Session 9: Microprobe application in microelectronics ; I8

Methodology to analyze the charge collection efficiency degradation induced by MeV ions in semiconductor diodes.

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ATOMKI, (Hu)

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SNL (USA)

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ANSTO, (Aus)

Outlines

- What
- Why
- Who, When, How:
    - The IAEA Coordinated Reseach Programme (CRP)
      «Utilization of ion accelerators for studying and modeling of radiation induced defects in semiconductors and insulators”
    - The model
    - The experimental protocol
    - Results
- Conclusions

What

Object of the research

Study of the radiation hardness of semiconductors

Tool

Focused MeV Ion beams to induce the damage and to probe the damage

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

Three main types of effects:

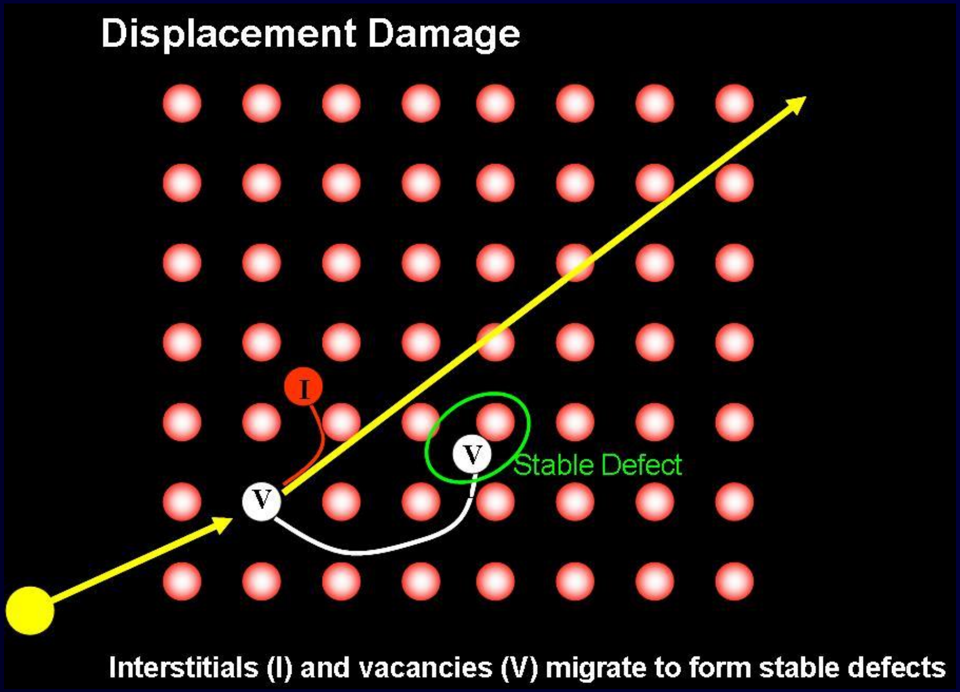
- Transient ionization. This effect produces electron-hole pairs; particle detection with semiconductors is based on this effect.

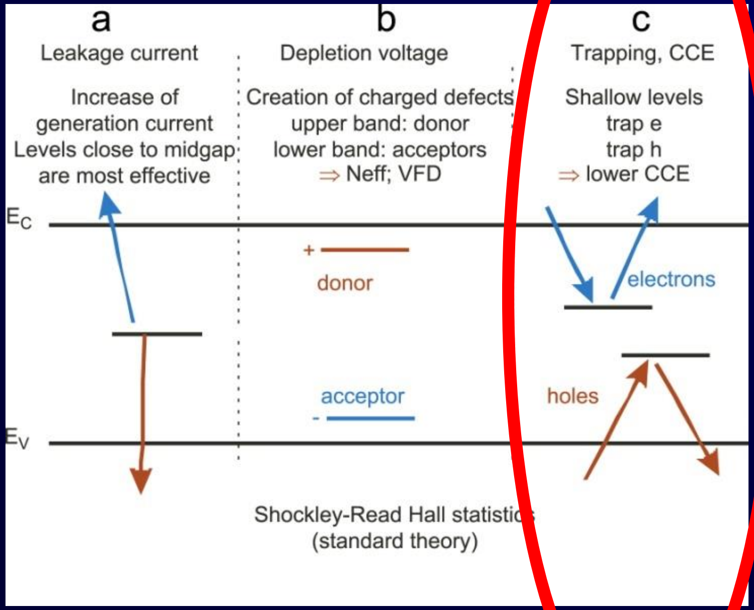
-Long term ionization. In insulators, the material does not return to its initial state, if the electrons and holes produced are fixed, and charged regions are induced.

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

V.A.J. van Lint, The physics of radiation damage in particle detectors, Nucl. Instrum. Meth. A253 (1987) 453.

- 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 it is relevant to the ICNMTA community

ICNMTA2016:
8 contributions mentioning STIM

ICNMTA 2014
13 contributions mentioning STIM

ICNMTA 2012
15 contributions mentioning STIM

Nuclear Instruments and Methods in Physics Research B77 (1993) 243–246
North-Holland

NIM B Beam Interactions with Materials & Atoms

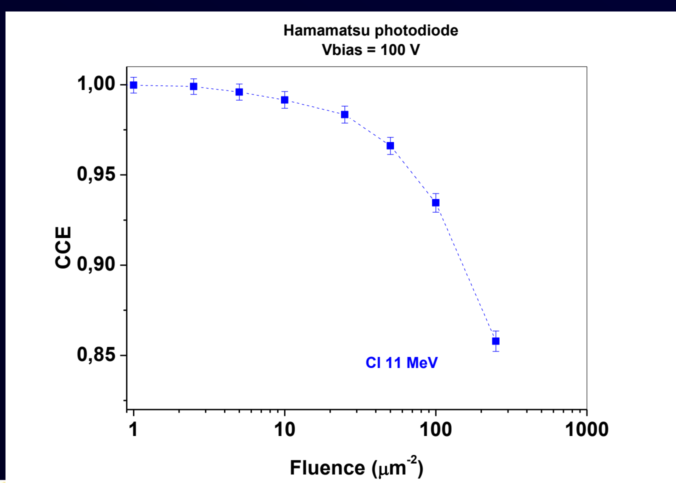
Study of nuclear microprobe beam halo using IBIC

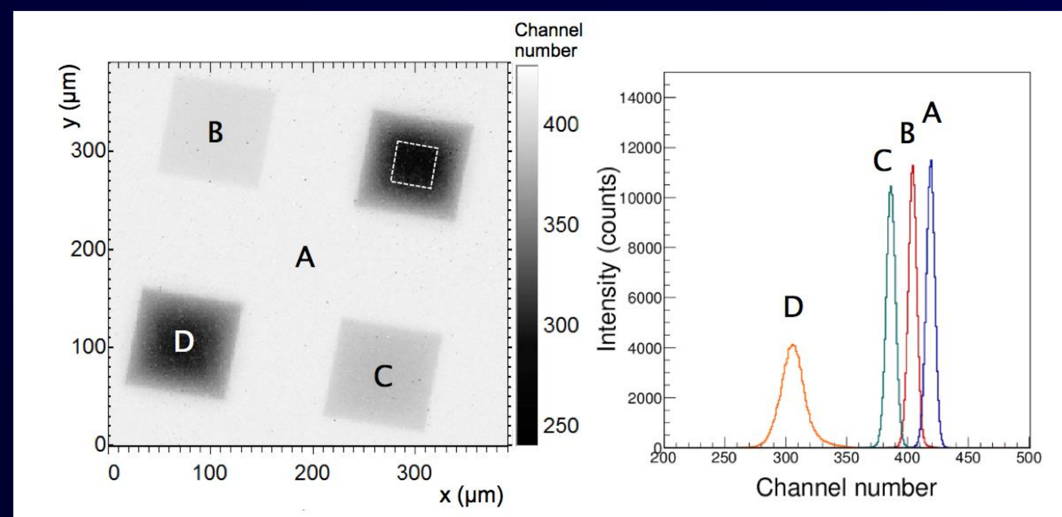
M.B.H. Breese, G.W. Grime and F. Watt
Nuclear Physics Laboratory, Keble Road, Oxford University, Oxford OX1 3RH, UK

There are many factors which can give rise to a halo around a focused MeV ion beam, and a method of detecting the distribution and determining the amount of beam current in the halo will help to assess its effect on spatial resolution. This paper describes how the technique IBIC (ion beam induced charge) can be used as an extremely sensitive method of imaging and quantifying the beam halo around focused 3 MeV proton beam current of 200 pA and 0.3 fA. It is also shown how the momentum of the beam fraction in the halo can be calculated from its spatial extent in the IBIC images.

μ-beam IRRADIATION
Silicon pin diodes

CCE degradation



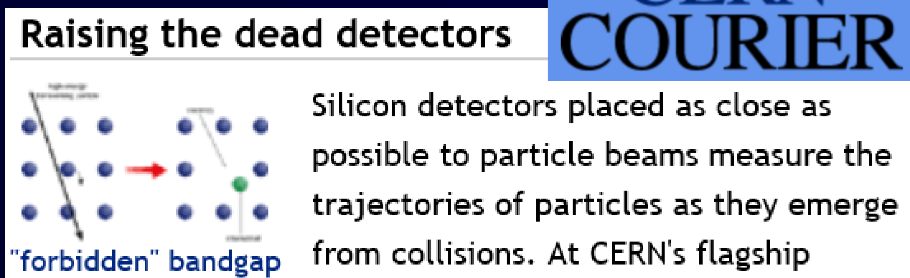


Credit: Milko Jaksic and RBI group

Why is important to mitigate radiation damage in semiconductor devices

CERN 1.2 G€; Italian contribution 10.5%

CERN COURIER

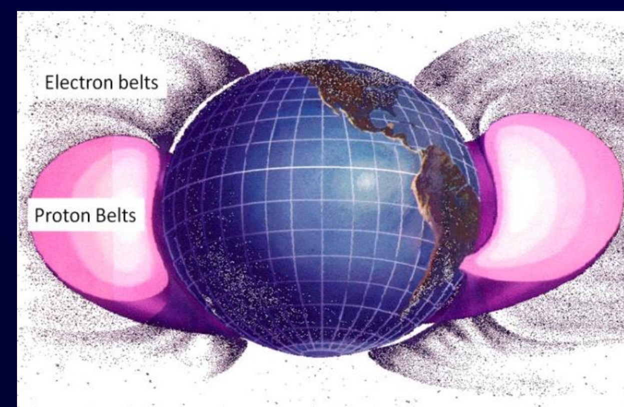

Raising the dead detectors

"forbidden" bandgap

Silicon detectors placed as close as possible to particle beams measure the trajectories of particles as they emerge from collisions. At CERN's flagship

MINISTERO DELL'ISTRUZIONE, DELL'UNIVERSITÀ E DELLA RICERCA

ESA 5.25 G€; Italian contribution: 10.6%



Characterization of radiation induced damage:

Device characteristic after irradiation

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

Device characteristic before irradiation

Particle Fluence

Equivalent damage factor

Displacement dose

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

Analogies

Ionizing radiation effects – Dosimetry

When ionizing radiation interacts with the human body, it gives its energy to the body tissues.

