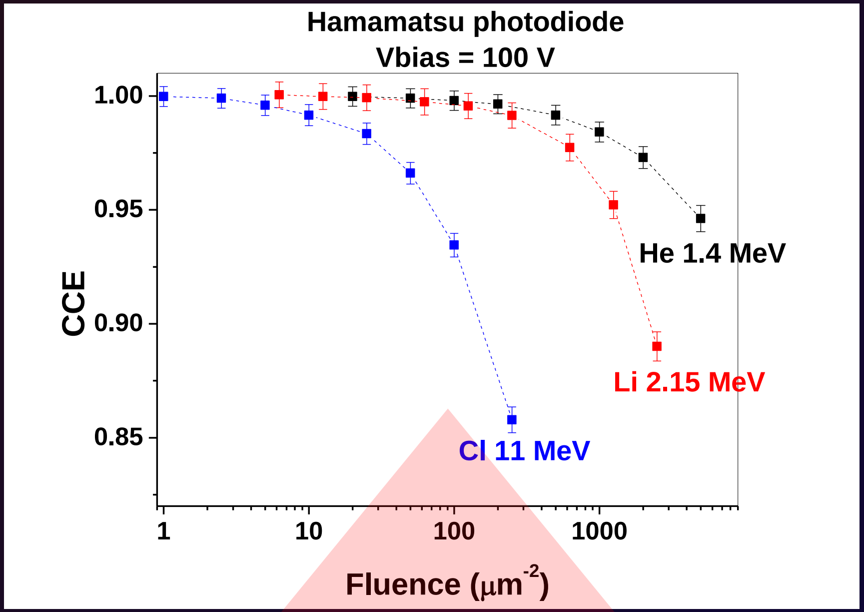


PIB = 1.4 MeV He probing ion beam



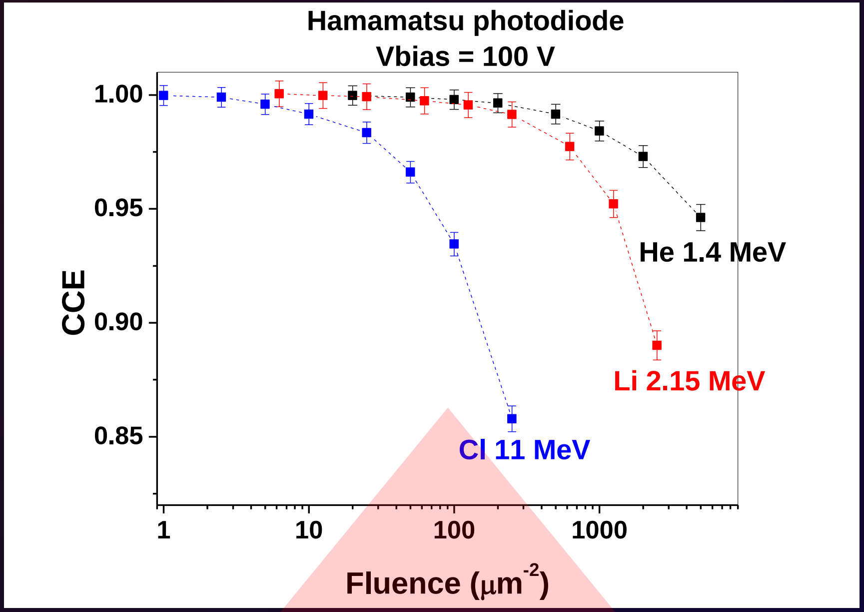
N-type Fz-Si
4H-SiC
Schottky diode
Hamamatsu
p-i-n diode
Material/Device
P-type Fz-Si
CCE
1.00
0.95
0.90
0.85
0.80
1
10
100
1000
10000
Fluence (μm^{-2})

Damaging Ion Mass/Energy Fluence



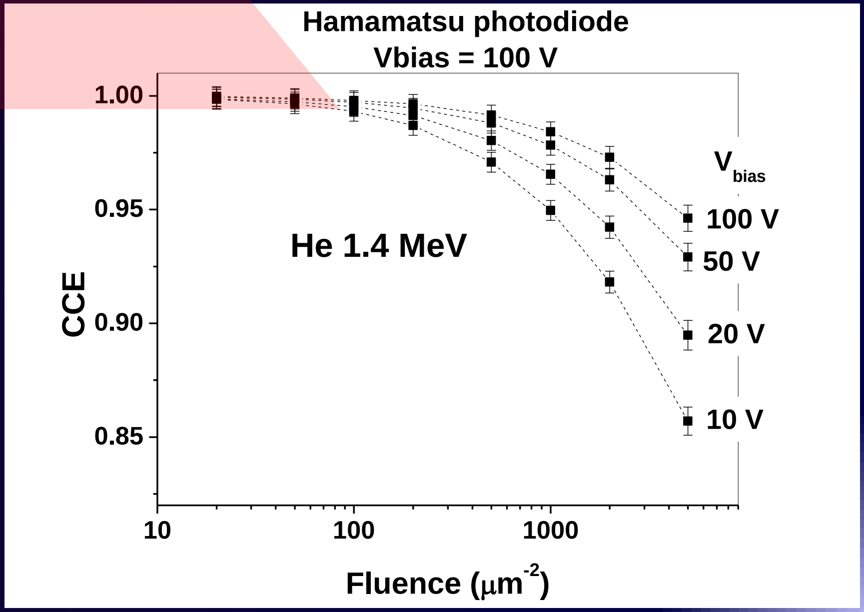
CCE DEGRADATION

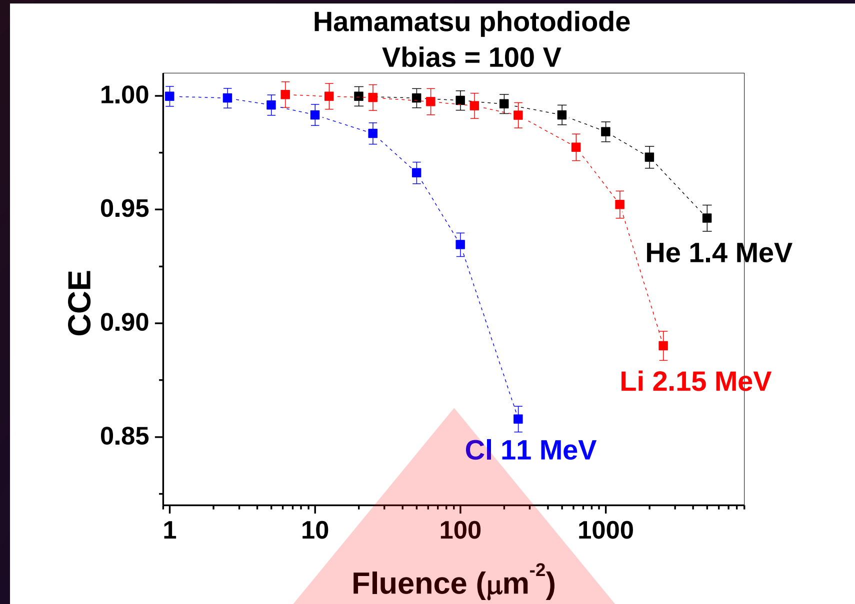
Damaging Ion Mass/Energy Fluence



CCE DEGRADATION

Electrostatics



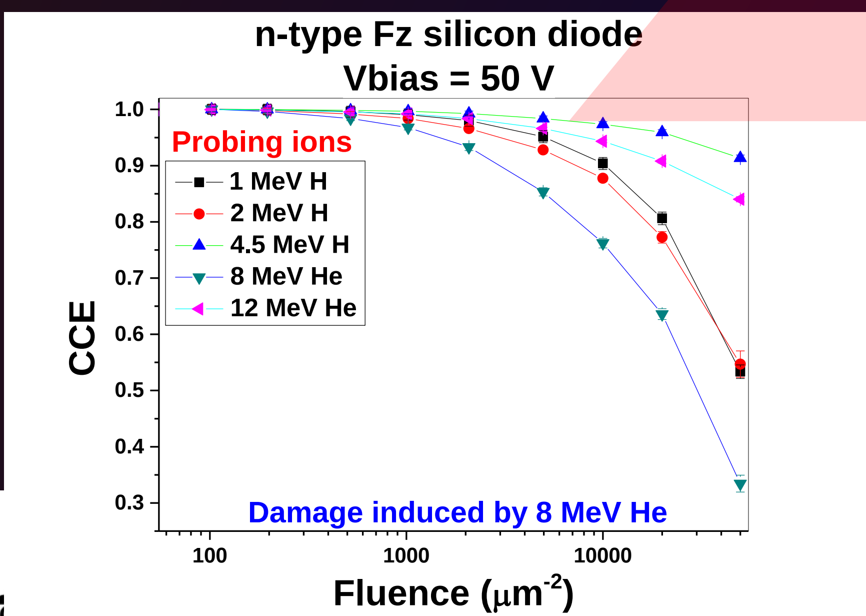


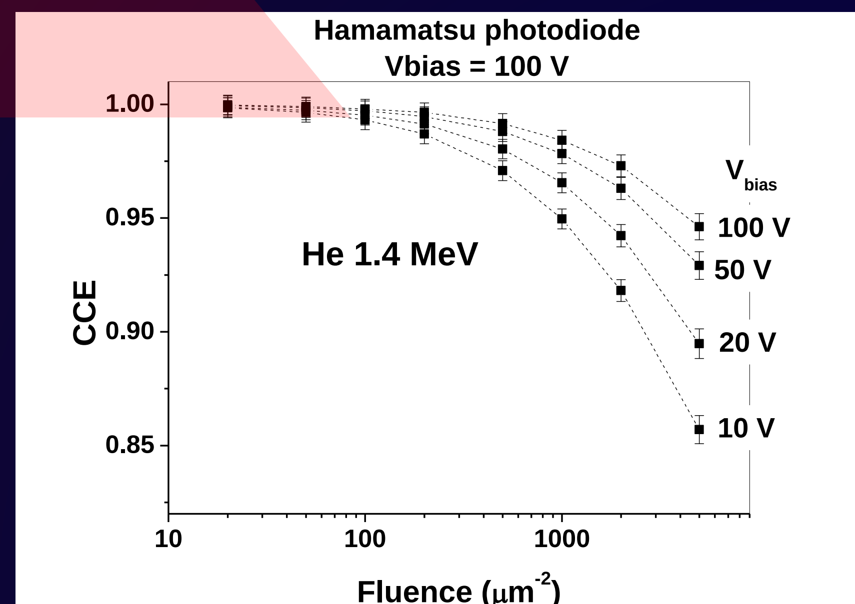
Damaging Ion Mass/Energy Fluence

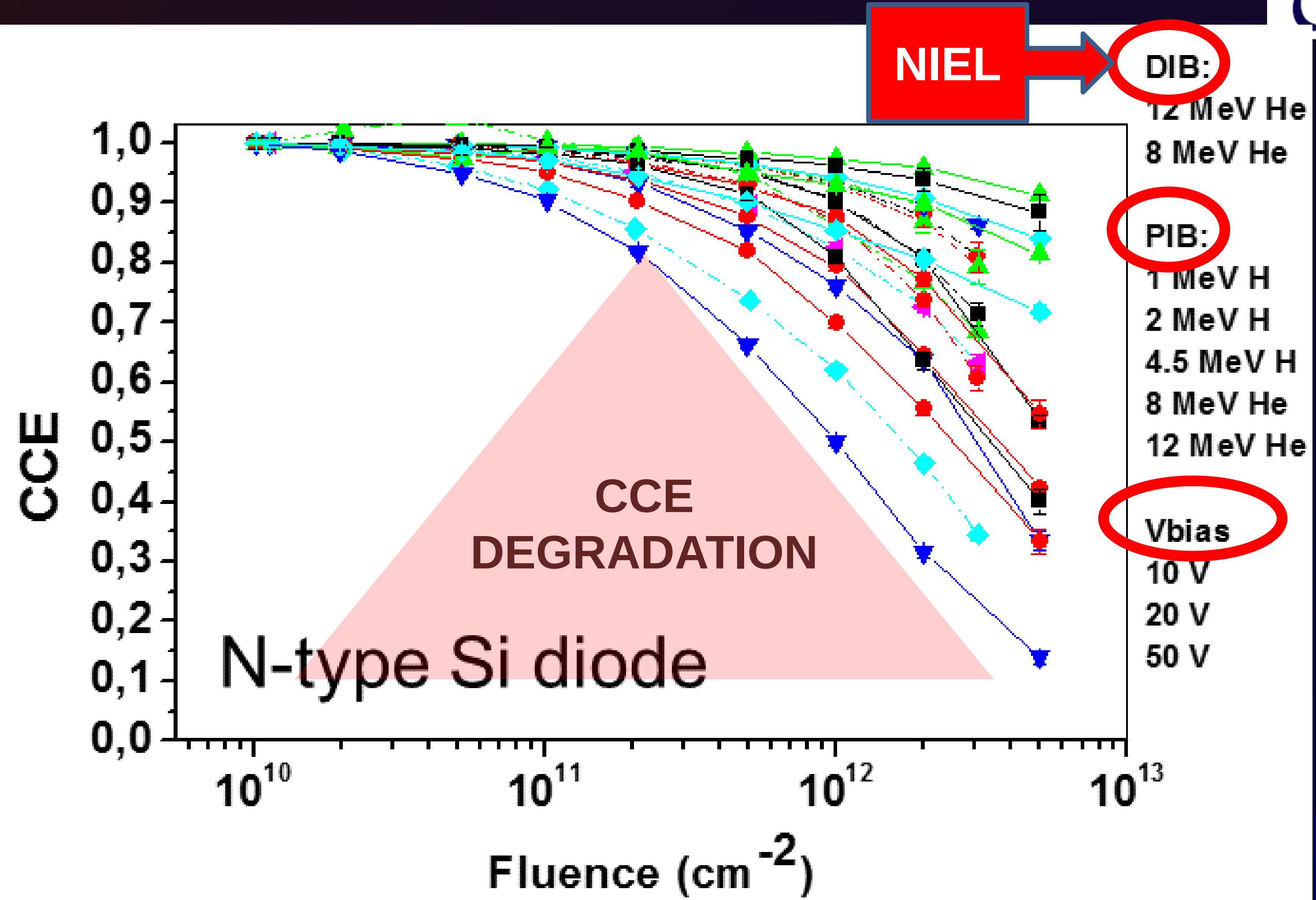
Probing Ion Mass/Energy

CCE DEGRADATION

Electrostatics







NIEL
DIB:
12 MeV He
8 MeV He
PIB:
1 MeV H
2 MeV H
4.5 MeV H
8 MeV He
12 MeV He
Vbias
10 V
20 V
50 V
CCE
CCE DEGRADATION
N-type Si diode
Fluence (cm -2)
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
10^10
10^11
10^12
10^13