Ionizing stopping power (Linear Energy Transfer) energy lost per unit path length by the particle:
SI units: J/m or J·m^2/kg.

Absorbed dose: the amount of energy absorbed per unit weight of the organ or tissue;
SI units: Gy.

Non Ionizing effects – Displacement damage

When ionizing radiation interacts with a semiconductor alterates its operational properties.

Vacancy density

Non ionizing energy loss (NIEL):
SI units: J/m or J·m^2/kg.

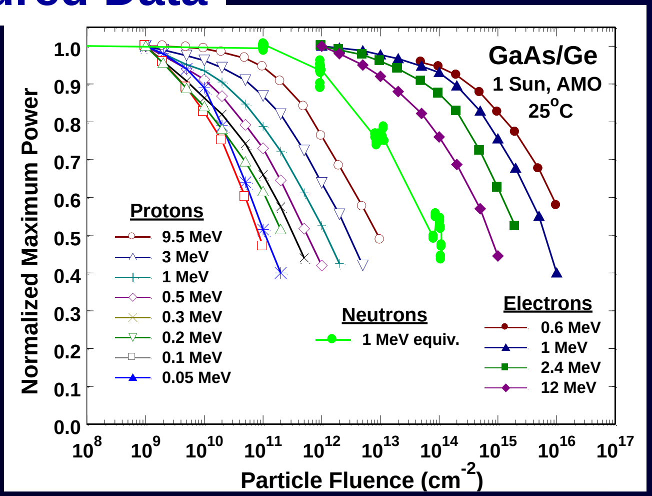
Displacement damage dose:

$D_d = NIEL \cdot \Phi$

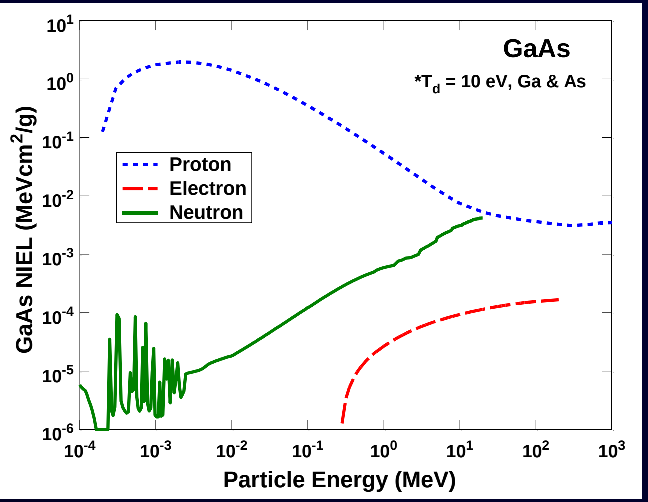
US Naval Research Laboratory (NRL)

Displacement Damage Dose Method

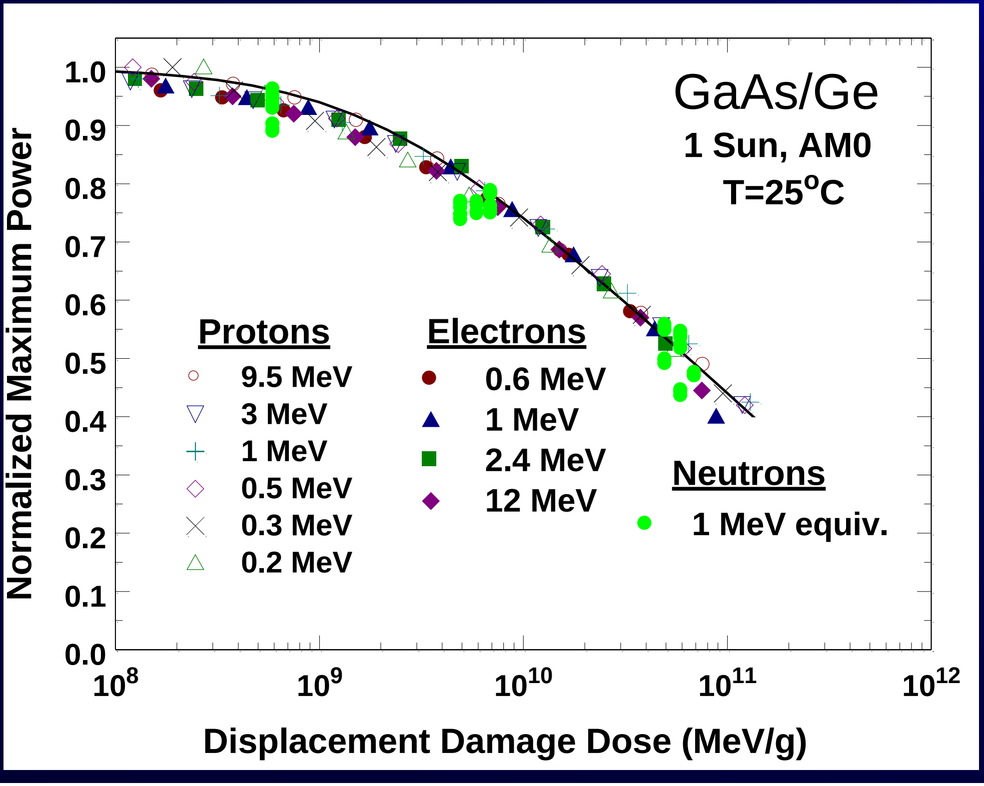
Measured Data



With NIEL



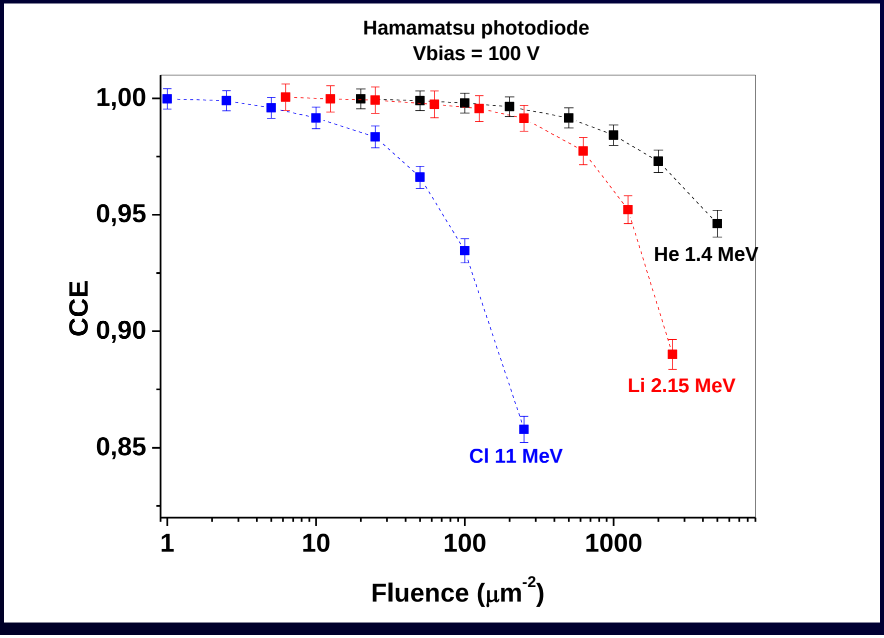
Characteristic Curve



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

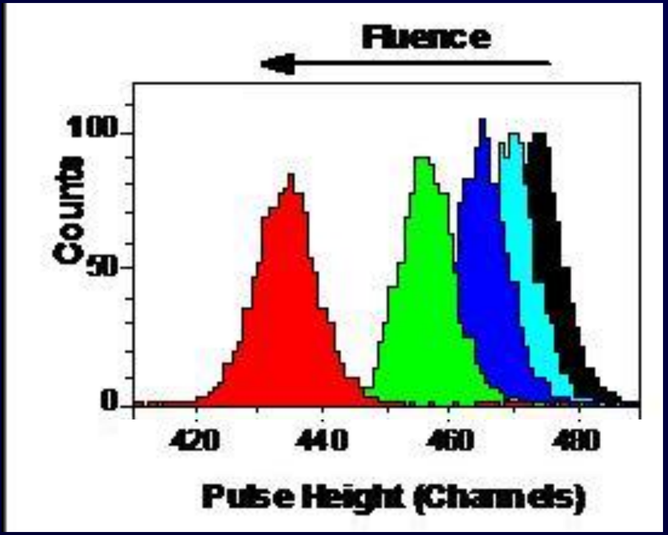
S. Messenger, SPENVIS Workshop 2005

CCE degradation induced by ion irradiation



$$\eta = CCE = \frac{Q}{Q_0} = 1 - K \cdot \Phi = 1 - K_{ed} \cdot D_d$$

11 MeV Cl 2.15 MeV Li 1.4 MeV He
Ions to induce damage

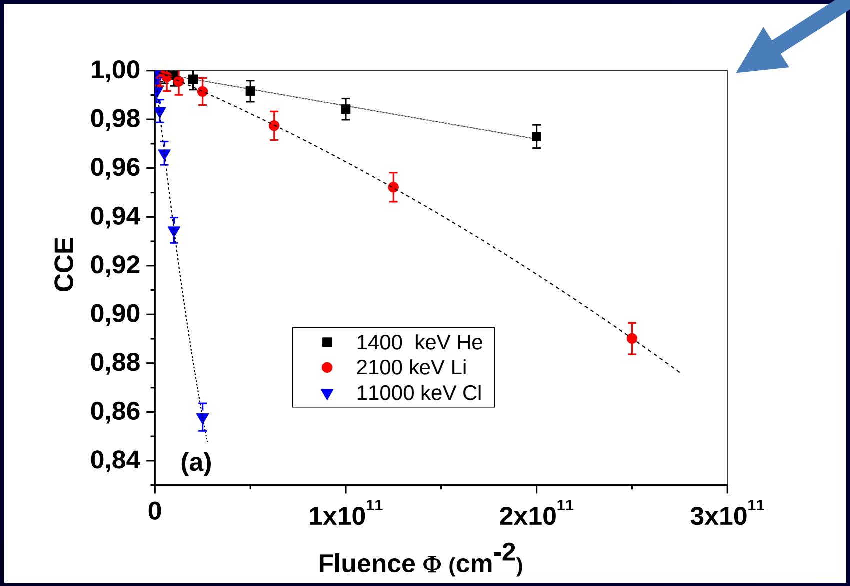


1.4 MeV He ions to probe the damage

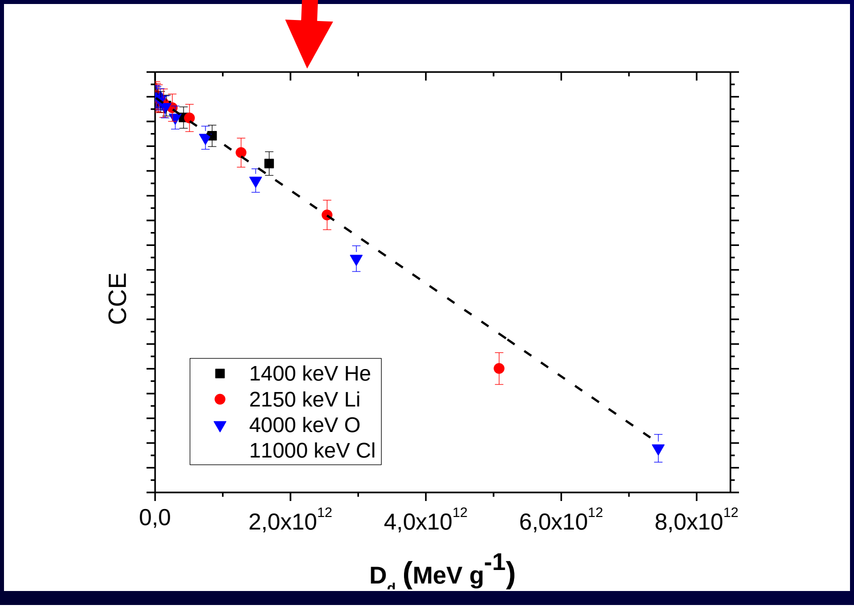
Silicon photodiode

V_{bias}=100 V
Fully depleted device

$$\eta = CCE = \frac{Q}{Q_0} = 1 - K \cdot \Phi = 1 - K_{ed} \cdot D_d$$



CCE behavior in regions damaged with different ions vs. ion fluence (Φ);