IAEA Coordinate Research Programme (CRP) F11016 (2011-2015)

“Utilization of ion accelerators for studying and modeling of radiation induced defects in semiconductors and insulators”

CRP Outcome

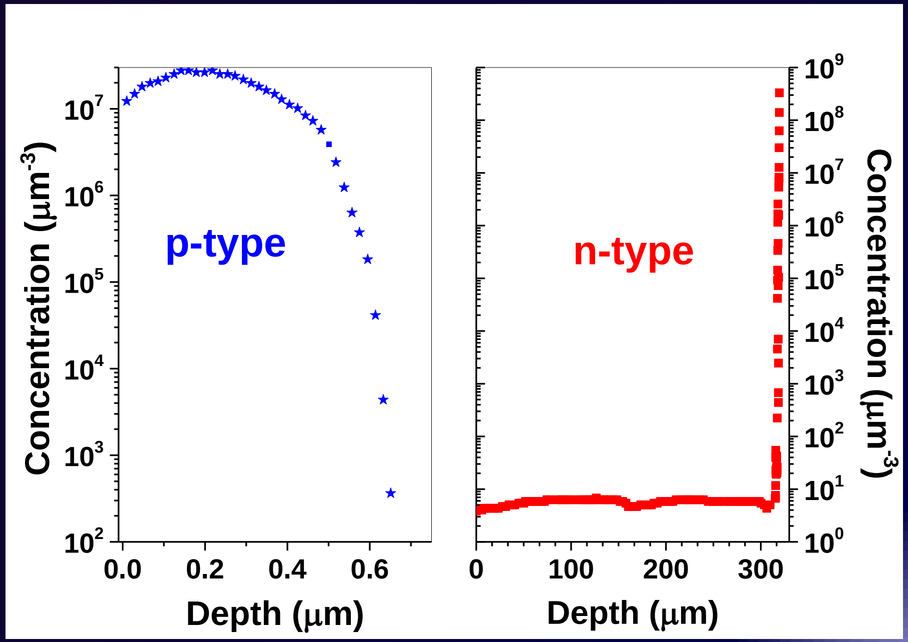
A methodology to establish material parameters which reflect semiconductor radiation hardness by their ability to predict CCE degradation as a function of accumulated structural radiation damage.

Sample under study

Commercially available p-i-n photodiode

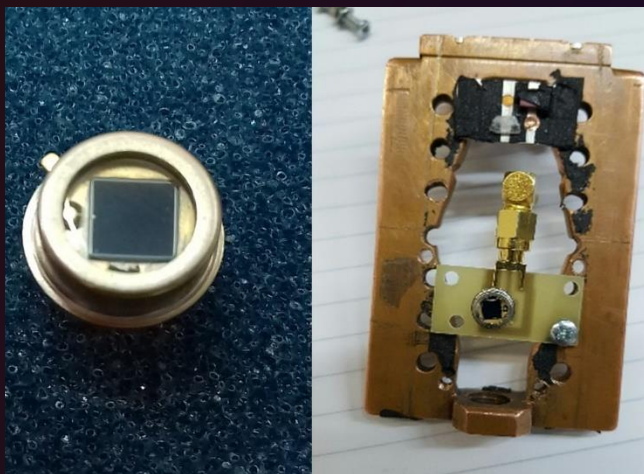
Electrical characterization

Doping profile:
Spreding Resistance

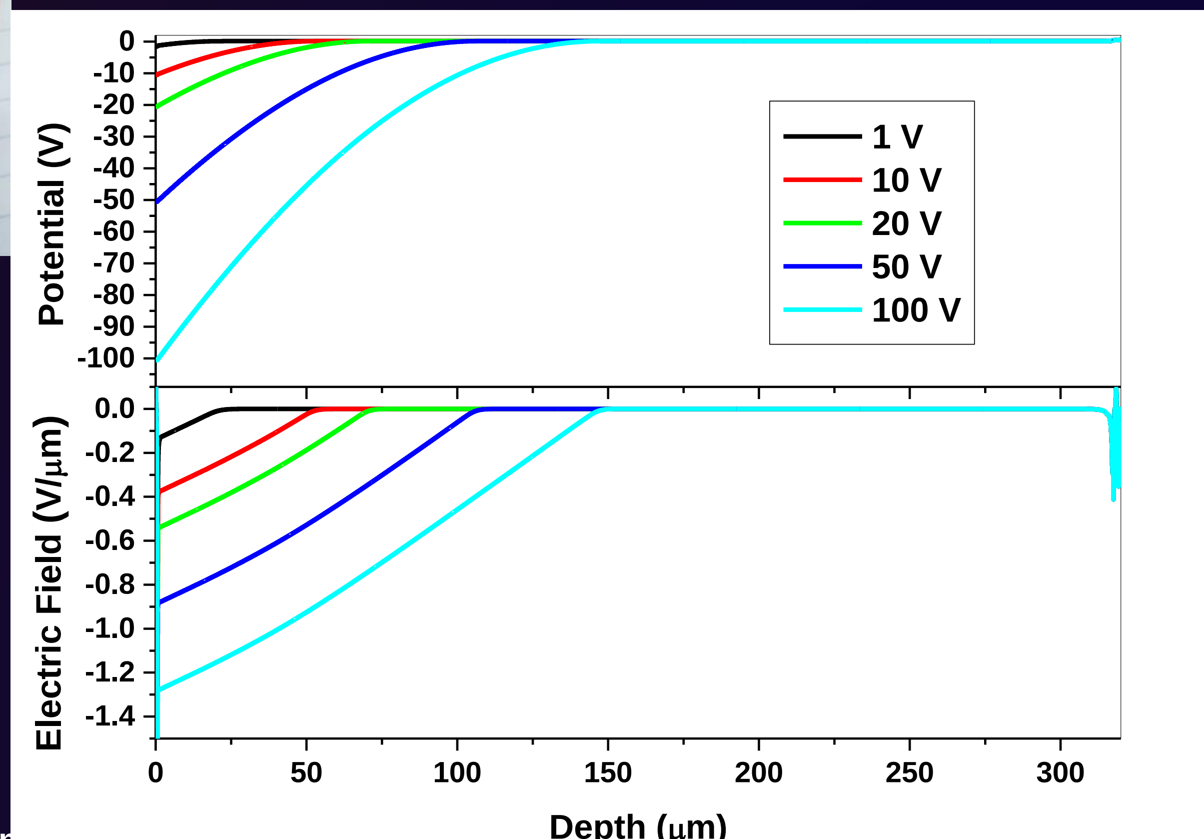


Sample under study

Commercially available p-i-n photodiode

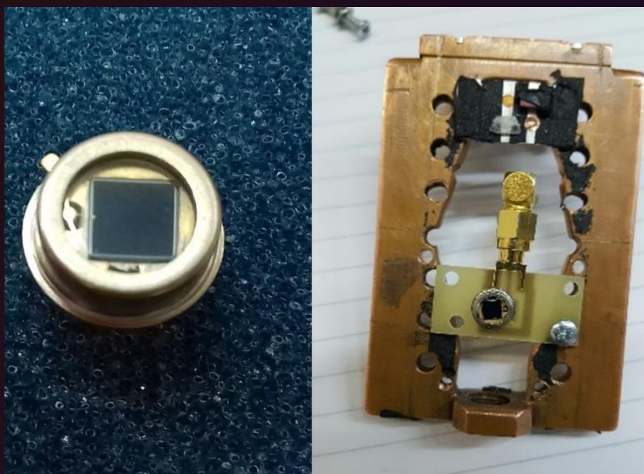


Device Modeling Electrostatics

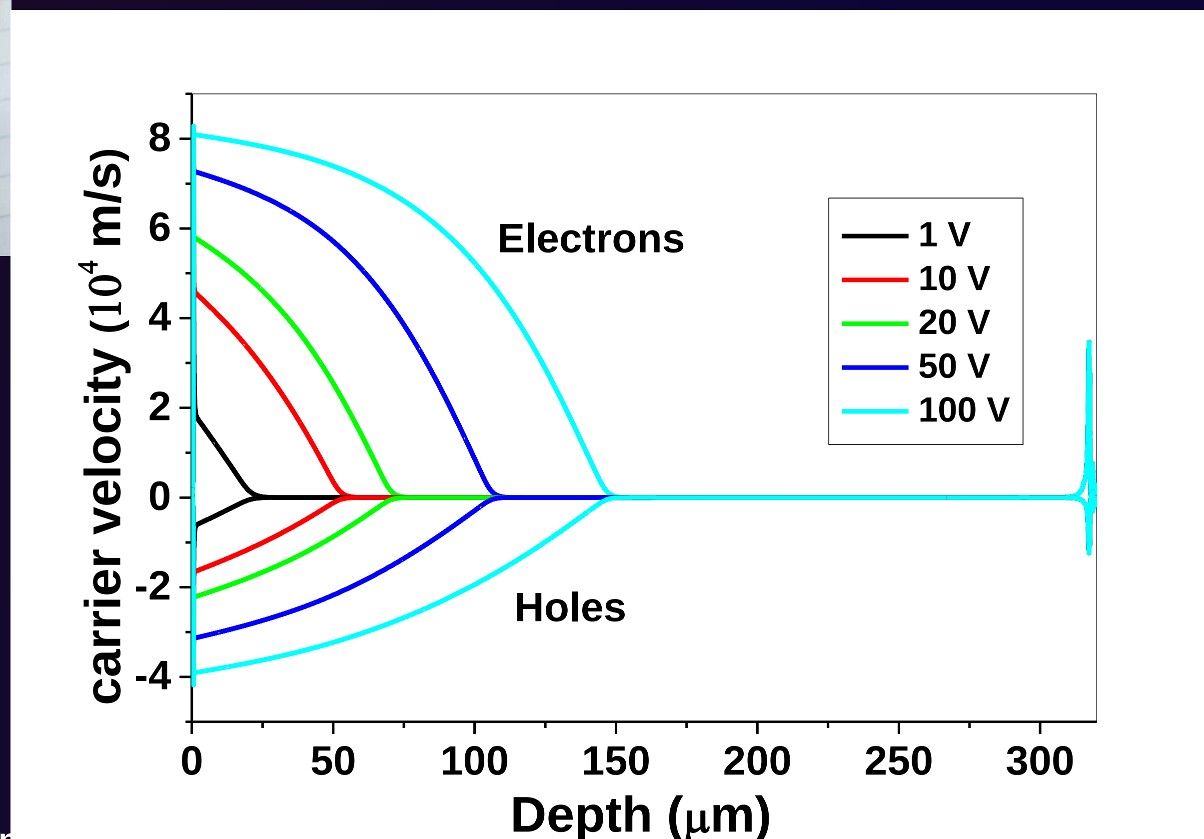


Sample under study

Commercially available p-i-n photodiode



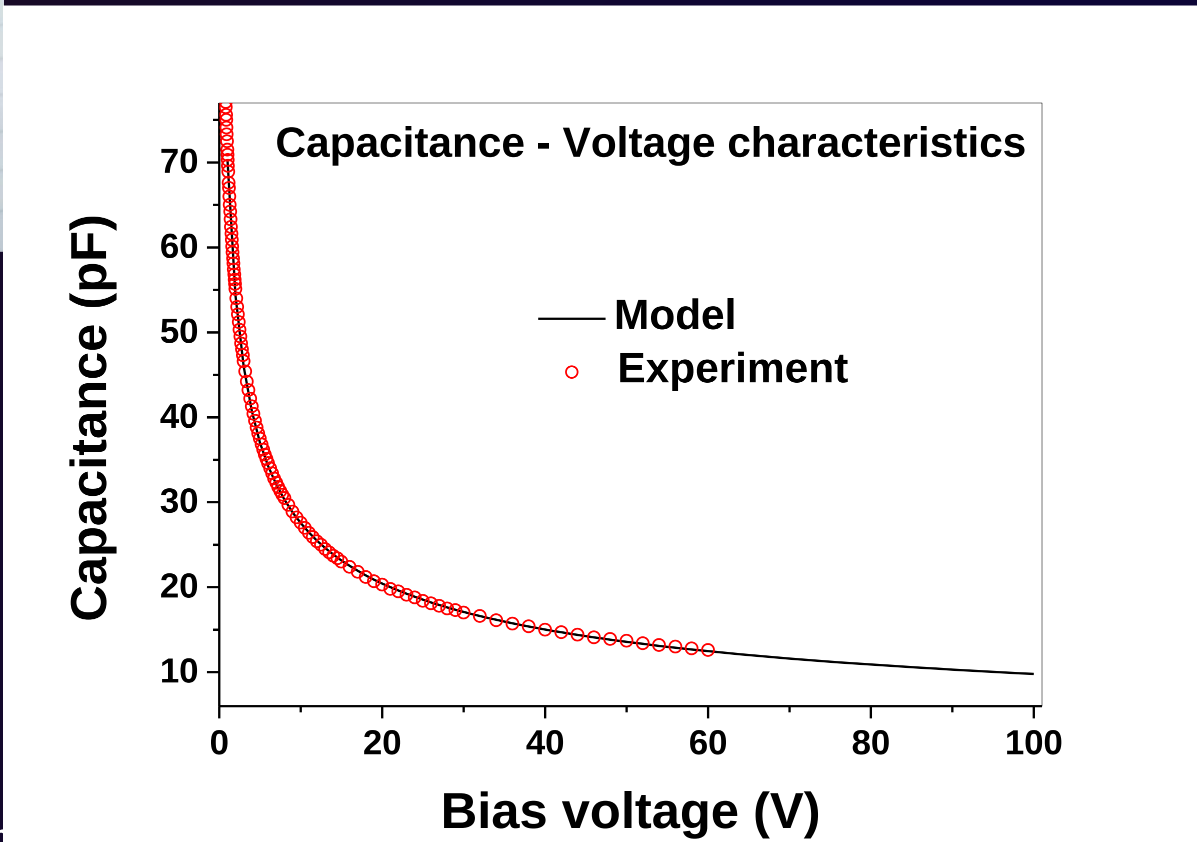
Device Modeling Transport



Sample under study

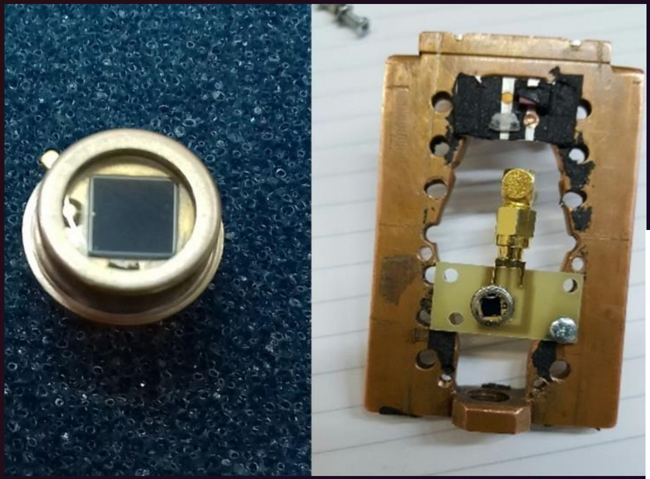
Commercially available p-i-n photodiode

Device Modeling Validation

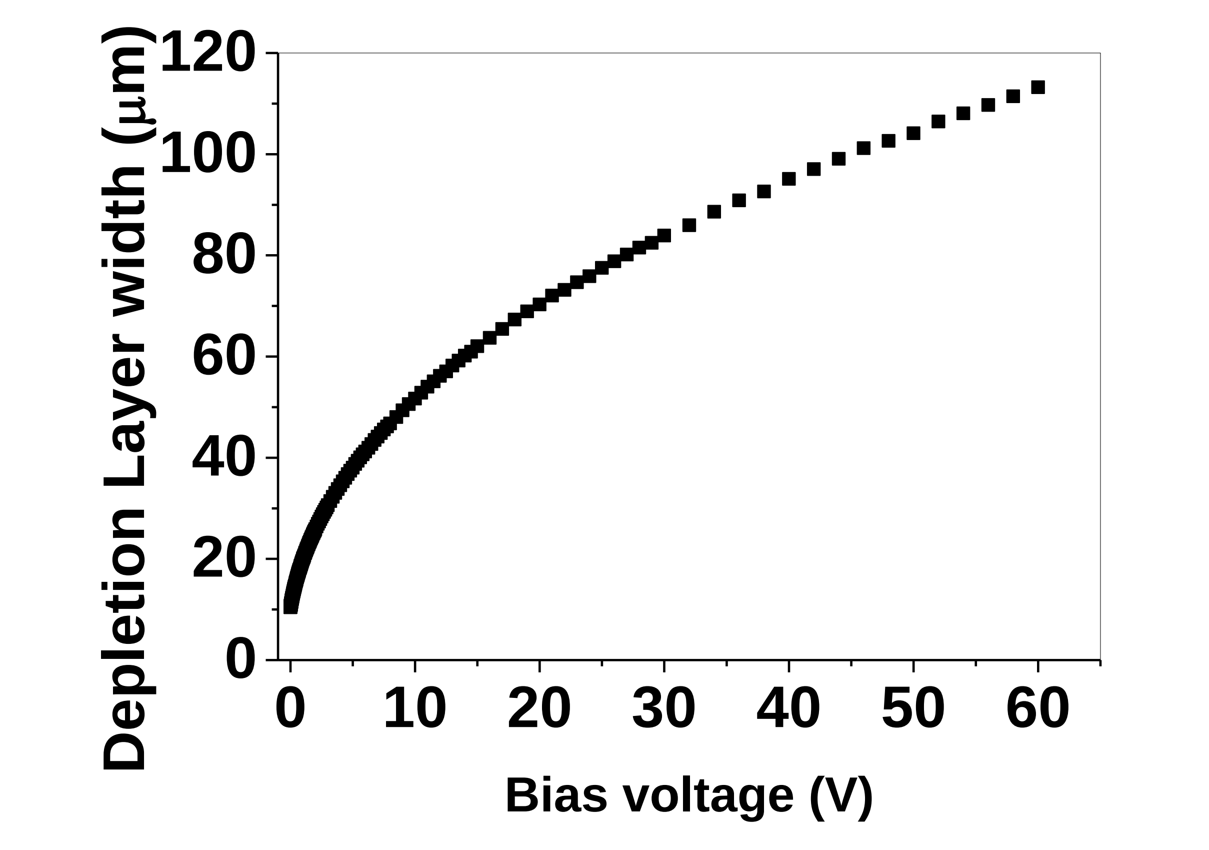


Sample under study

Commercially available p-i-n photodiode

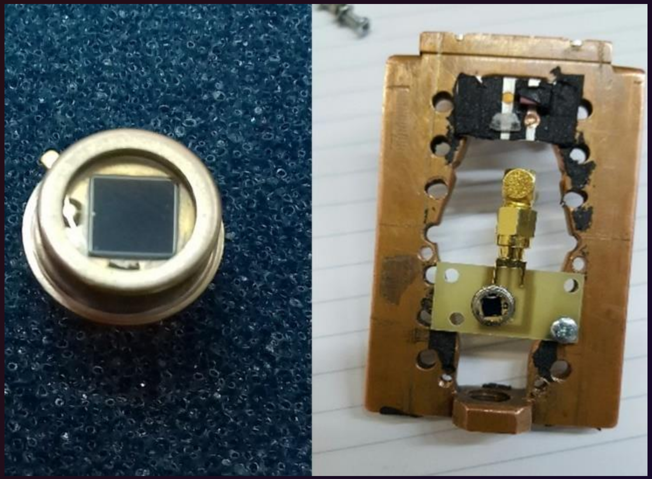


Device Modeling
Depletion Layer width

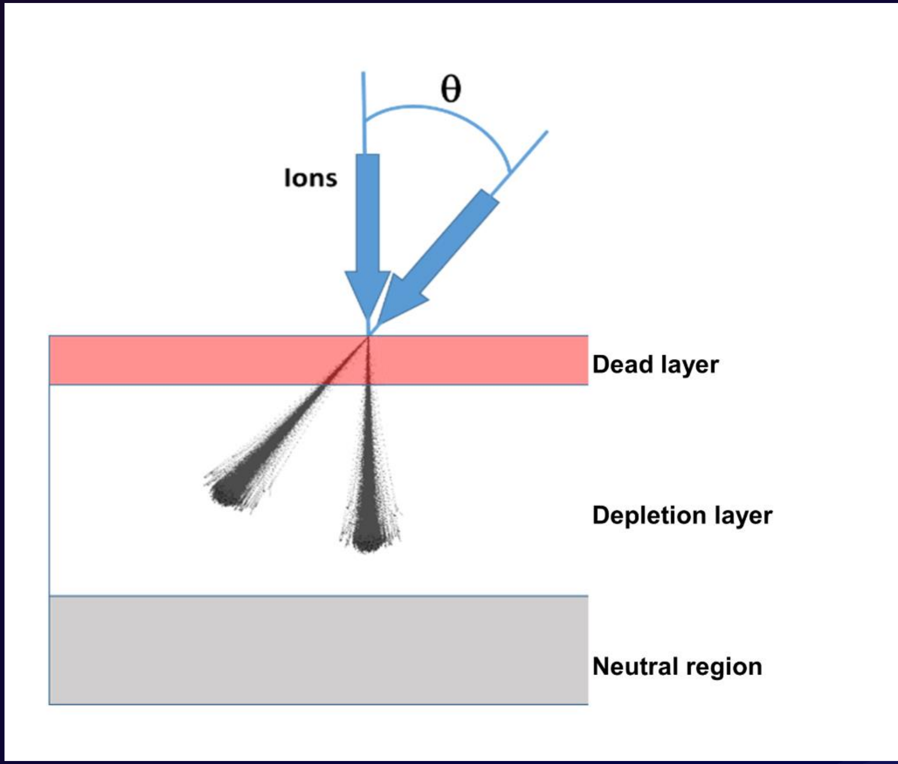


Sample under study

Commercially available p-i-n photodiode

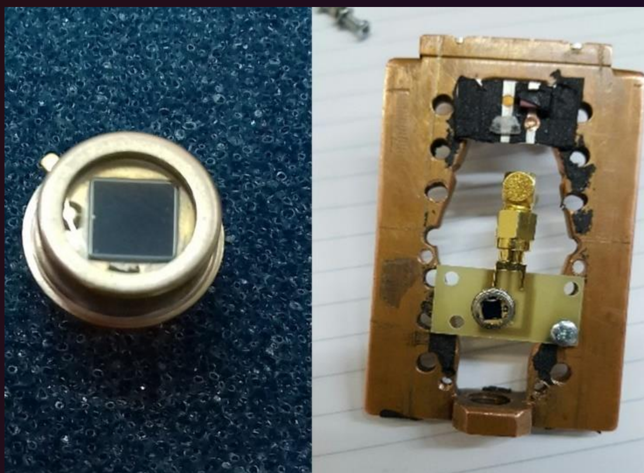


Dead layer
ARIBIC



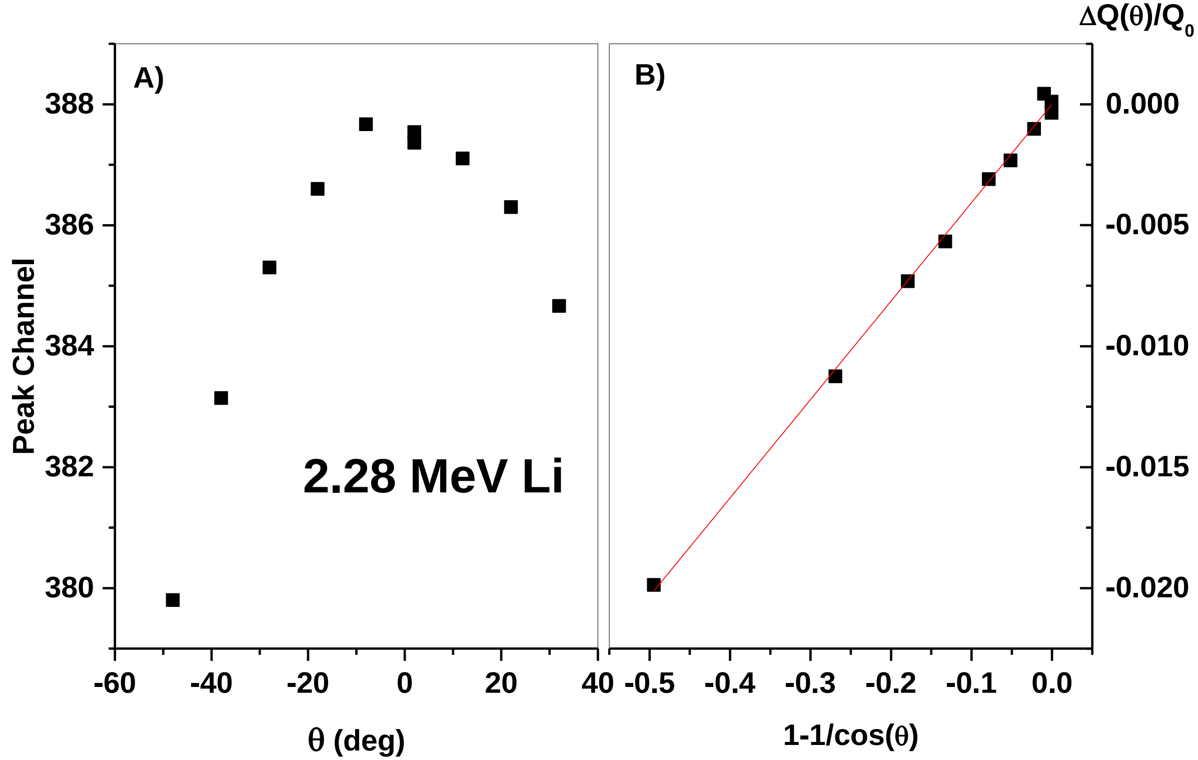
Sample under study

Commercially available p-i-n photodiode



Dead layer
ARIBIC

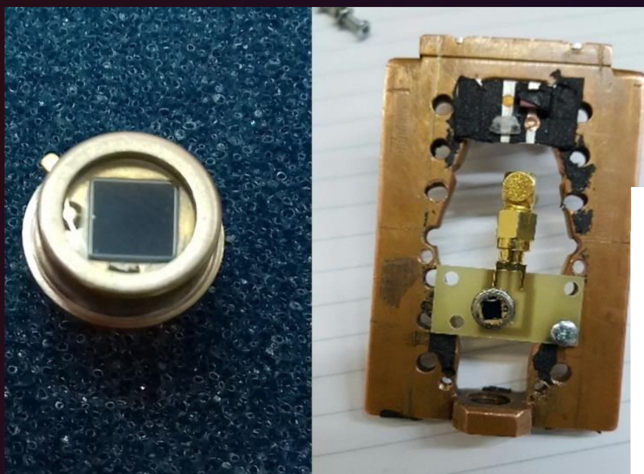
$$\frac{\Delta Q^*(\theta)}{Q_0} = \frac{1}{E_{\mathrm{ion}}} \frac{\mathrm{d}E}{\mathrm{d}x}\bigg|_0 t^* \cdot \left(1 - \frac{1}{\cos(\theta)}\right)$$