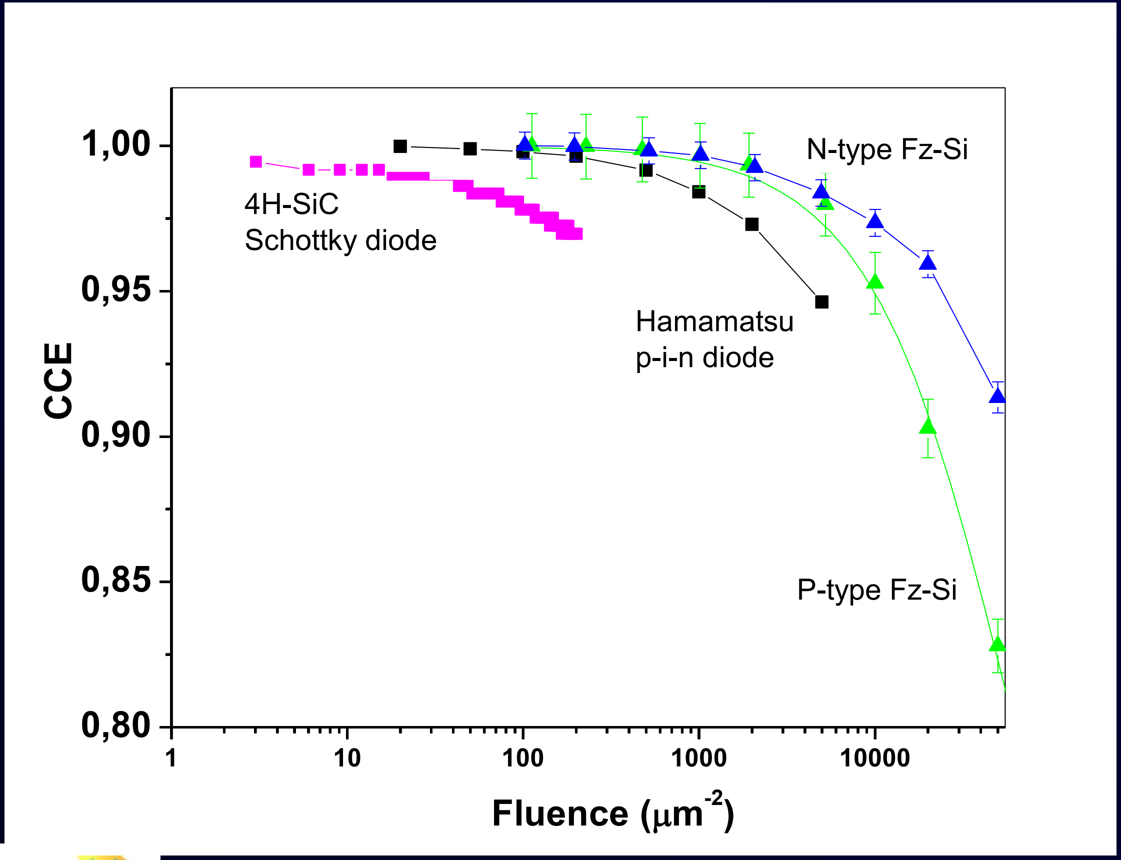
The same data points shown in Fig. 4 for plotted against the adjusted damage dose D_d.

Z. Pastuovic et al., IEEE Trans on Nucl. Sc. 56 (2009) 2457; APL (98) 092101 (2011)

CCE degradation induced by ion irradiation

Is a function of the material and/or device

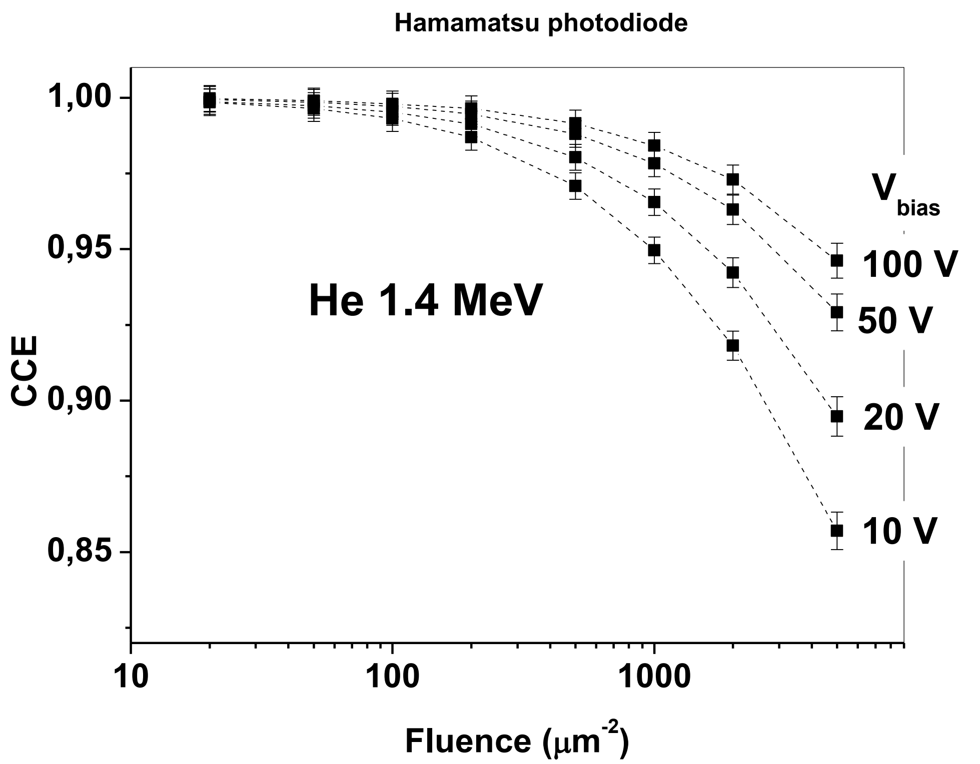
$$\eta = \frac{Y}{Y_0} = 1 - K \cdot \Phi = 1 - K_{ed} \cdot D_d$$



CCE degradation induced by ion irradiation

Is a function of the polarization state of the device

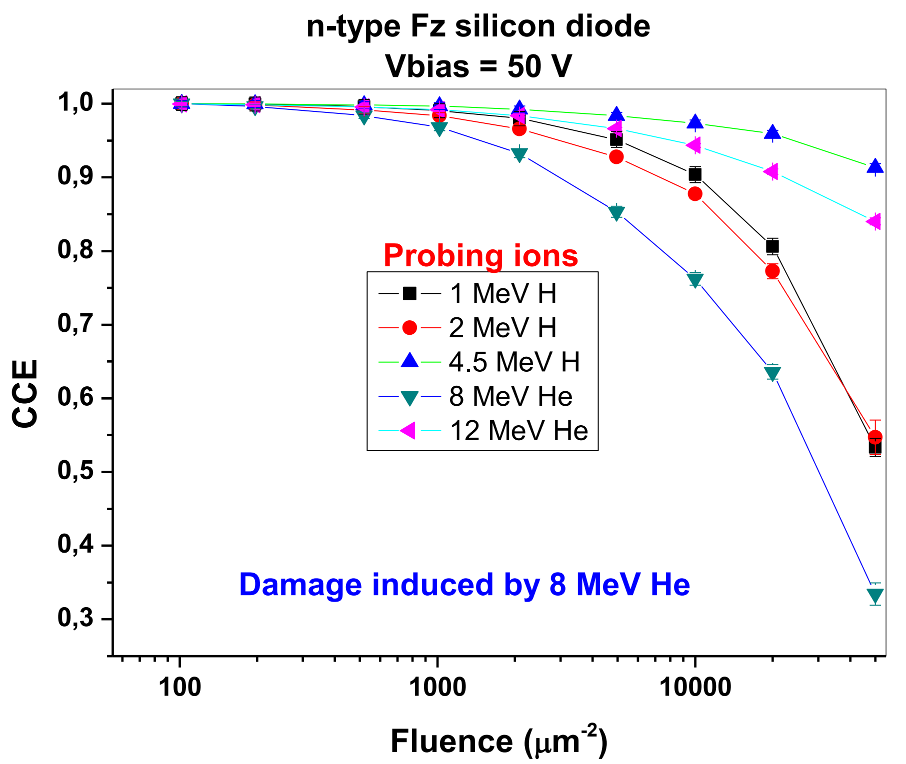
$$\eta = \frac{Y}{Y_0} = 1 - K(V_{bias}) \cdot \Phi = 1 - K_{ed} \cdot D_d$$



CCE degradation induced by ion irradiation

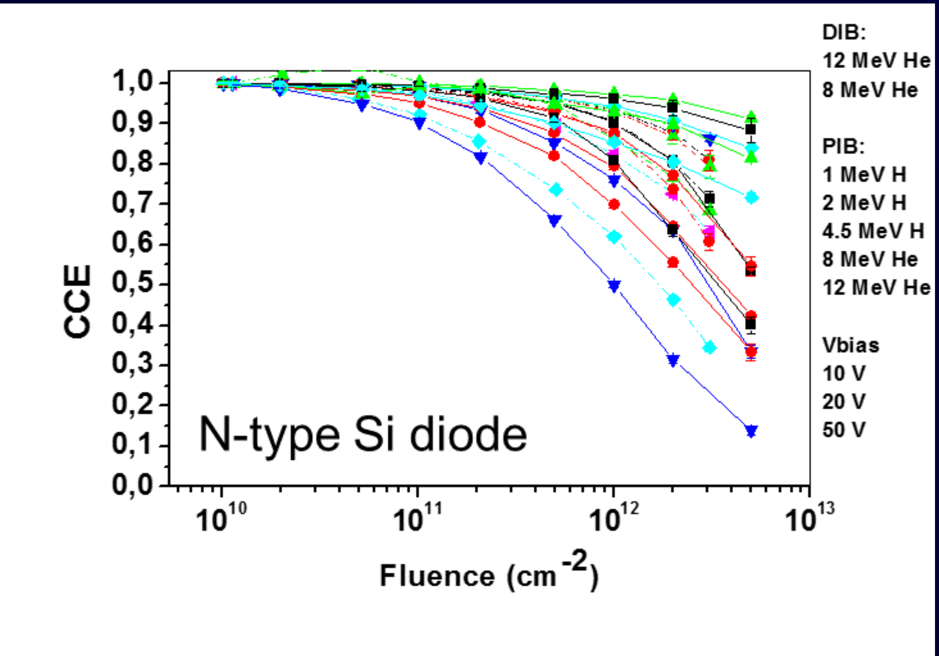
Is a function of the ion used to measure the CCE