Effective thickness in Si
t^*=180 nm
RBS = 110 nm of SiO_2

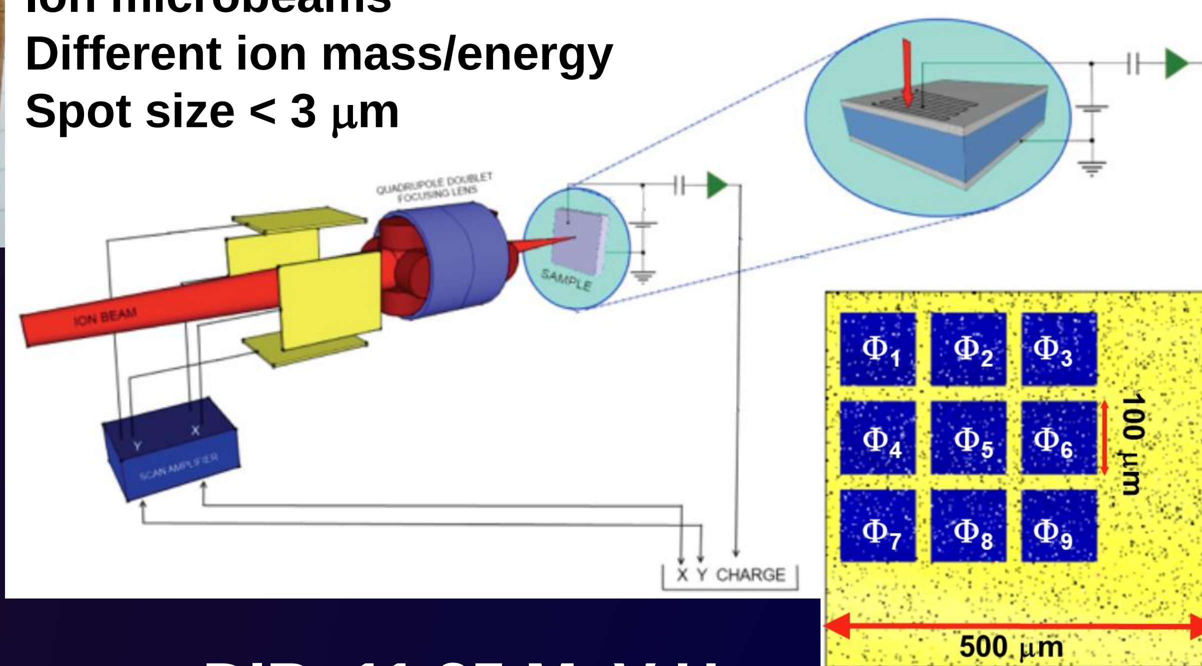
Sample under study

Commercially available p-i-n photodiode



Inducing the damage

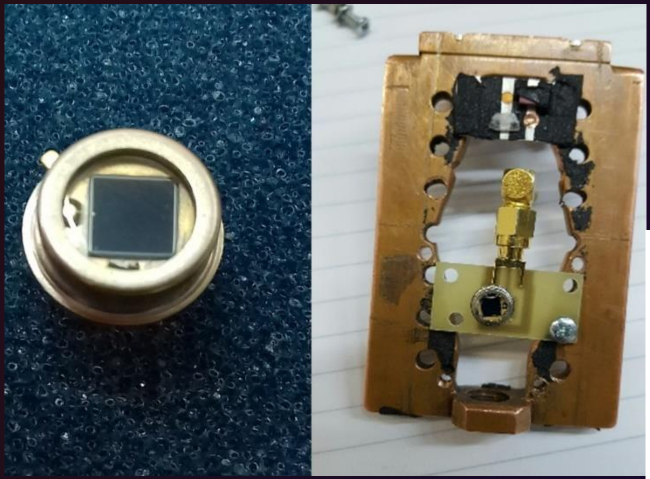
Ion microbeams
Different ion mass/energy
Spot size < 3 μm



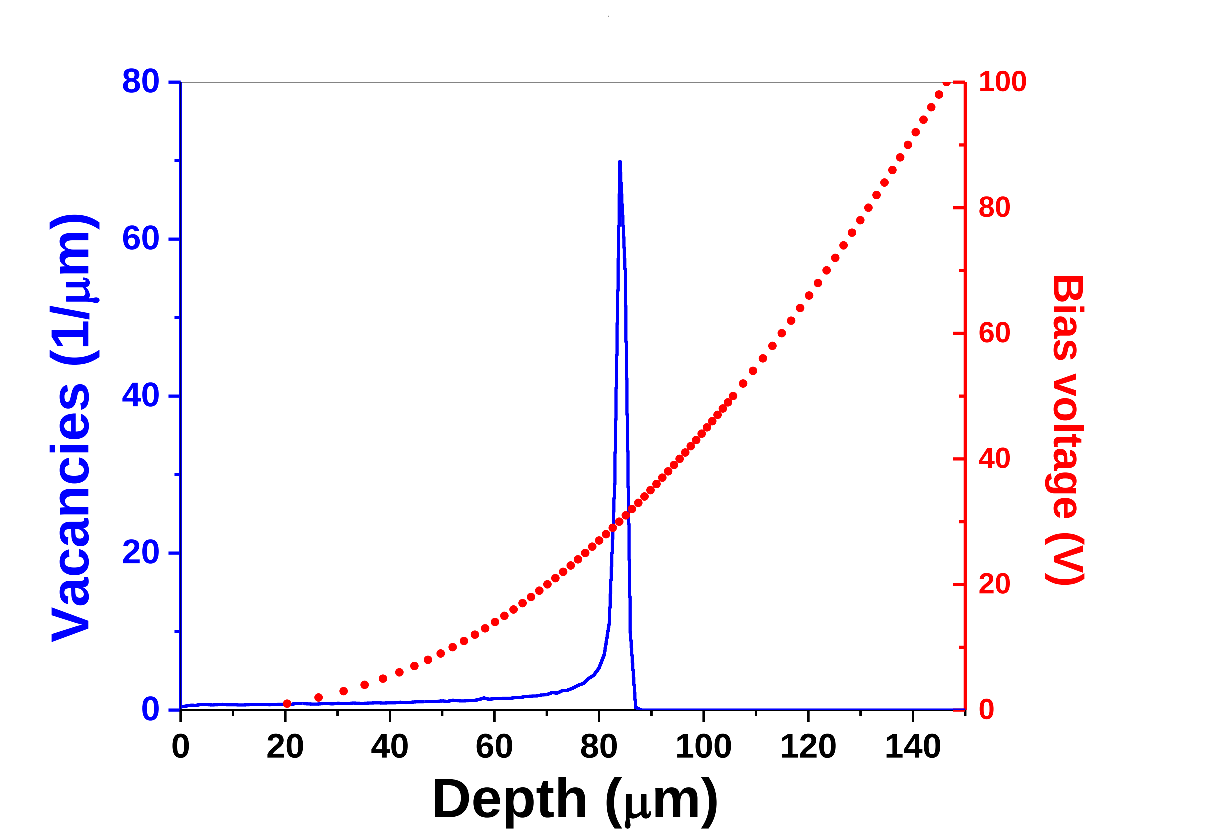
DIB=11.25 MeV He

Sample under study

Commercially available p-i-n photodiode

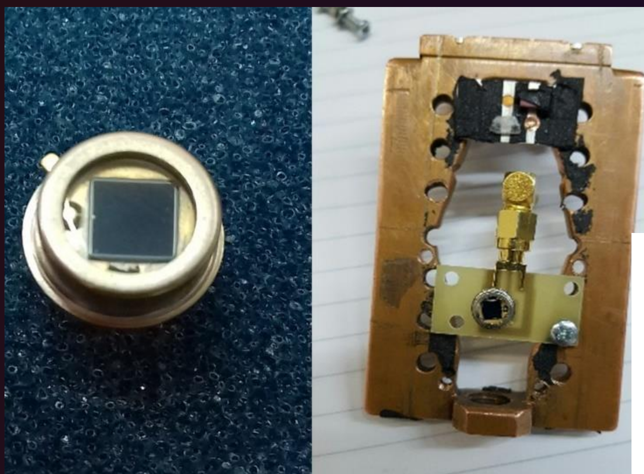


Inducing the damage



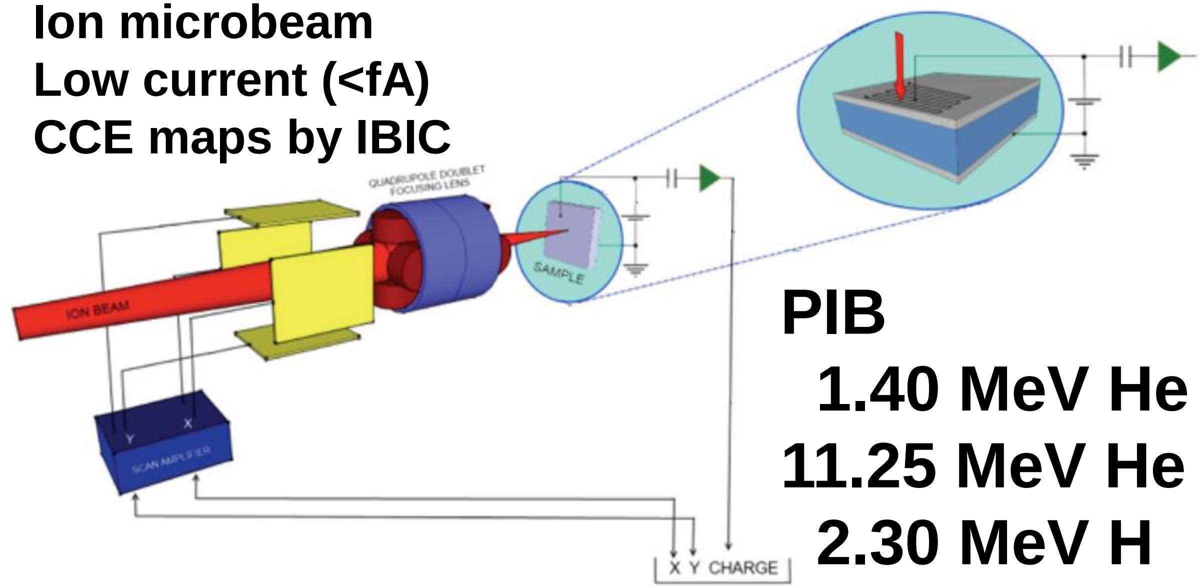
Sample under study

Commercially available p-i-n photodiode



Probing the damage

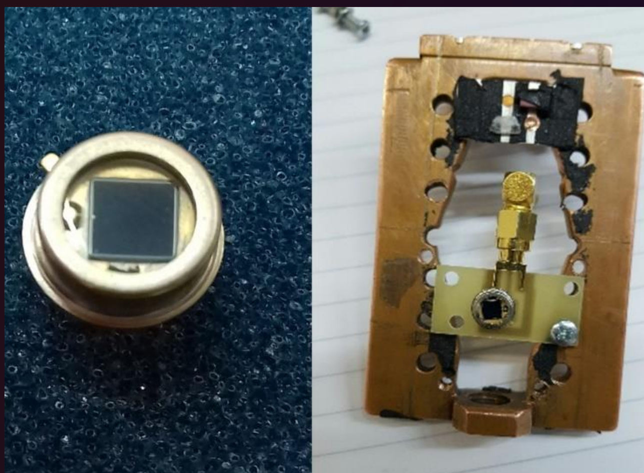
Ion microbeam
Low current (<fA)
CCE maps by IBIC