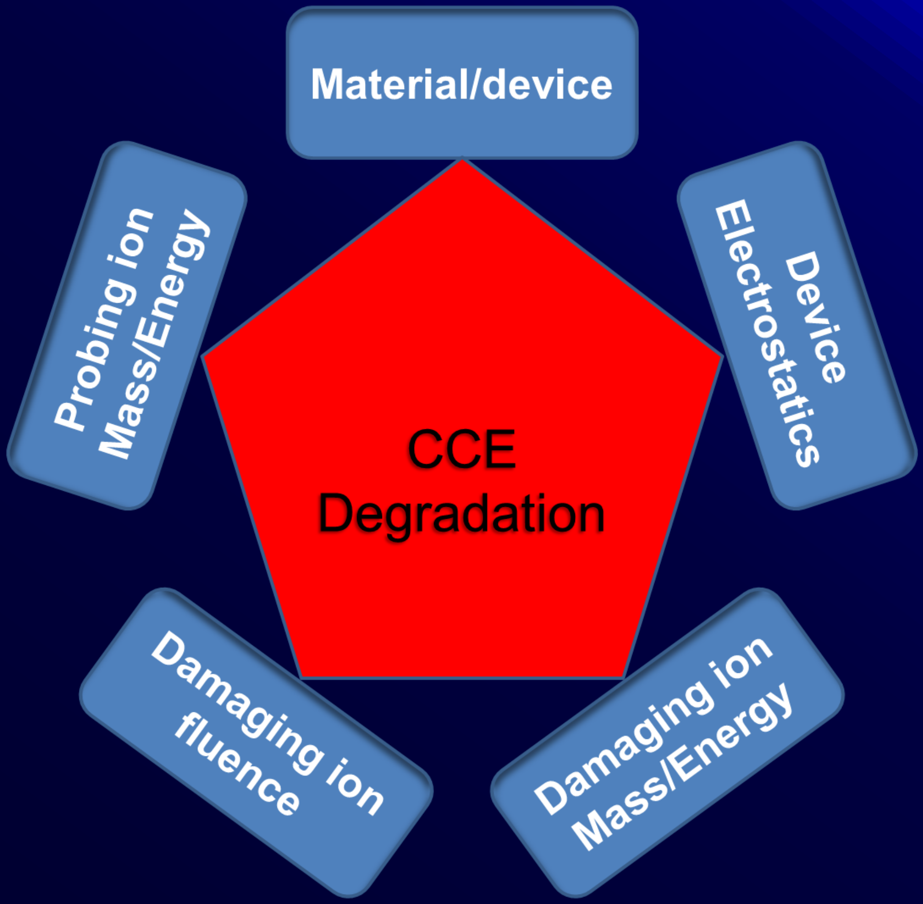
$$\eta = \frac{Y}{Y_0} = 1 - K(V_{bias}, \text{Ion probe}) \cdot \Phi = 1 - K_{ed} \cdot D_d$$



Summary

CCE degradation induced by ion irradiation





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

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

ANSTO
Australia

SNL
USA

Surrey University
United Kingdom

Ruđer Bošković Inst.
Croatia

CNA
Spain

Helsinki University
Finland

NUS
Singapore

Leipzig University
Germany

MNA
Malaysia

Delhi Univ.
India

JAEA & Kyoto University
Japan

Torino University
Italy

Goals

To correlate the effect of different kinds of radiation on the properties of materials and devices

To predict the effects of one radiation relative to another

To extract parameters directly correlated with the radiation hardness of the material

Experimental protocol

Model for charge pulse formation (IBIC theory)

Model for CCE degradation (SRH model)

Model for charge pulse formation (IBIC theory)

- Formalism based on the Shockley-Ramo-Gunn theorem
- The charge induced by the motion of free carriers is the Green's function of the continuity equations
- Adjoint equation method: the CCE is the solution of the Adjoint Equation[1]

[1]T.H.Prettyman, Nucl. Instr. and Meth. in Phys. Res. A 422 (1999) 232-237.

Model for charge pulse formation (IBIC theory)

1D

↓

Fully depleted device

↓

No diffusion

↓

Ramo Theorem

Ionization profile

Gunn's weighting field

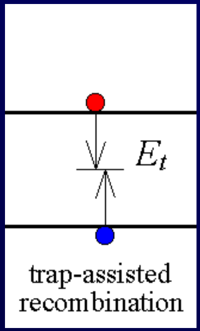
$$Q_S = q \cdot \int_0^d dx \cdot \Gamma(x) \left\{ \begin{array}{l} \int_x^d dy \cdot \frac{\partial F(y)}{\partial V_S} \cdot \exp\left[-\int_x^y dz \left(\frac{1}{v_p \cdot \tau_p} \right) \right] + \\ \int_0^x dy \cdot \frac{\partial F(y)}{\partial V_S} \cdot \exp\left[-\int_y^x dz \left(\frac{1}{v_n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

Holes

Electrons

Drift lengths

Model for CCE degradation
Shockley-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

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

Capture coefficient

Vacancy Density Profile

Fluence

SRIM The Stopping and Range of Ions in Matter

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

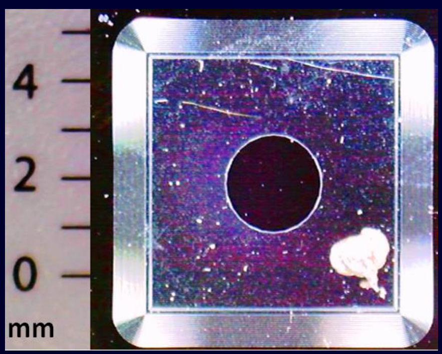
LOW DENSITY OF TRAPS -> NOT INTERACTING TRAPS

The experimental protocol

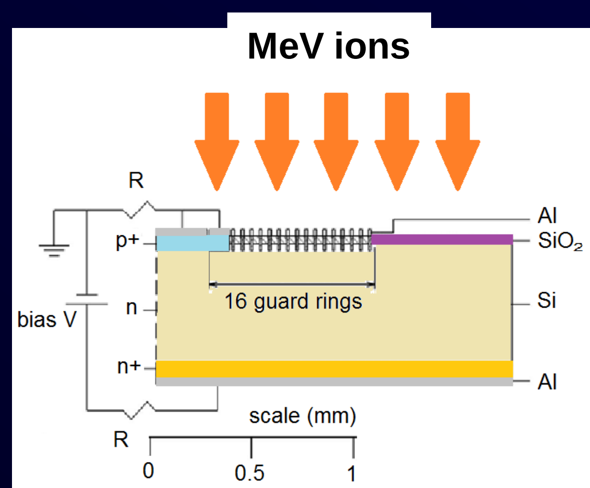
Z. Pastuovic et al., IEEE Trans on Nucl. Sc. 56 (2009) 2457; APL (98) 092101 (2011)

Samples under study

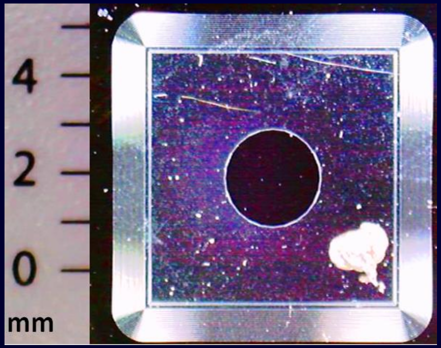
n- and p- type Fz p-i-n Si diodes
Fabricated by the Institute of Physics, University of Helsinki



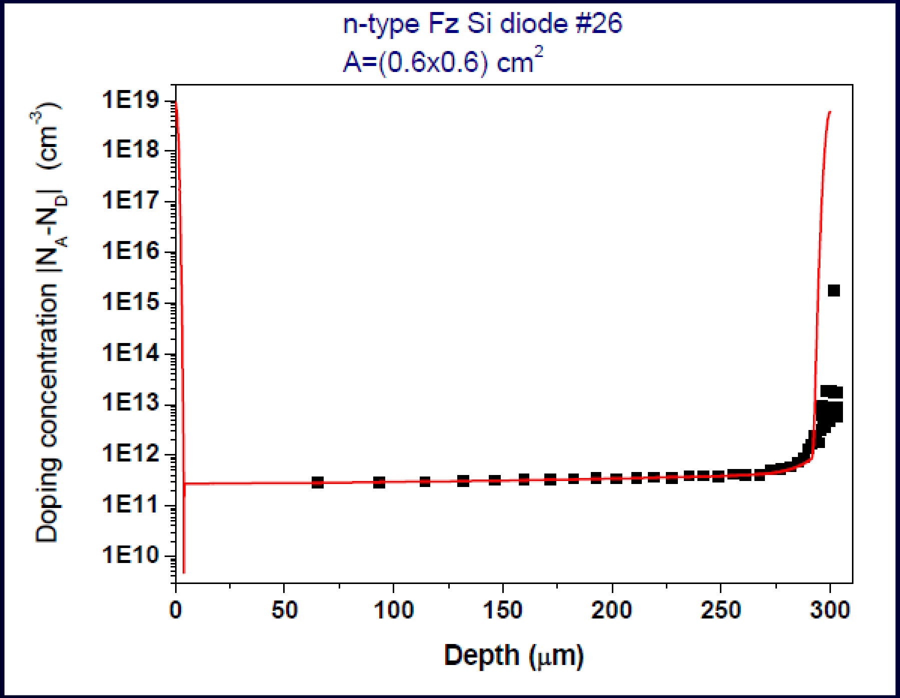
16 floating guard rings
The frontal electrode and the guard rings
are coated with Al (0.5 µm]).
The Al electrode has a hole in the center, 1 mm diameter.
Different dimensions: 5 or 2.5 mm



Experimental protocol



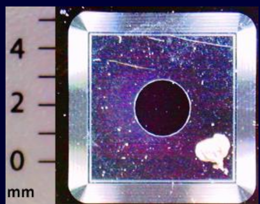
C-V characteristics
Depletion width-voltage