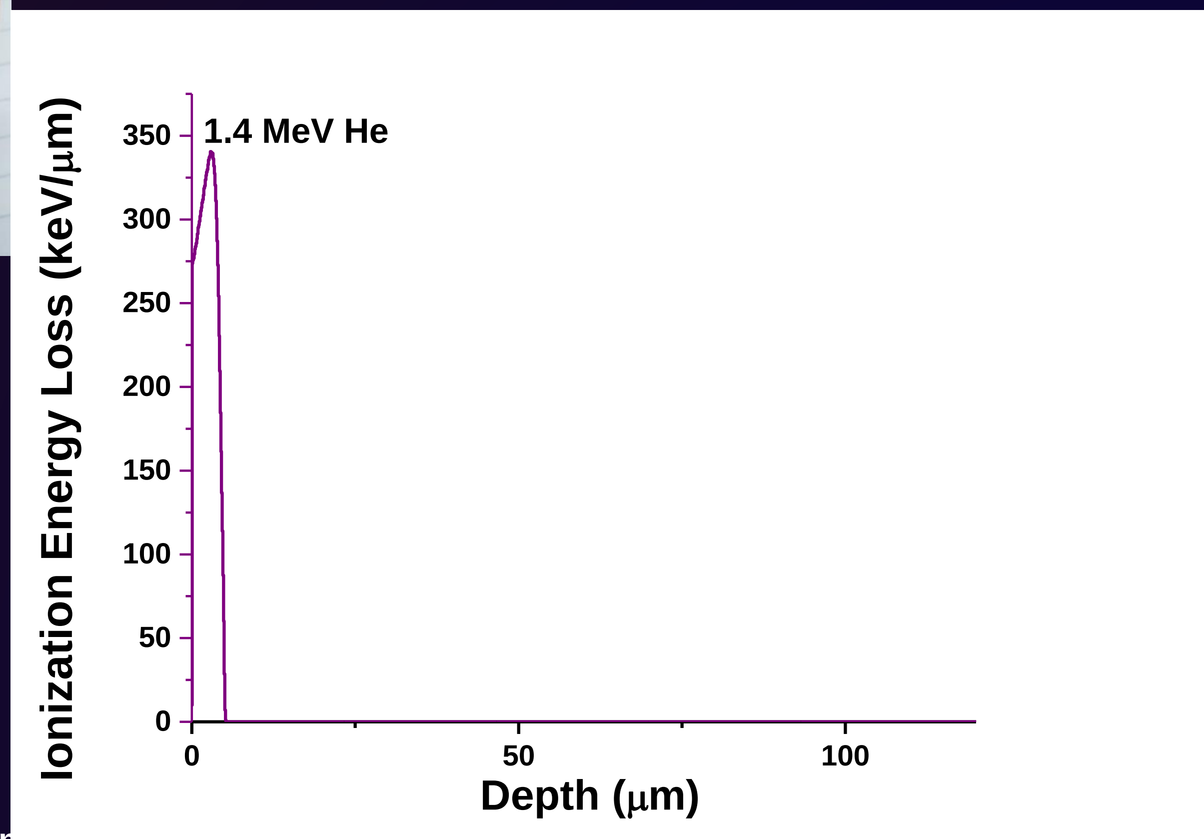
PIB
1.40 MeV He
11.25 MeV He
2.30 MeV H

Sample under study

Commercially available p-i-n photodiode

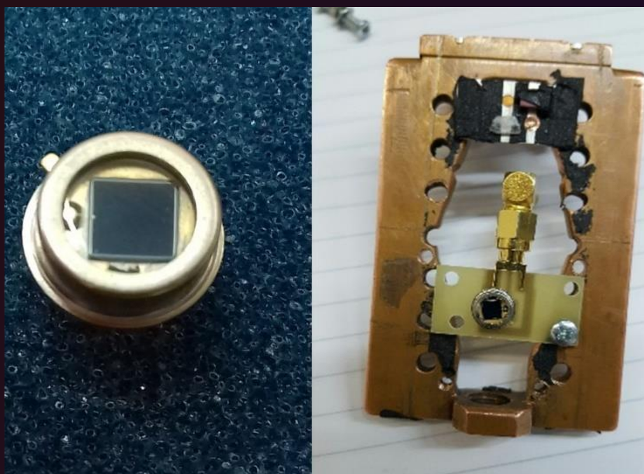


Probing the damage

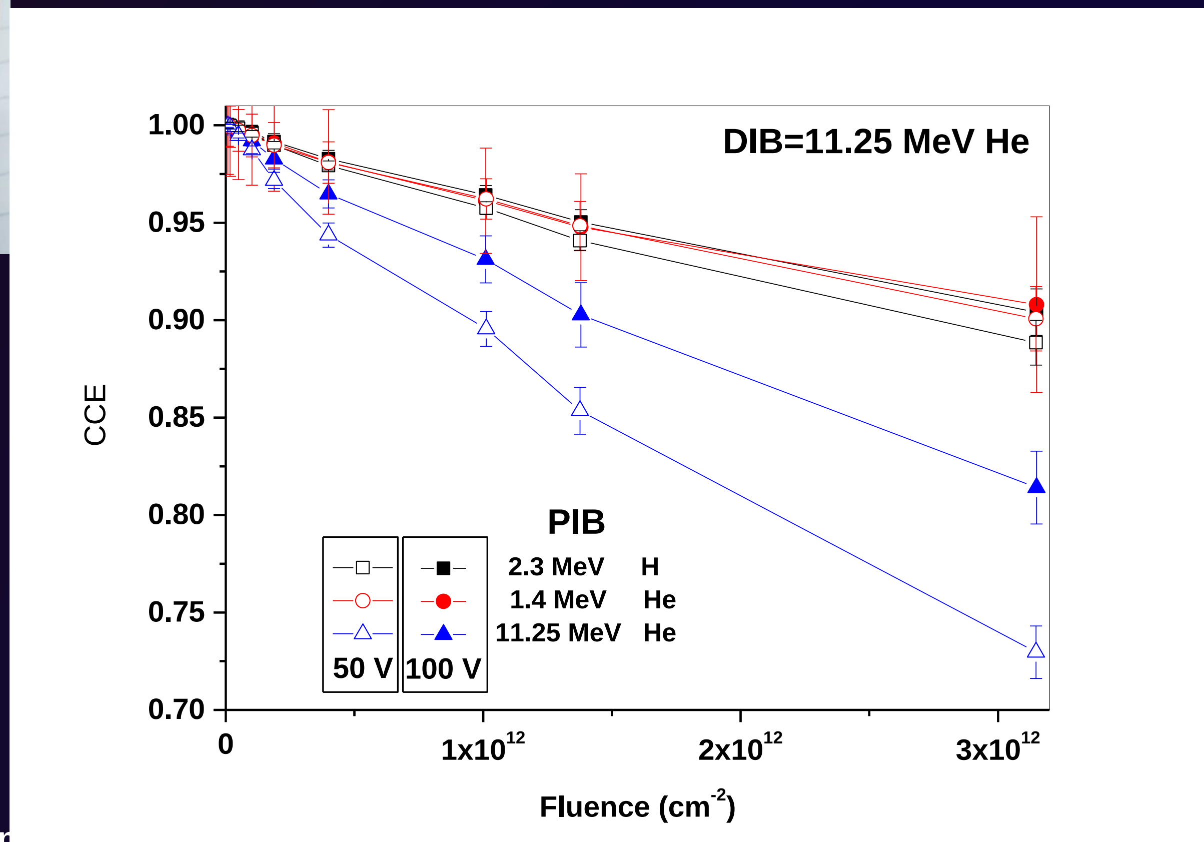


Sample under study

Commercially available p-i-n photodiode



Probing the damage
CCE at different bias
from different PIBs



Model for charge pulse formation (IBIC theory)

based on the Shockley-Ramo-Gunn theorem

Model for CCE degradation

Based on theShockley-Read-Hall model

Basic assumption:

1) In the linear regime, the ion induced damage affects mainly the carrier lifetime τ
2) The ion induced trap density is proportional to the VACANCY DENSITY

$$\frac{1}{\tau} = \frac{1}{\tau_0} + \alpha \cdot \mathrm{Vac}(x) \cdot \Phi$$

Fluence

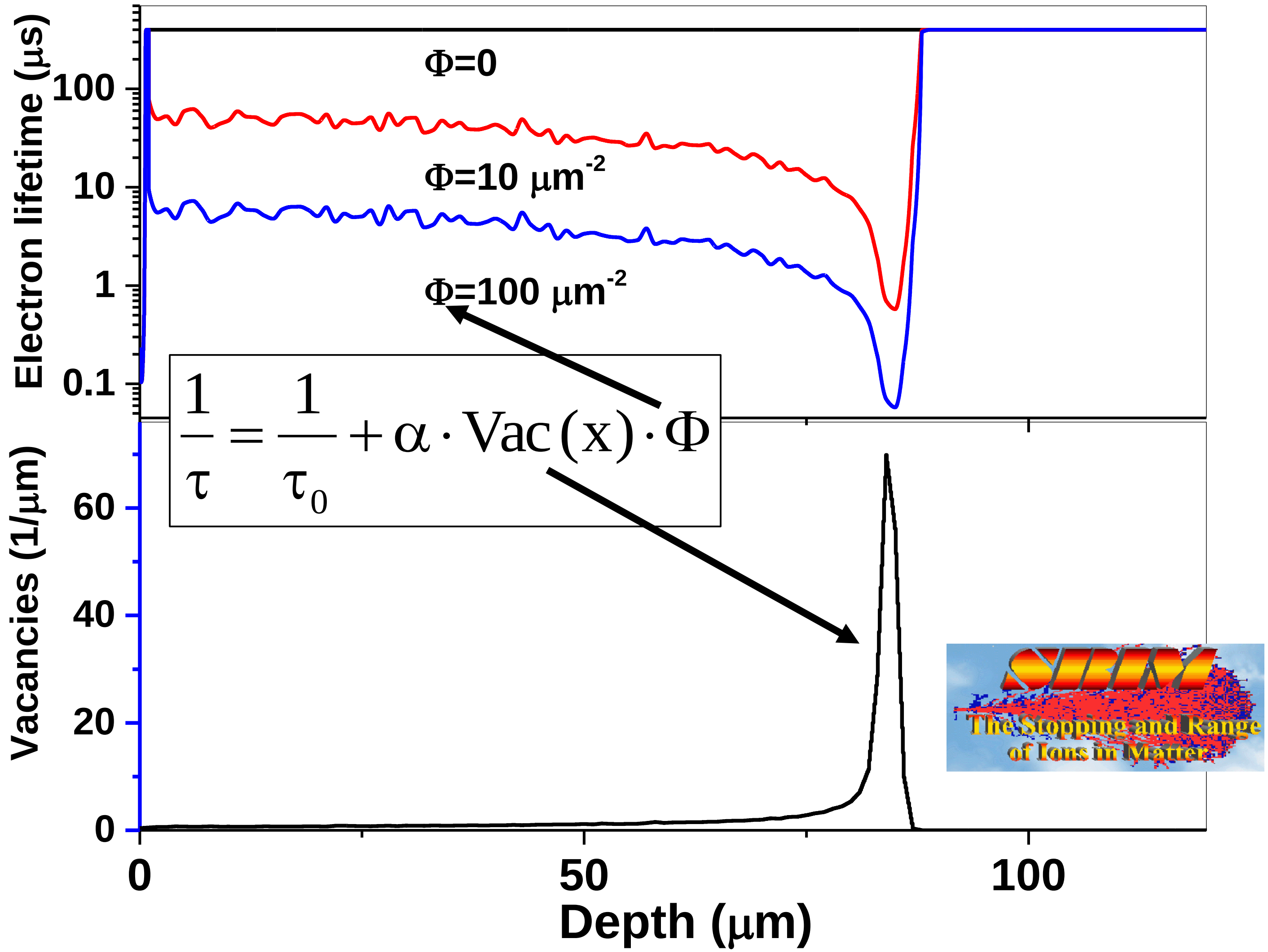
Capture coefficient

Vacancy Density Profile

The Stopping and Range of Ions in Matter

Low level of damage: $\Phi < 10^{12}$ cm^{-2} = (100x100) nm^2

LOW DENSITY OF TRAPS -> NOT INTERACTING TRAPS


Electron lifetime (µs)
100
10
1
0.1
Φ=0
Φ=10 µm-2
Φ=100 µm-2
$$\frac{1}{\tau} = \frac{1}{\tau_0} + \alpha \cdot \mathrm{Vac}(x) \cdot \Phi$$
Vacancies (1/µm)
60
40
20
0
0
50
100
Depth (µm)
SRIM
The Stopping and Range of Ions in Matter

Model for charge pulse formation (IBIC theory)