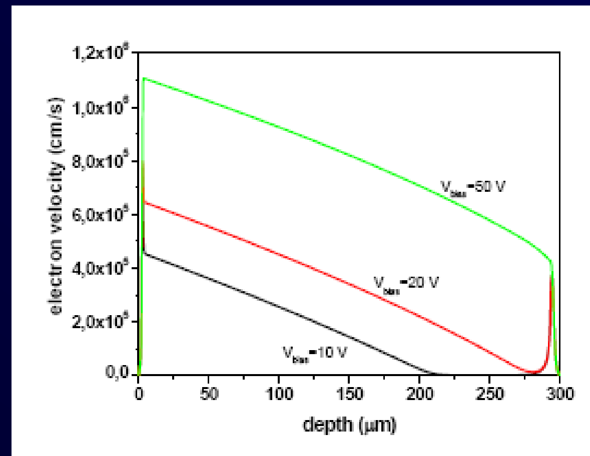


Experimental protocol

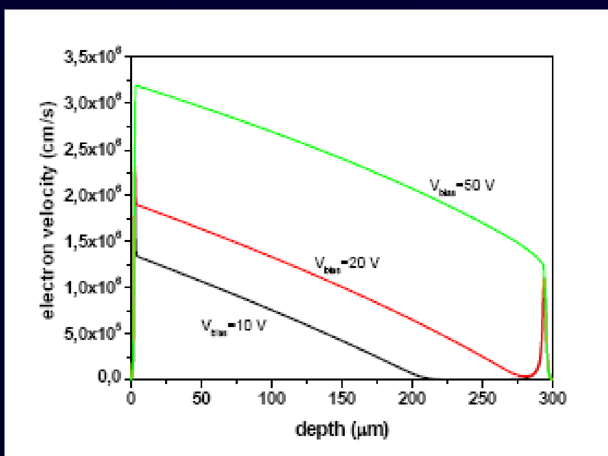
✓**Electrical characterization**

Experimental protocol



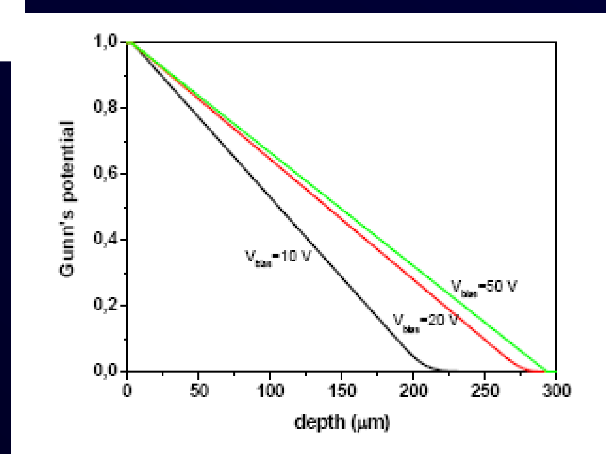


hole drift velocity profiles

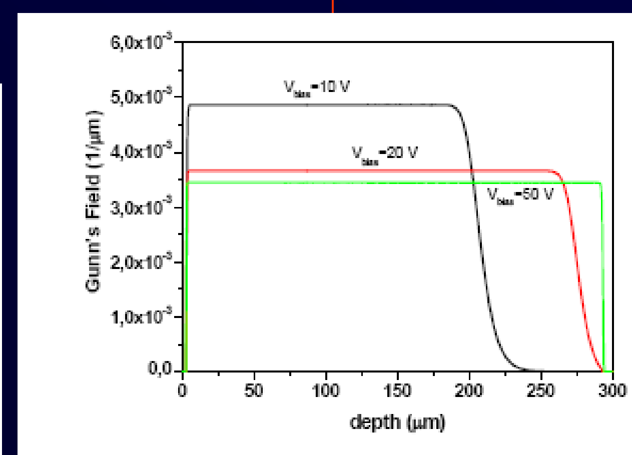


Electron drift velocity profiles

Gunn's weighting potential

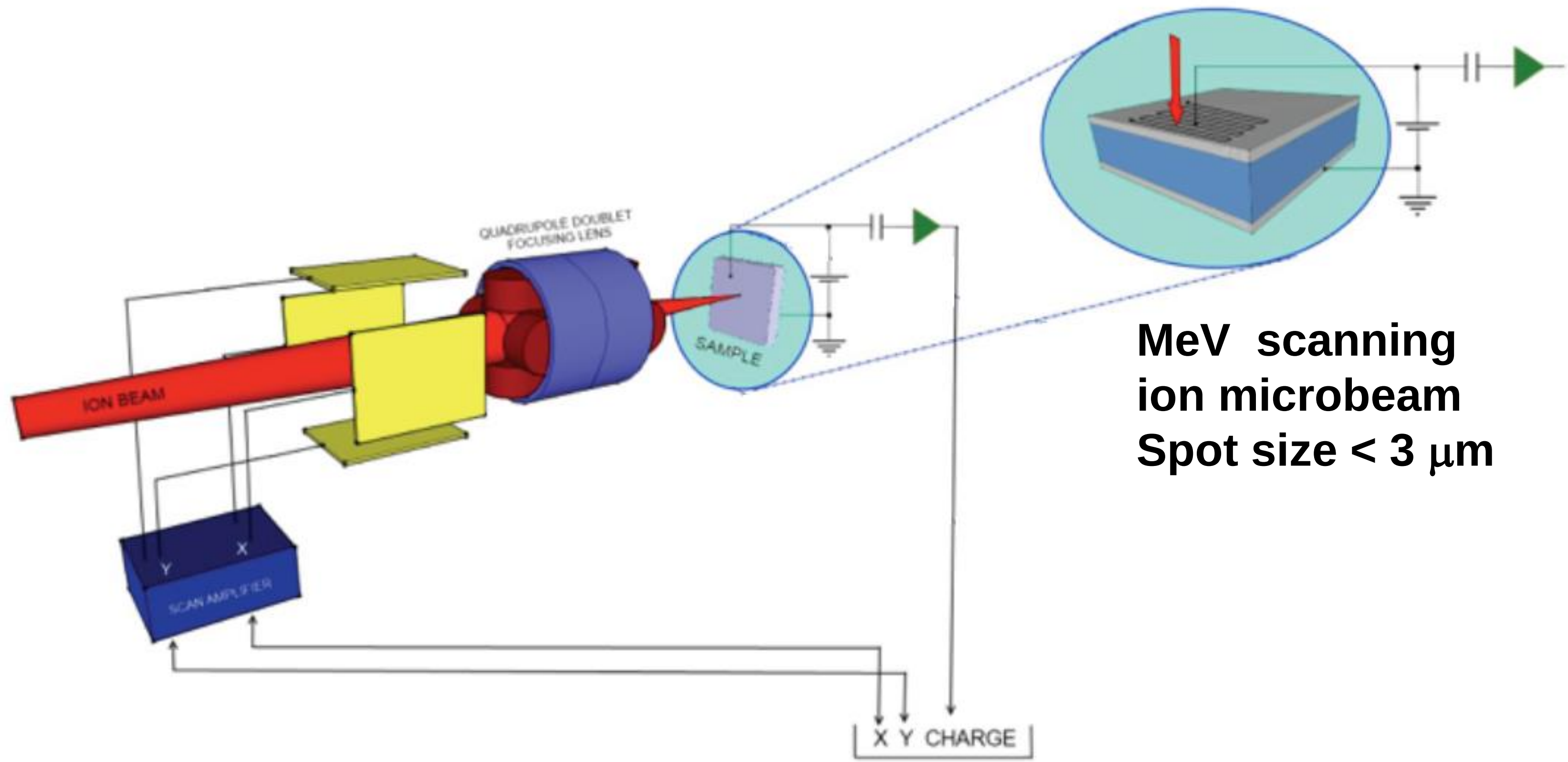


Gunn's weighting field



Experimental protocol

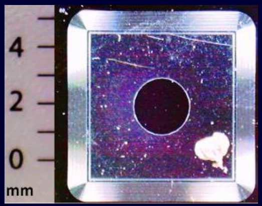
- ✓ Electrical characterization
- ✓ Electrostatic modeling

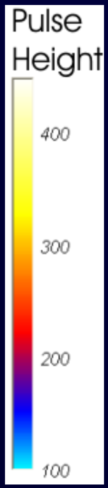


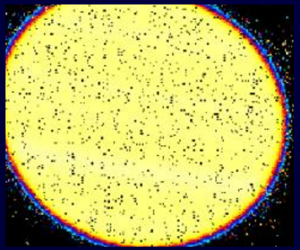
MeV scanning ion microbeam
Spot size < 3 μm

PROBING THE PRISTINE SAMPLE

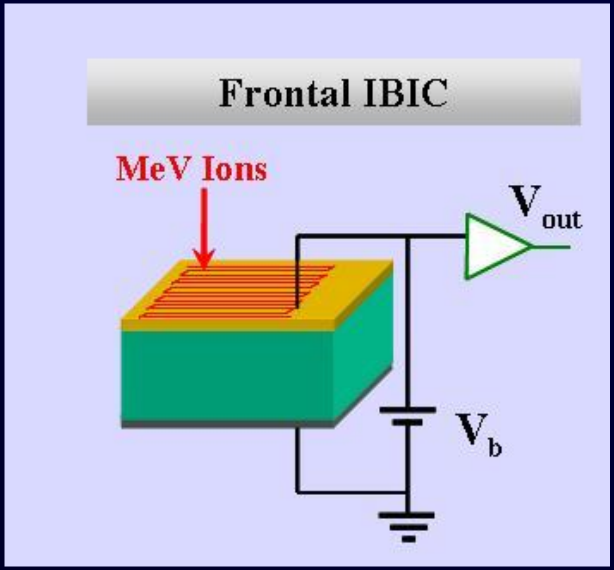
IBIC map on a pristine diode probed with a scanning 1.4 MeV He microbeam;







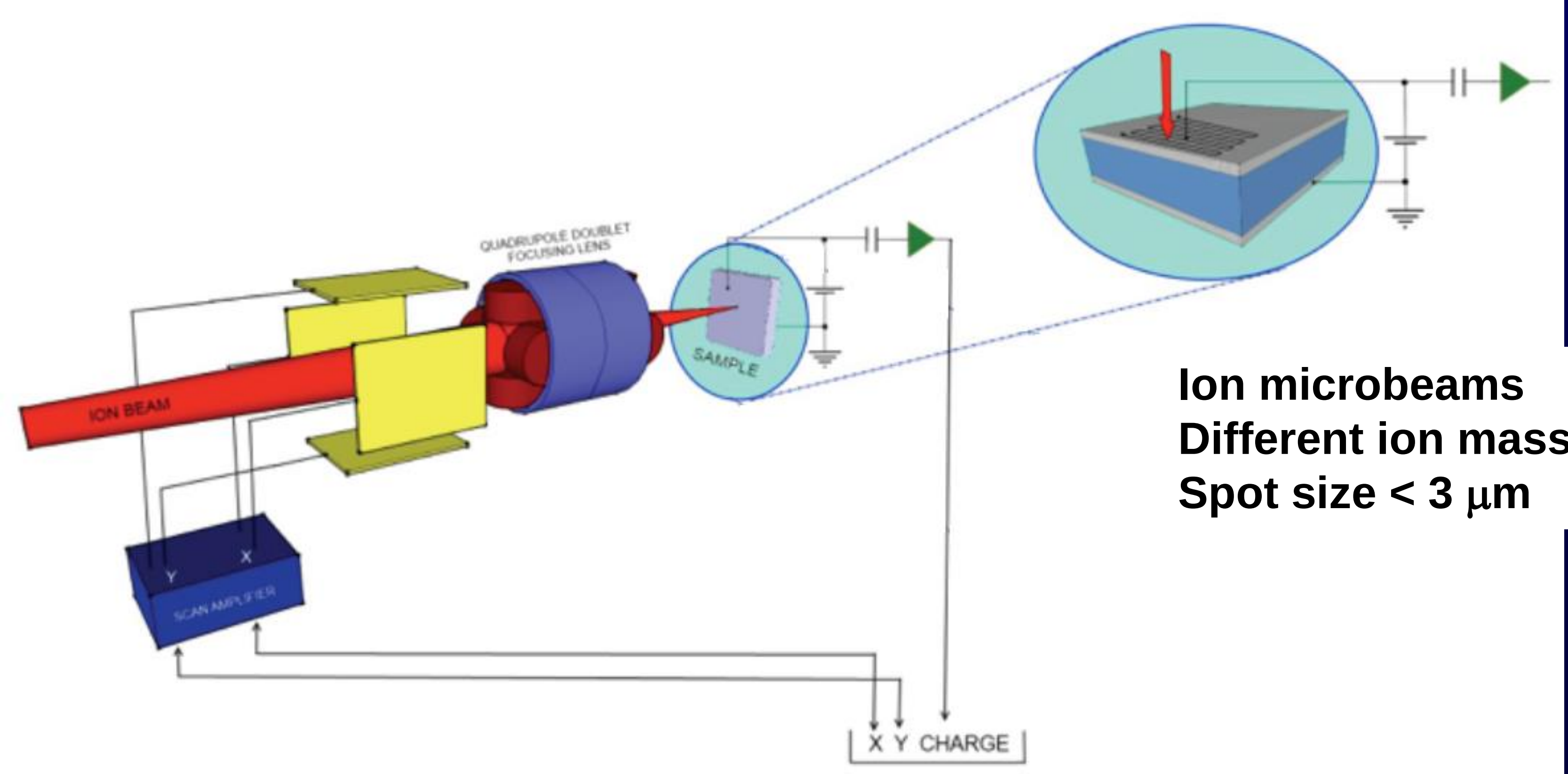
Uniform CCE map



Experimental protocol

- ✓Electrical characterization
- ✓Electrostatic modeling
- ✓IBIC map on pristine sample

Z. Pastuovic et al., IEEE Trans on Nucl. Sc. 56 (2009) 2457; APL (98) 092101 (2011)

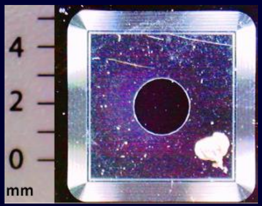


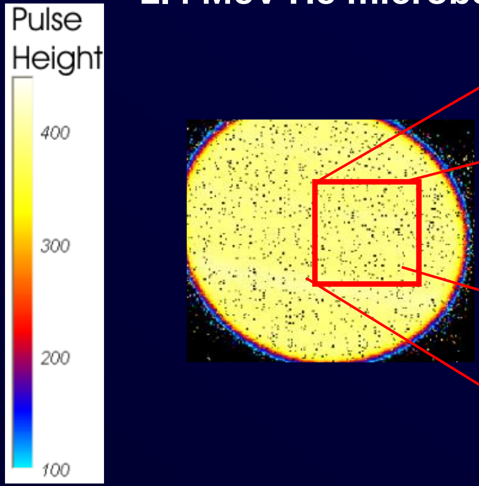
Ion microbeams
Different ion mass/energy
Spot size < 3 μm

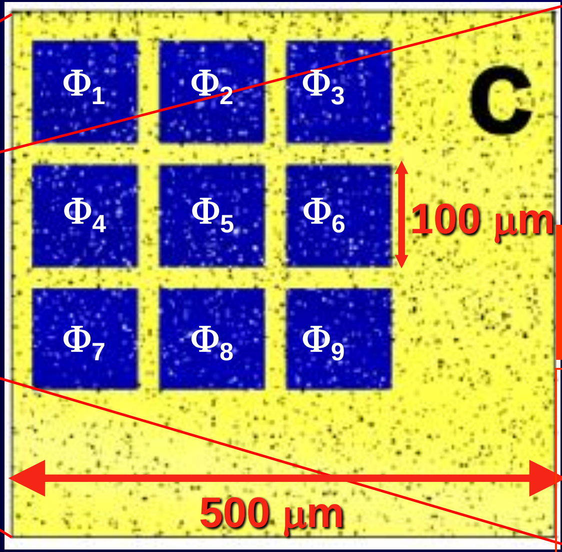
DAMAGING SELECTED AREAS 100X100 μm^2

IBIC map on a pristine diode probed with a scanning 1.4 MeV He microbeam;

ZOOM in view of the selected area for focused ion beam irradiation at different fluences Φ



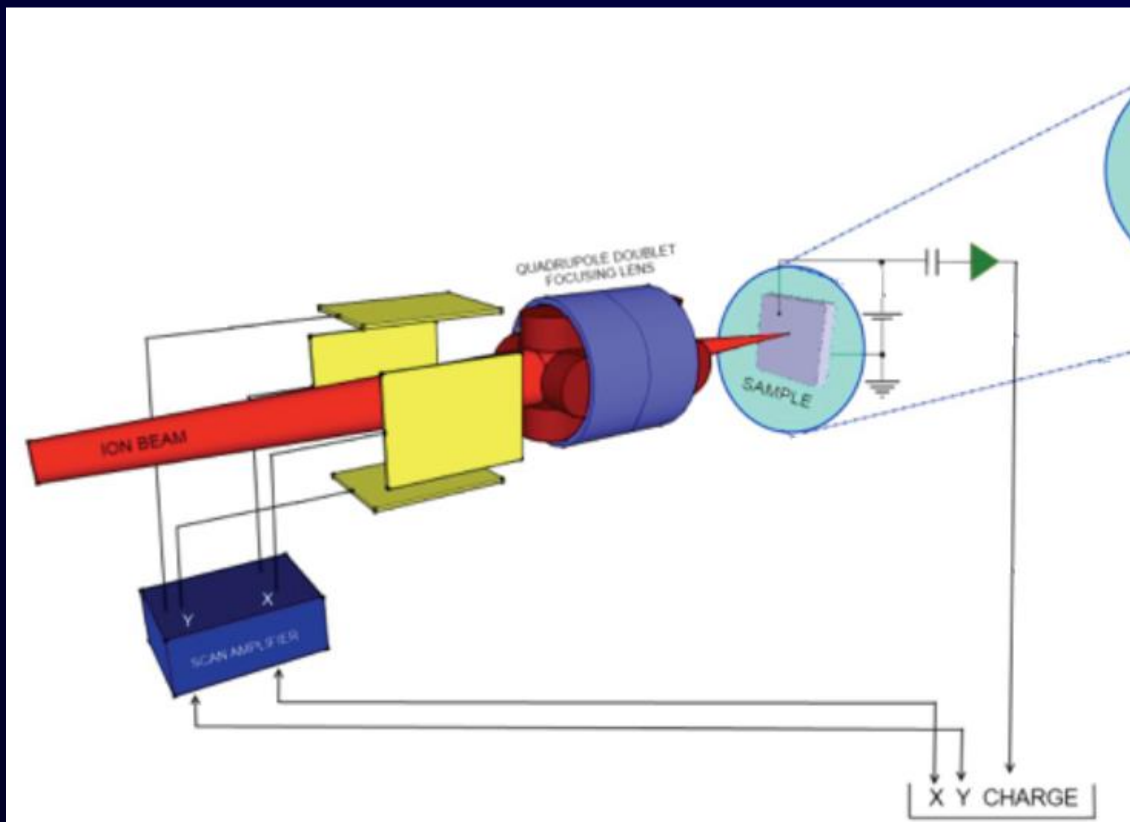




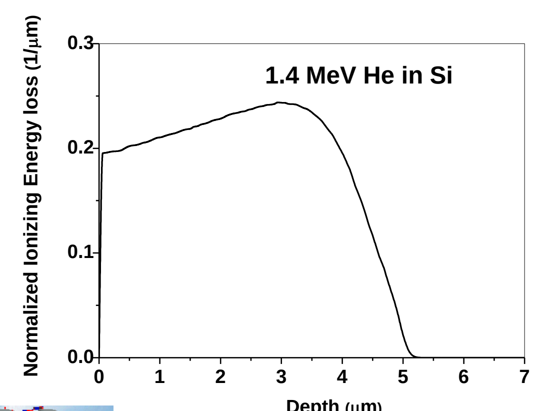
Experimental protocol

- ✓Commercial p-i-n diodes
- ✓Electrical characterization
- ✓IBIC map on pristine sample
- ✓Irradiation of 9 regions at different fluences

Z. Pastuovic et al., IEEE Trans on Nucl. Sc. 56 (2009) 2457; APL (98) 092101 (2011)



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

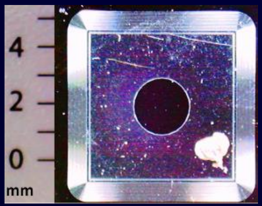


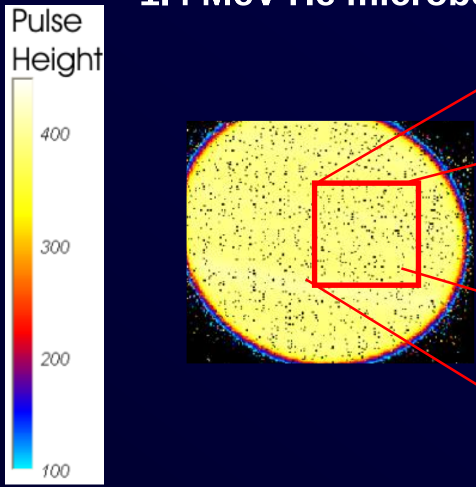
Data from SRIM

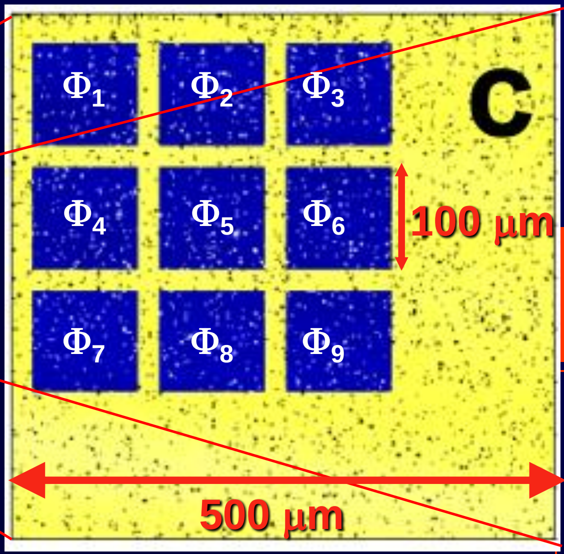
PROBING DAMAGED AREAS

The Stopping and Range of Ions in Matter

IBIC map on a pristine diode probed with a scanning 1.4 MeV He microbeam;