1D

Fully depleted device

No diffusion

Ramo Theorem

Ionization profile

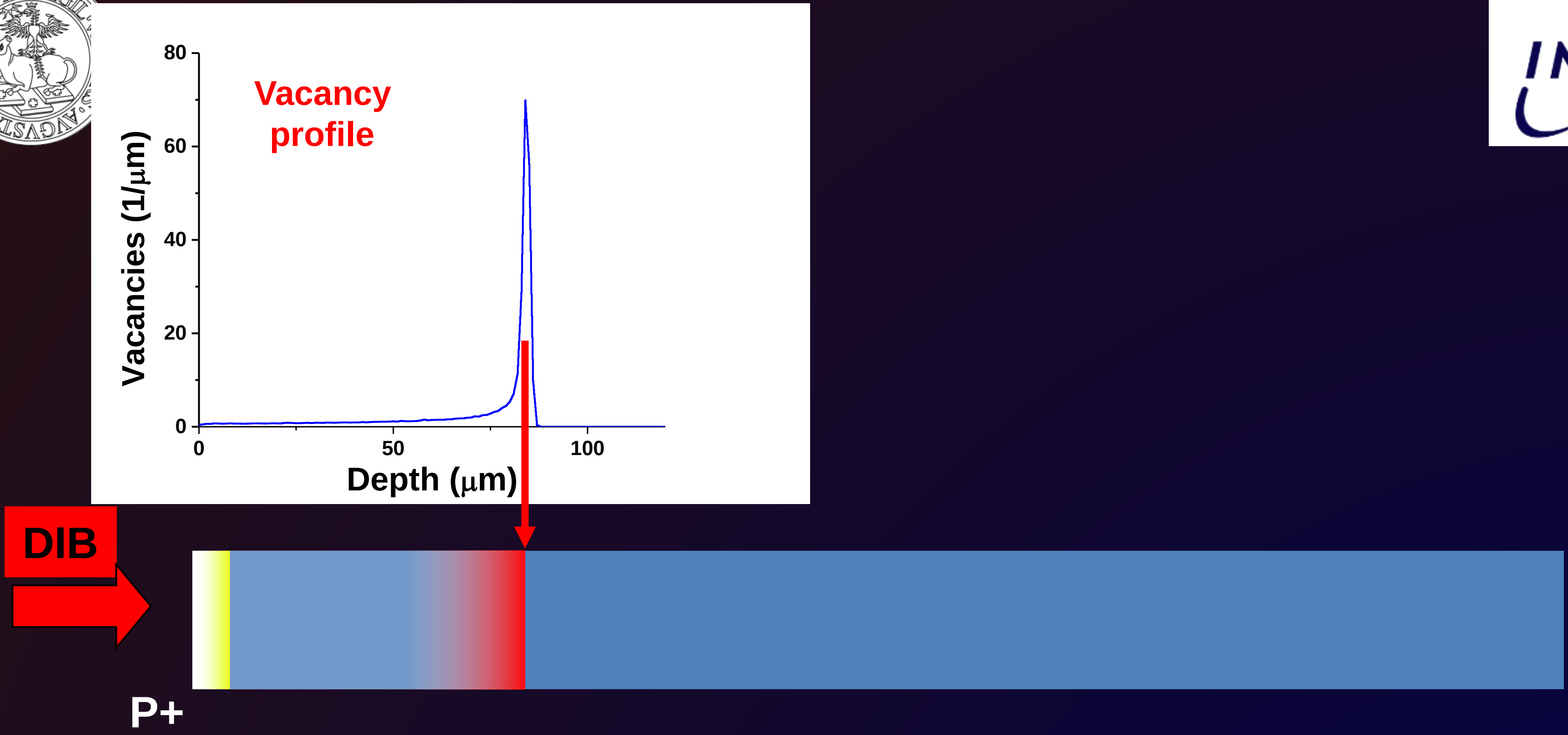
Gunn's weighting field

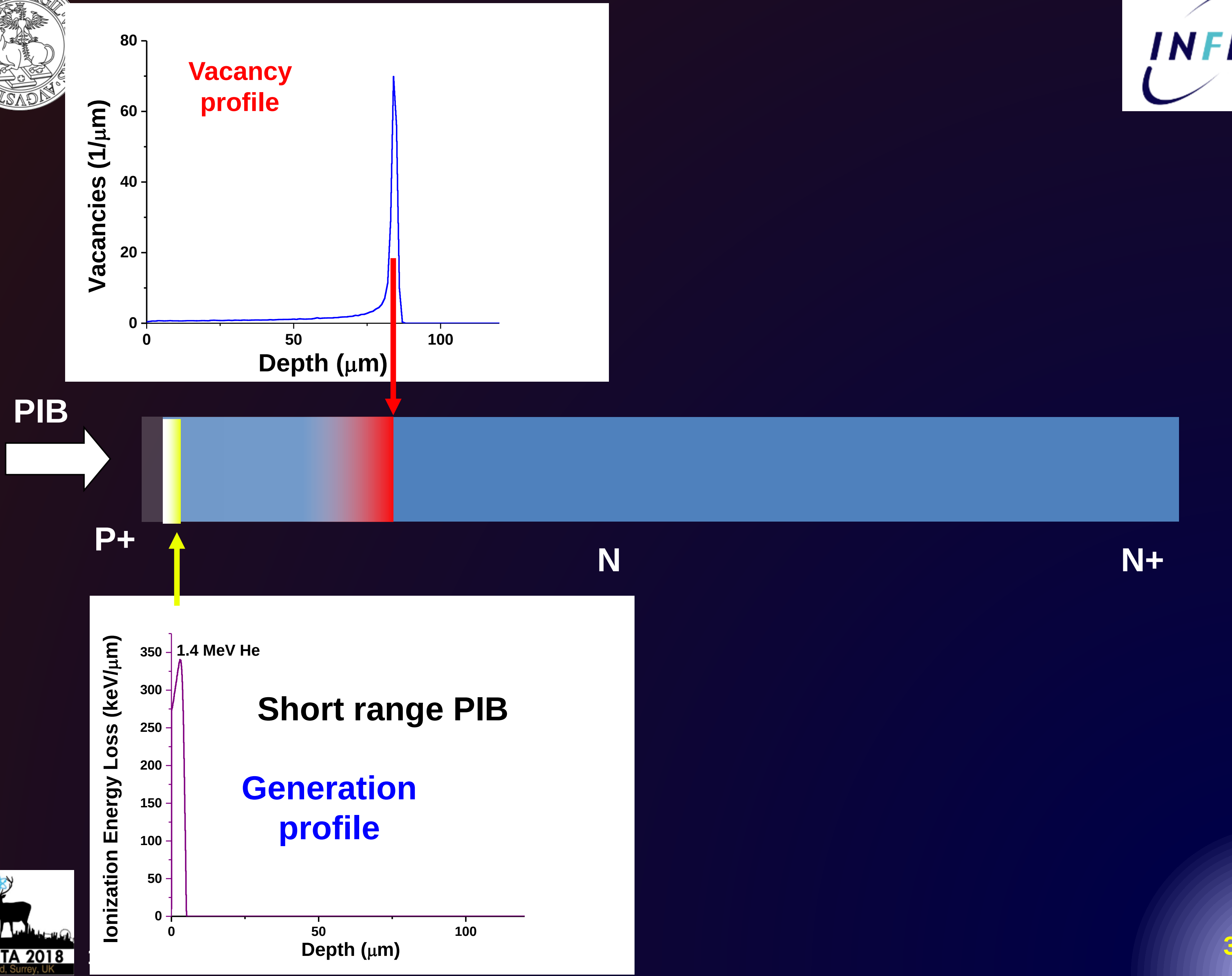
$$Q_S = q \cdot \int_0^d dx \cdot \Gamma(x) \left\{ \begin{array}{l} \int_x^d dy \cdot \frac{\partial F(y)}{\partial V_S} \cdot \exp\left[-\int_x^y dz \left(\frac{1}{v_p \cdot \tau_p} \right) \right] + \\ \int_0^x dy \cdot \frac{\partial F(y)}{\partial V_S} \cdot \exp\left[-\int_y^x dz \left(\frac{1}{v_n \cdot \tau_n} \right) \right] \end{array} \right\}$$

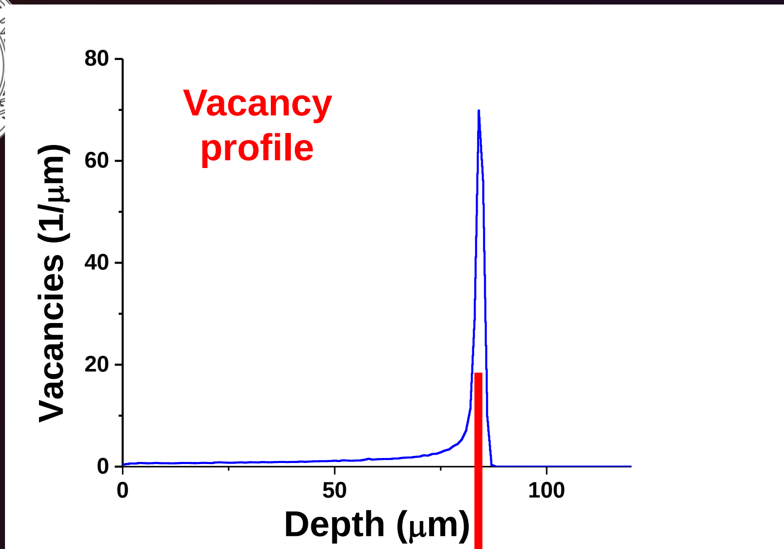
Holes

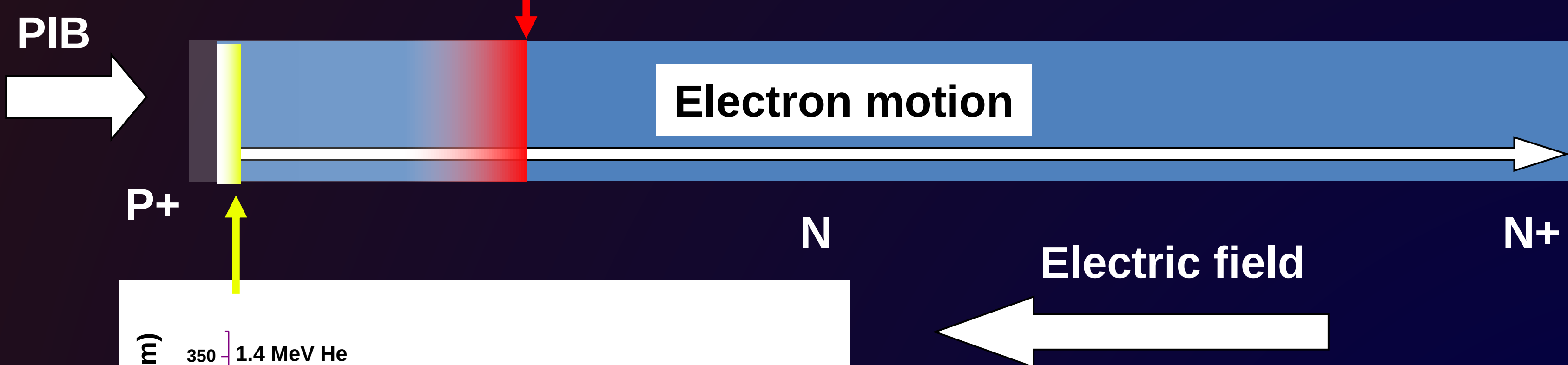
Electrons

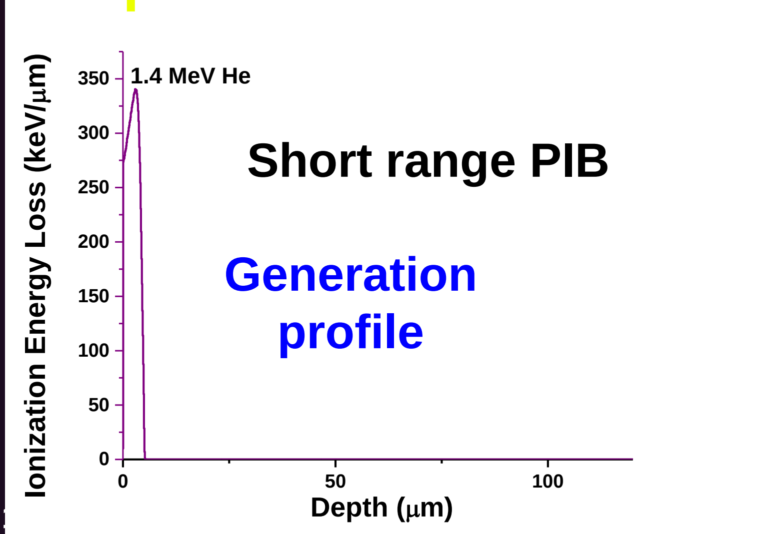
Drift lengths

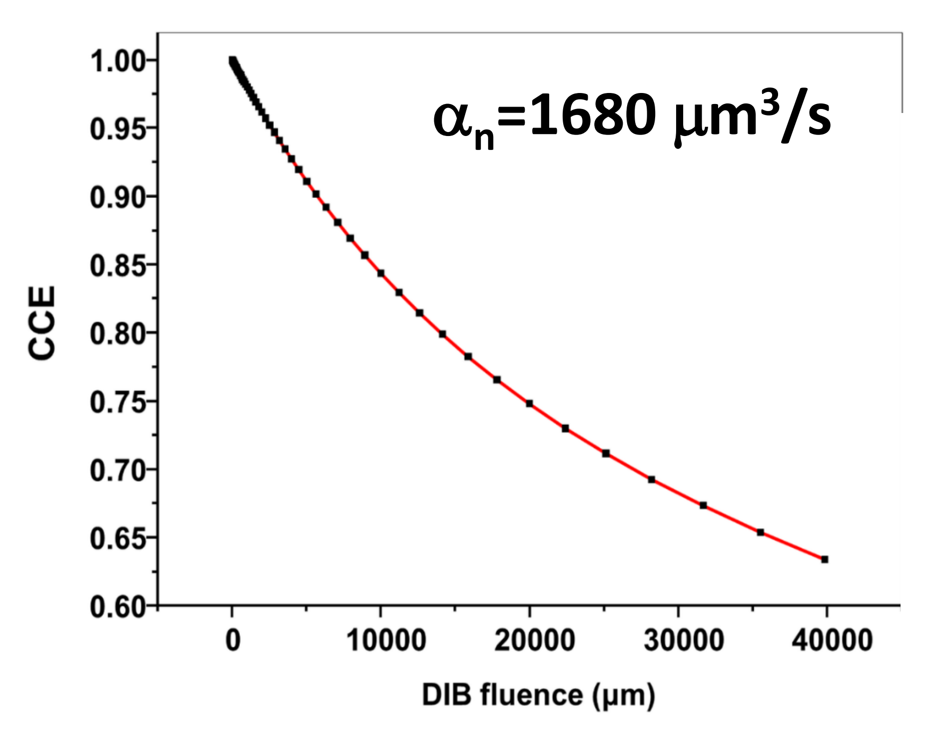

Vacancy profile
Vacancies (1/μm)
80
60
40
20
0
0
50
100
Depth (μm)
DIB
P+

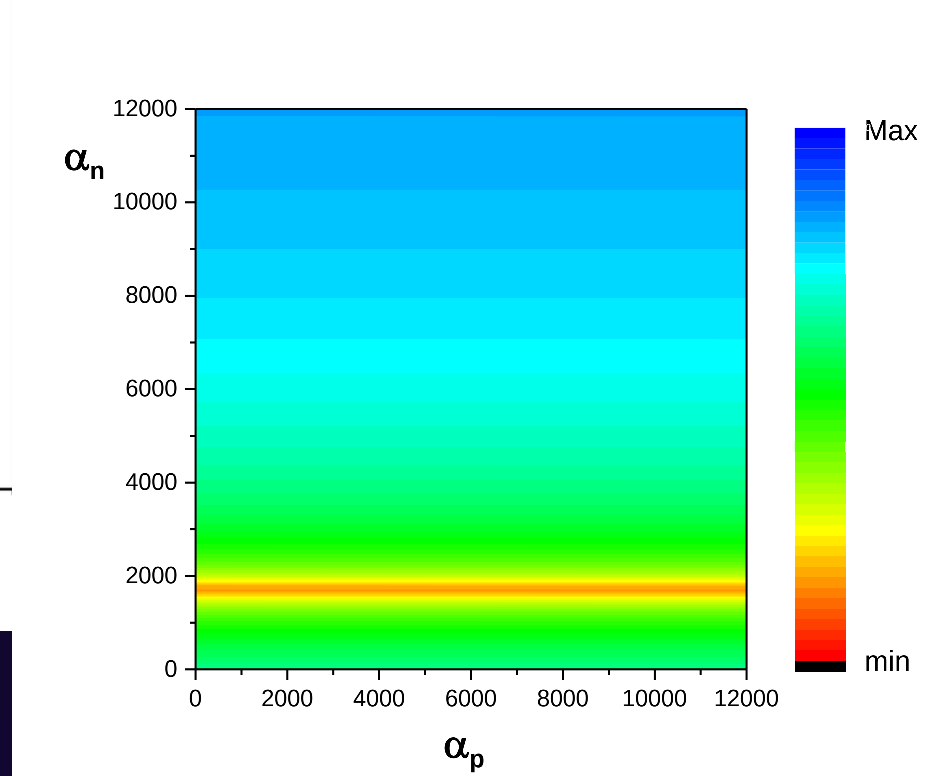

Vacancy profile
Vacancies (1/µm)
0
20
40
60
80
0
50
100
Depth (µm)
PIB
P+
N
N+
1.4 MeV He
Short range PIB
Generation profile
Ionization Energy Loss (keV/µm)
0
50
100
150
200
250
300
350
0
50
100
Depth (µm)


Vacancy profile
Vacancies (1/µm)
Depth (µm)
0
20
40
60
80
0
50
100


PIB
P+
Electron motion
N
N+
Electric field

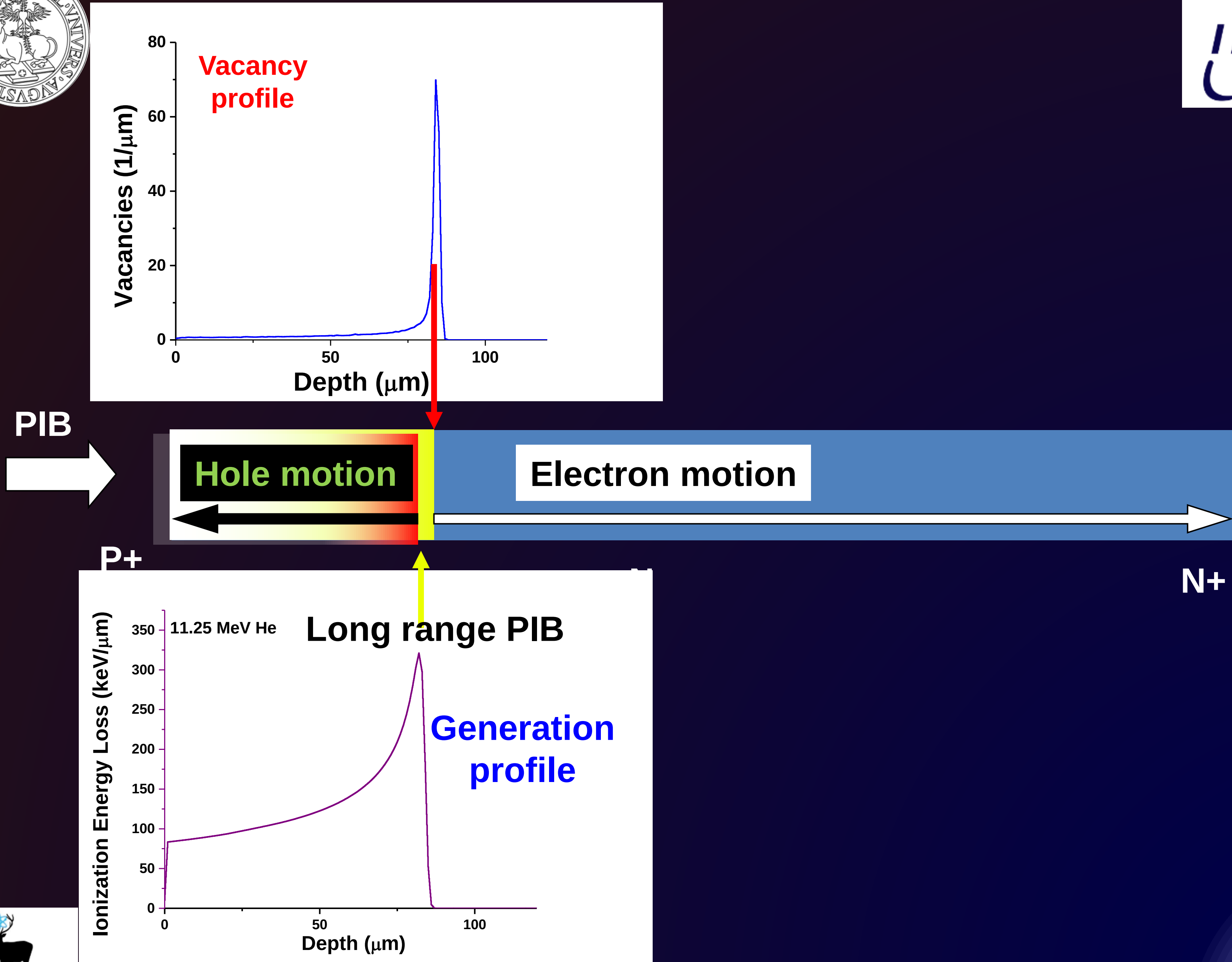

1.4 MeV He
Short range PIB
Generation profile
Ionization Energy Loss (keV/µm)
Depth (µm)
0
50
100
150
200
250
300
350
0
50
100





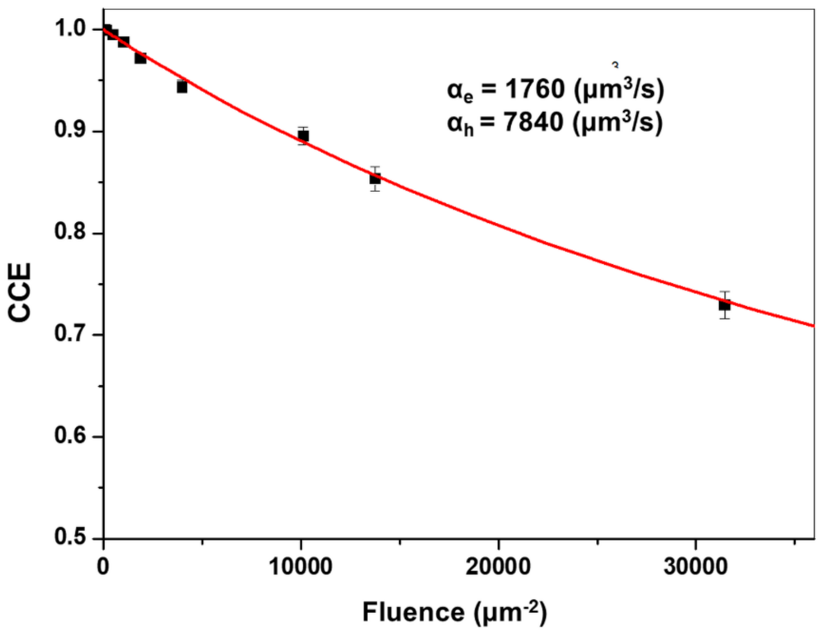
α_n Recombination Coefficient
Free parameter

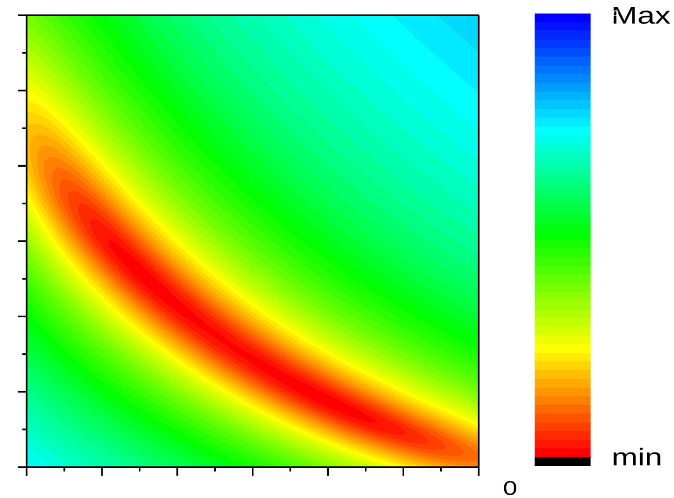
$$Q_S = q \cdot \int_0^d dx \cdot \Gamma(x) \left\{ \int_x^d dy \cdot \frac{\partial F(y)}{\partial V_S} \cdot \exp\left[-\int_x^y dz \frac{1}{v_n} \cdot \left(\frac{1}{\tau_0} + \alpha_n \cdot Vac(x) \cdot \Phi \right) \right] \right\}$$



Vacancy profile
Vacancies (1/μm)
80
60
40
20
0
0
50
100
Depth (μm)
PIB
Hole motion
Electron motion
P+
N+
11.25 MeV He
Long range PIB
Generation profile
Ionization Energy Loss (keV/μm)
350
300
250
200
150
100
50
0
0
50
100
Depth (μm)