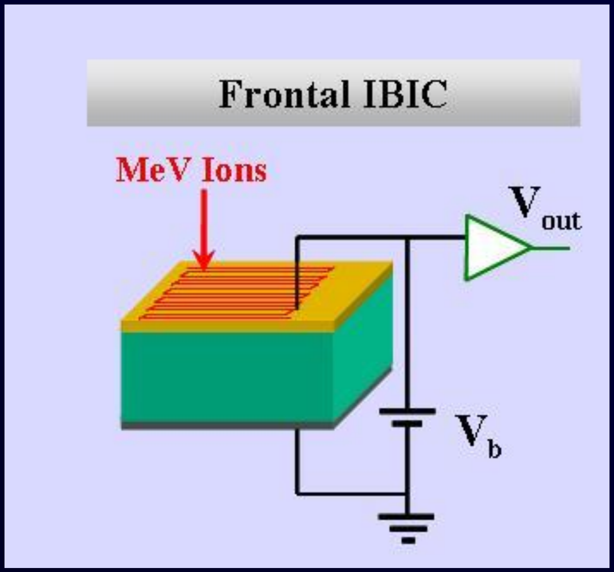


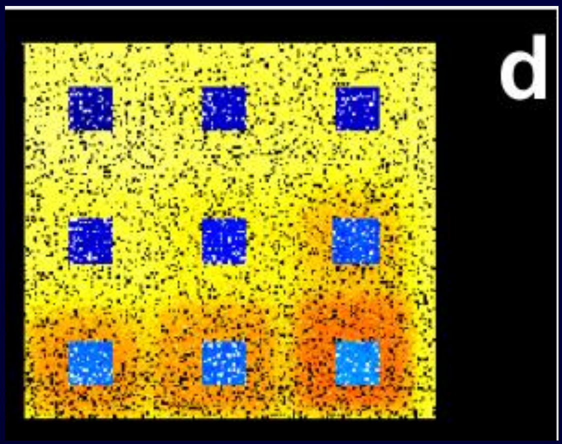




Experimental protocol

- ✓Commercial p-i-n diodes
- ✓Electrical characterization
- ✓IBIC map on pristine sample
- ✓Irradiation of 9 regions at different fluences
- ✓IBIC map of irradiated regions

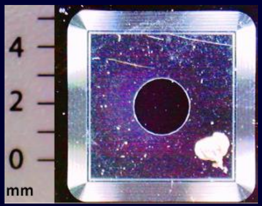


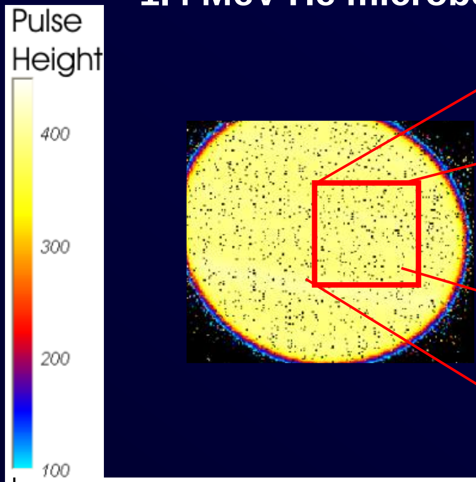


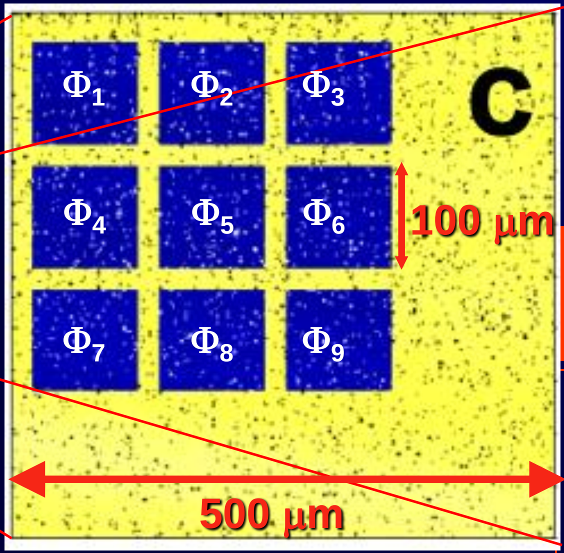
a measured 2D distribution of the IBIC signal amplitude after irradiation

Z. Pastuovic et al., IEEE Trans on Nucl. Sc. 56 (2009) 2457; APL (98) 092101 (2011)

IBIC map on a pristine diode probed with a scanning 1.4 MeV He microbeam;







Experimental protocol

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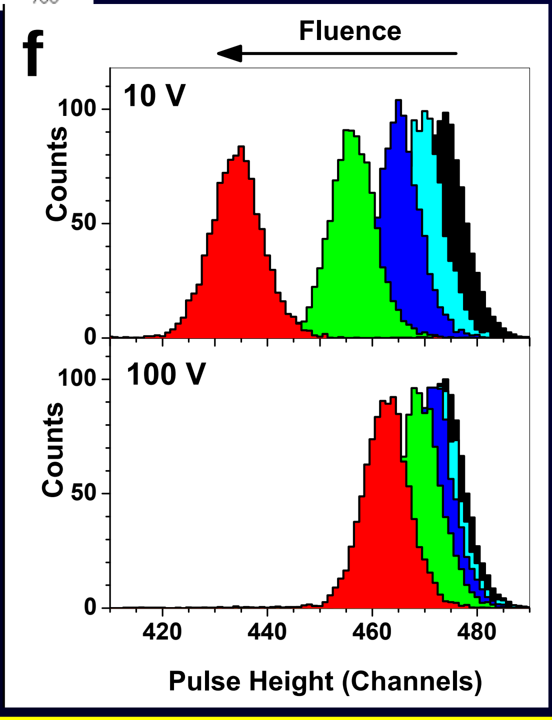
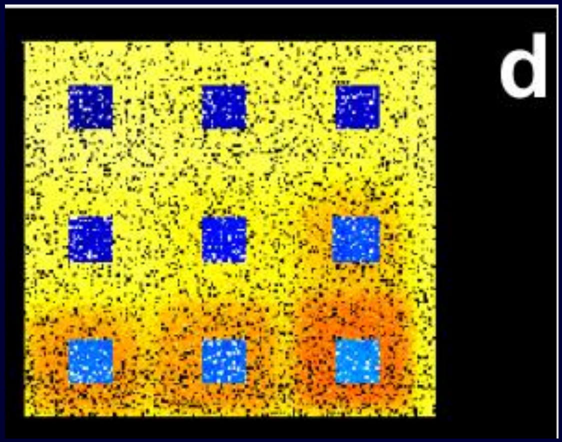


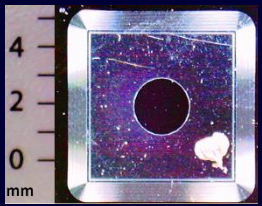
IBIC spectra (bias voltage = 10 V and 100 V) from the central regions of four of the areas shown in Fig. c

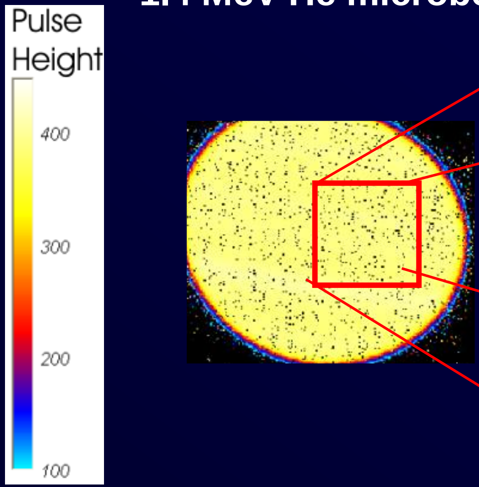


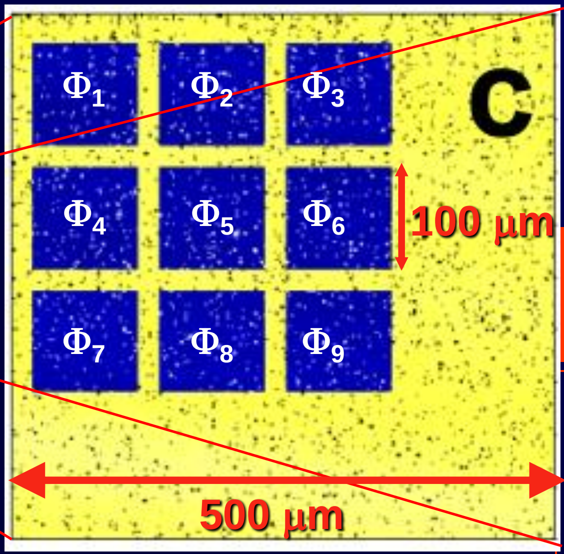
a measured 2D distribution of the IBIC signal amplitude after irradiation

Z. Pastuovic et al., IEEE Trans on Nucl. Sc. 56 (2009) 2457; APL (98) 092101 (2011)

IBIC map on a pristine diode probed with a scanning 1.4 MeV He microbeam;

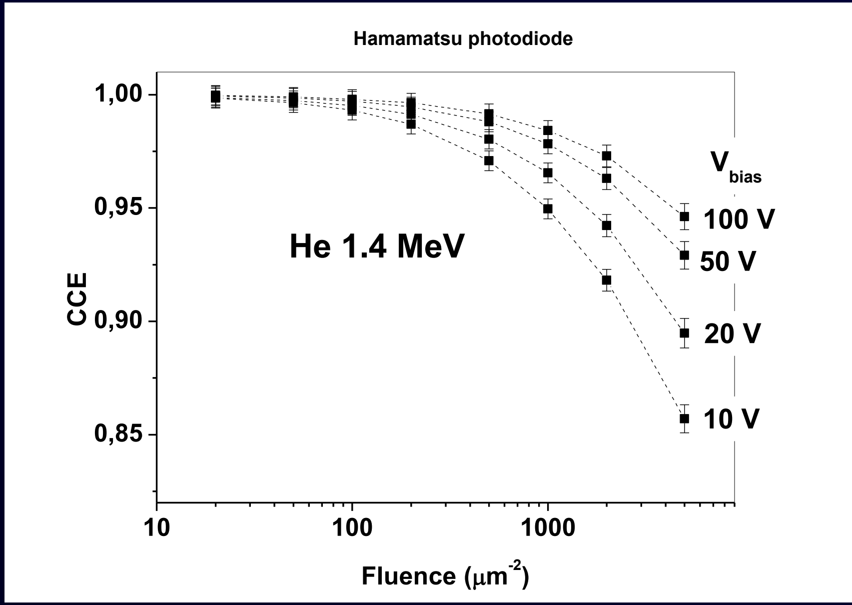


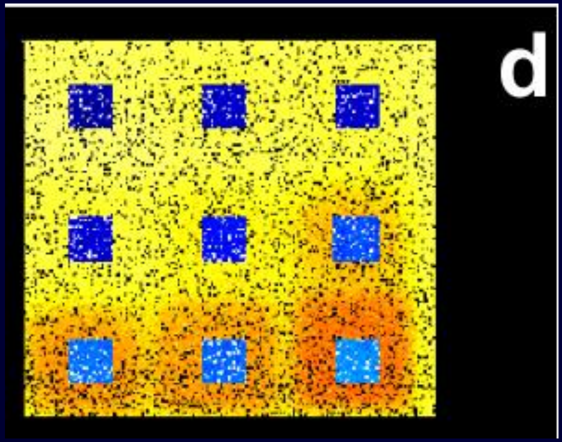




Experimental protocol

- ✓Commercial p-i-n diodes
- ✓Electrical characterization
- ✓IBIC map on pristine sample
- ✓Irradiation of 9 regions at different fluences
- ✓IBIC map of irradiated regions