Residual map



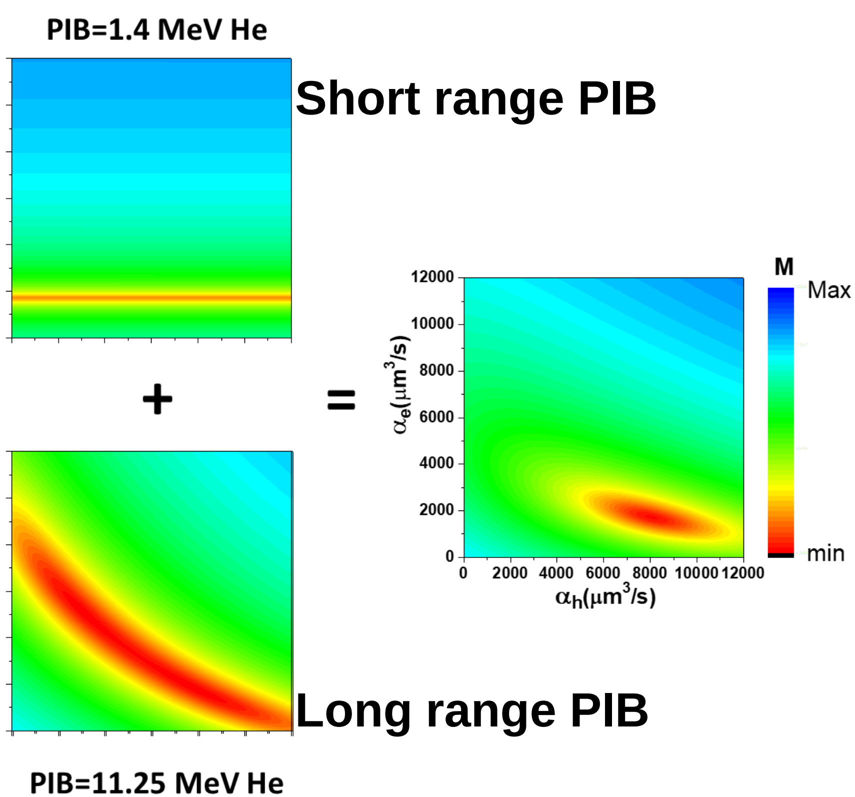


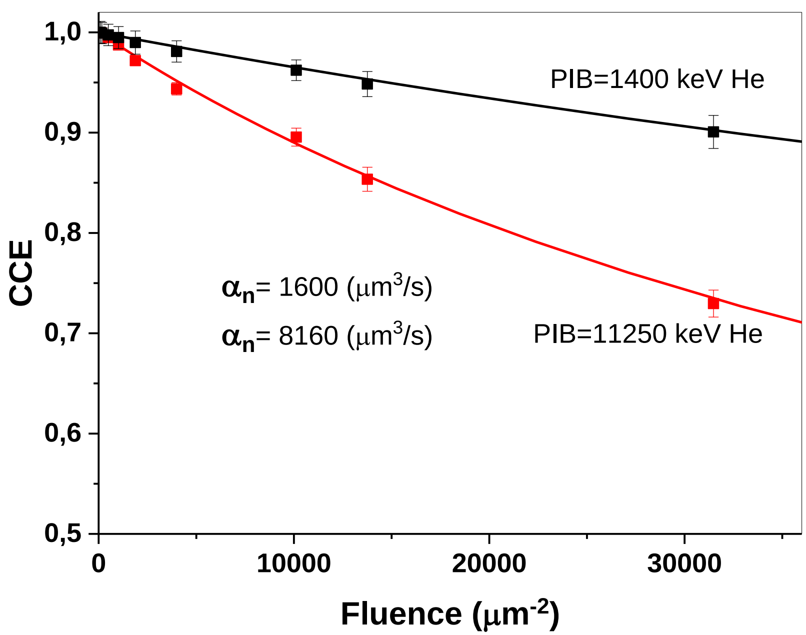
α_n , α_p

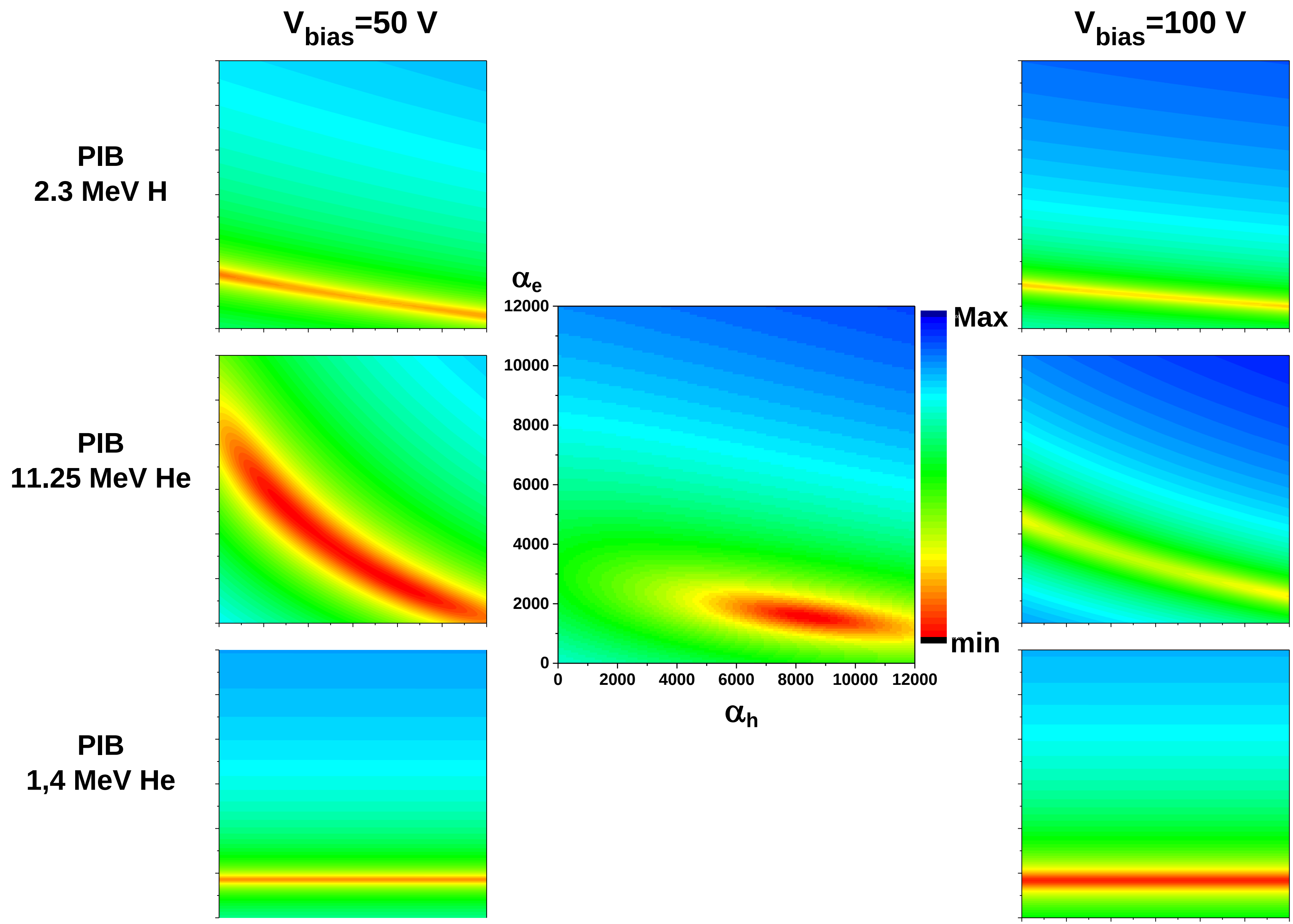
Recombination Coefficients

Free parameters

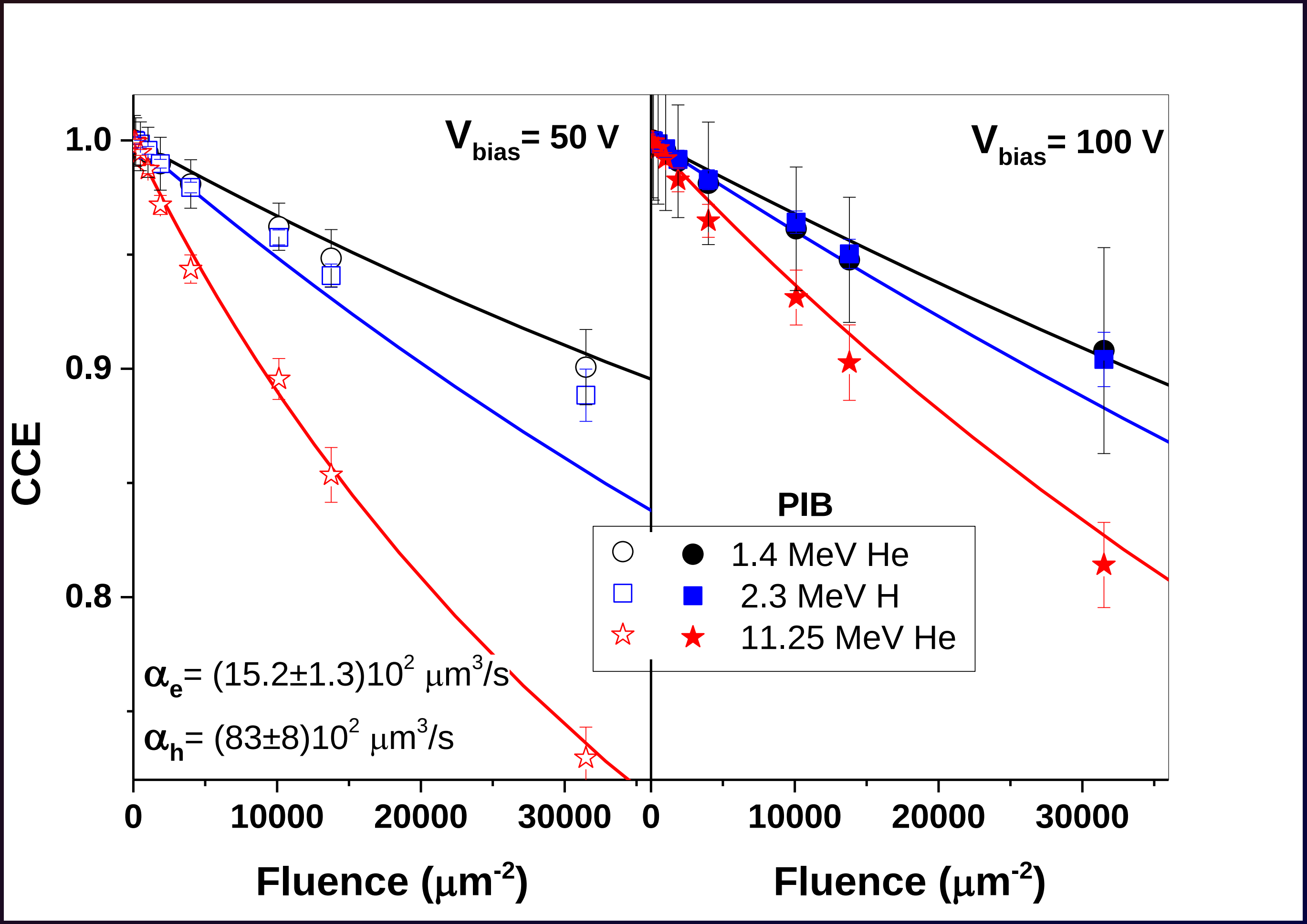
$$Q_S = q\cdot\int_0^d dx\cdot\Gamma(x)\left\{\int_0^x dy\cdot\frac{\partial F(y)}{\partial V_S}\cdot\exp\left[-\int_y^x dz\,\frac{1}{v_p}\cdot\left(\frac{1}{\tau_0}+\alpha_p\cdot Vac(x)\cdot\Phi\right)\right]+\int_x^d dy\cdot\frac{\partial F(y)}{\partial V_S}\cdot\exp\left[-\int_x^y dz\,\frac{1}{v_n}\cdot\left(\frac{1}{\tau_0}+\alpha_n\cdot Vac(x)\cdot\Phi\right)\right]\right\}$$


PIB=1.4 MeV He
Short range PIB
+
=
12000
10000
8000
6000
4000
2000
0
$\alpha_e(\mu m^3/s)$
0
2000
4000
6000
8000
10000
12000
$\alpha_h(\mu m^3/s)$
M
Max
min
Long range PIB
PIB=11.25 MeV He


1,0
0,9
0,8
0,7
0,6
0,5
CCE
0
10000
20000
30000
Fluence (μm^{-2})
PIB=1400 keV He
PIB=11250 keV He
α_n= 1600 ($\mu m^3/s$)
α_n= 8160 ($\mu m^3/s$)

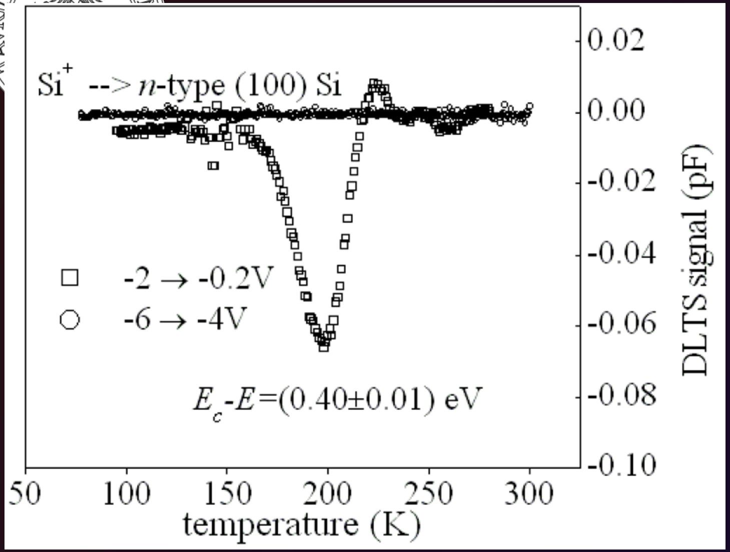


V_{bias}=50 V
V_{bias}=100 V
PIB
2.3 MeV H
PIB
11.25 MeV He
PIB
1,4 MeV He
α_e
12000
10000
8000
6000
4000
2000
0
0
2000
4000
6000
8000
10000
12000
α_h
Max
min



The solid lines are the best fits obtained by means of our model considering

- **Different PIBs**
- **Different biases (50 V, 100 V)**



N-type silicon
DLTS measurements
singly V2(−/0) negatively charged divacancy

$\sigma_n \approx 5\cdot10^{-15}$ cm^2
$\alpha_n \approx 1520\cdot10^{-12}$ cm^3/s
$v_{th} \approx 2.05\cdot10^7$ cm/s

$\alpha = k\cdot\sigma\cdot v_{th}$ ⇒ $k=0.016$

about 60 radiation induced vacancies are required to form one stable electron recombination centre.

Limits of applicability

Basic Hypotheses

DIB : low level of damage

$$\frac{1}{\tau_{e,h}} = \frac{1}{\tau_{0,e,h}} + \alpha_{n,p} \cdot Vac(x) \cdot \Phi = \frac{1}{\tau_{0,e,h}} + \left(\sigma_{e,h} \cdot v_{th}\right) \cdot Vac(x) \cdot \Phi$$

"linear model"
Independent traps, no clusters

Unperturbed electrostatics (i.e. doping profile) of the device

PIB : ion probe
CCE is the sum of the individual e/h contributions

No plasma effects induced by probing ions

Recombination coefficient: $\alpha = k \cdot \sigma \cdot v_{th}$

Ref.	Diode	PIBs	DIBs	Max Fluence (μm^{-2})	α_e ($\mu m^3/s$)	α_h ($\mu m^3/s$)
[2]	Hamamatsu S5821	1.4 MeV He	1.4 MeV He 2.15 MeV Li 4.0 MeV O 11.0 MeV Cl	5000 2000 500 200	8800±1200	--
[3]	Hamamatsu S5821*	1.036 MeV He	1.036 MeV He 2 MeV He	4000	10270±260	23500±2800
[1]	n.type Si PIN diode from Helsinki University	2 MeV He 2 MeV H 8 MeV He 12 MeV He 4.5 MeV H	4 MeV He 8 MeV He	20000	2500±300	210±160
[1]	p.type Si PIN diode from Helsinki University	2 MeV He 2 MeV H 8 MeV He 12 MeV He 4.5 MeV H	4 MeV He 8 MeV He	20000	2200±300	1310±90
[4]	Hamamatsu S1223	1.4 MeV He 2.3 MeV H 11.25 MeV He	11.25 MeV He	30000	1520±130	8300±800

[1] E. Vittone et al. Nuclear Instr. and Methods in Physics Research B 372 (2016) 128–142
[2] Ž. Pastuović et al. Applied Physics Letters 98, 092101 (2011)
[3] J. Garcia et al. Unpublished
[4] This work

CONCLUSIONS

The IAEA methodology has been used to study the radiation hardness of a commercially available silicon p-i-n diode
This methodology contribute towards a standardized quantification of radiation hardness of semiconductor materials.

The capture coefficient is directly related to the radiation hardness of the material

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Submitted in 2018

IAEA Coordinate Research Programme (CRP) F11016 (2011-2015)

"Utilization of ion accelerators for studying and modeling of radiation induced defects in semiconductors and insulators"

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