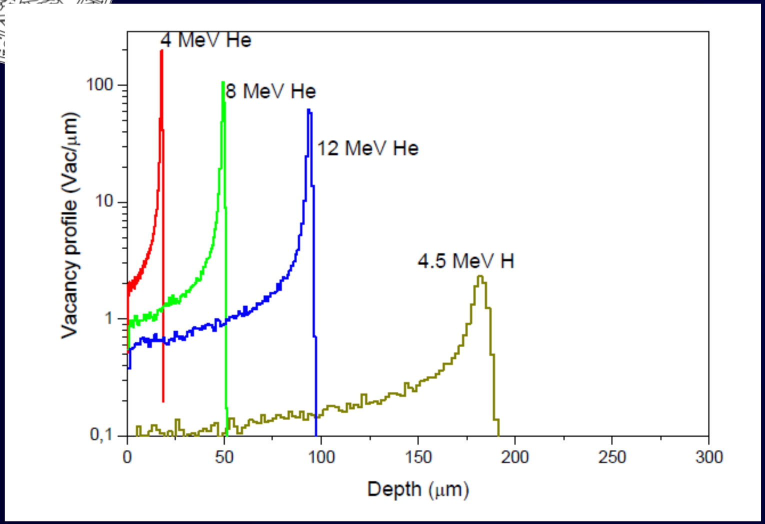




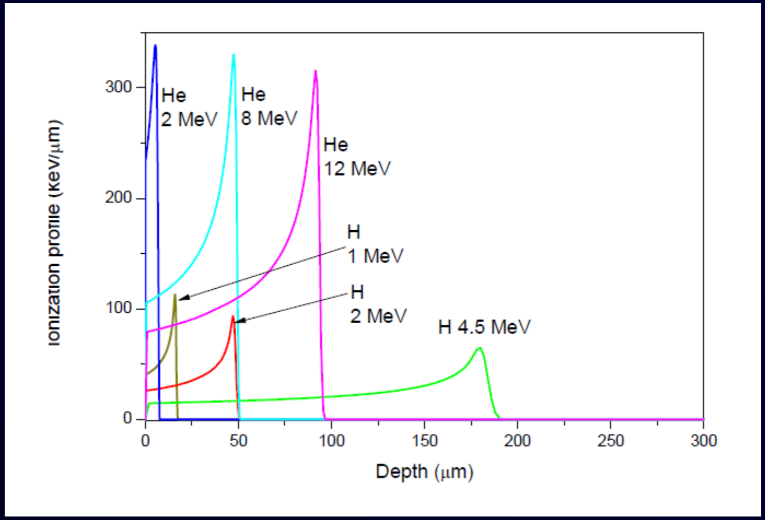
a measured 2D distribution of the IBIC signal amplitude after irradiation

Z. Pastuovic et al., IEEE Trans on Nucl. Sc. 56 (2009) 2457; APL (98) 092101 (2011)

DIB: Vacancy profiles



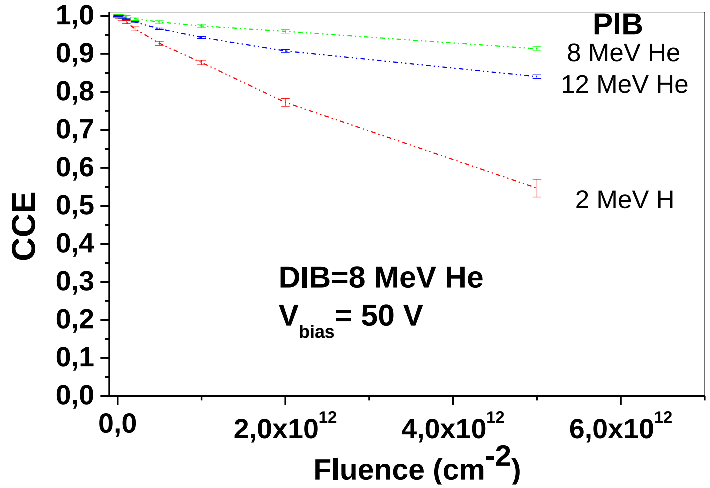
PIB: Ionization profiles



PIB = Probing ion beam
DIB = Damaging ion beam

PIB\DIB	He 4 MeV	He 8 MeV	He 12 MeV	H 4.5MeV
H 1 MeV Bias (V)				
H 2 MeV Bias (V)		(ANSTO) 10,20,50	(ANSTO) 10,20,50	
H 4.5 MeV Bias (V)		(ANSTO) 10,20,50	(ANSTO) 10,20,50	
He 2 MeV Bias (V)	(SNL) 10,50	(SNL) 10,50		(SNL) 10,50
He 4 MeV Bias (V)		(ANSTO) 10,20,50	(ANSTO) 10,20,50	
He 8 MeV Bias (V)		(ANSTO) 10,20,50	(ANSTO) 10,20,50	
He 12 MeV Bias (V)			(ANSTO) 10,20,50	

Different bias voltages



Fixed DIB

Variable PIBs

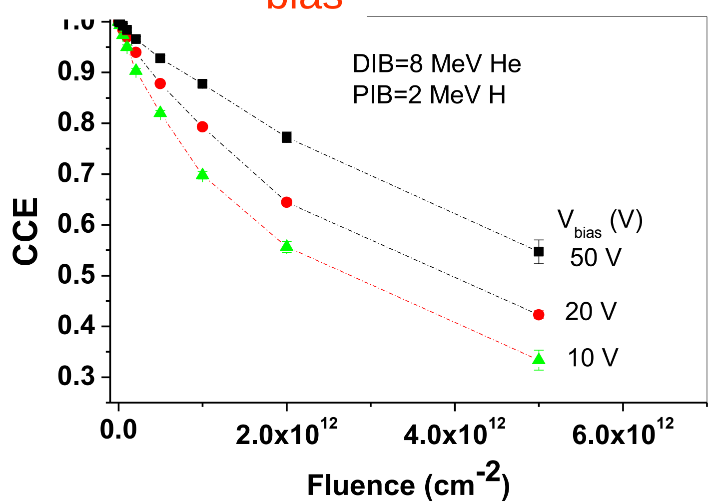
Fixed V_{bias}

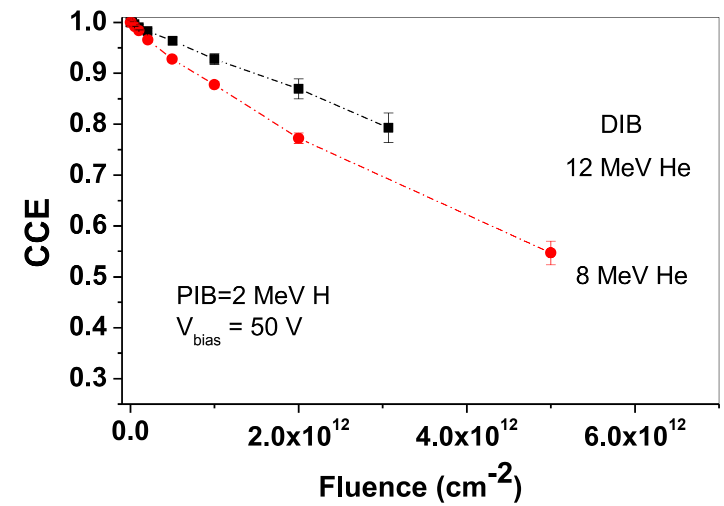
DIB=damaging
PIB=probing
} Ion beam

Fixed DIB

Fixed PIB

Variable V_{bias}

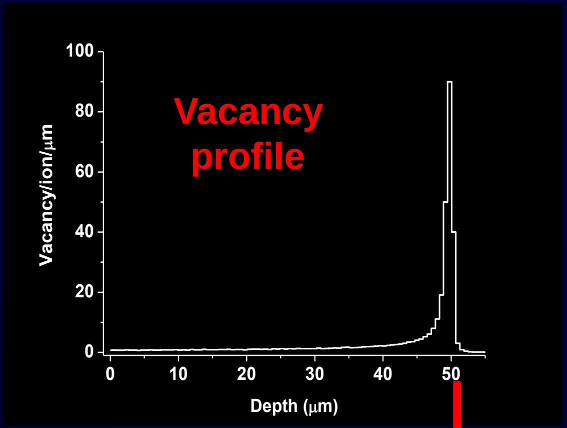


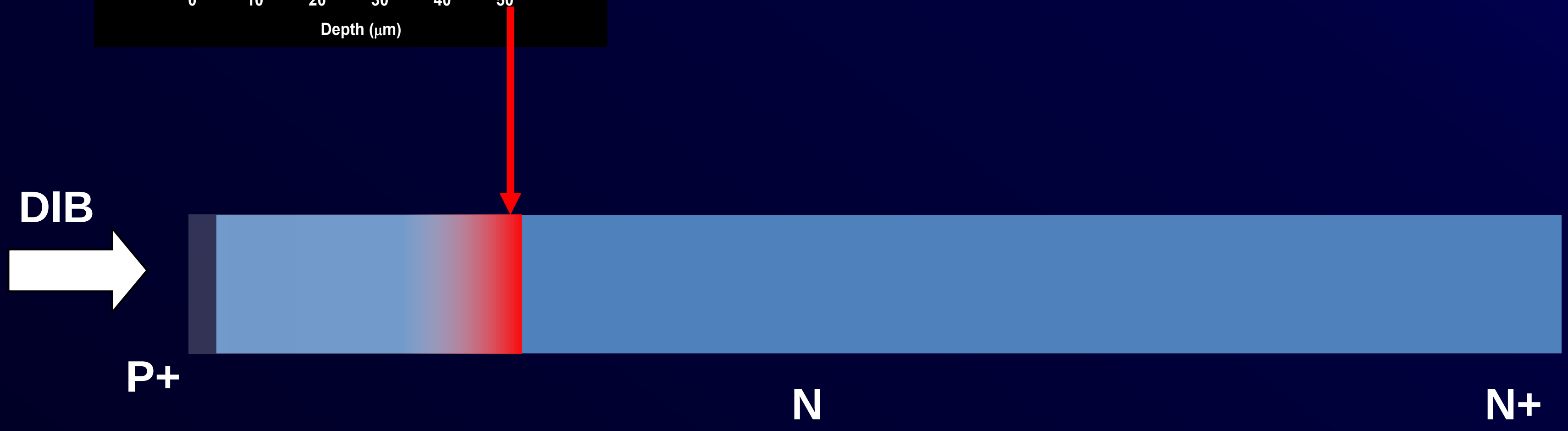


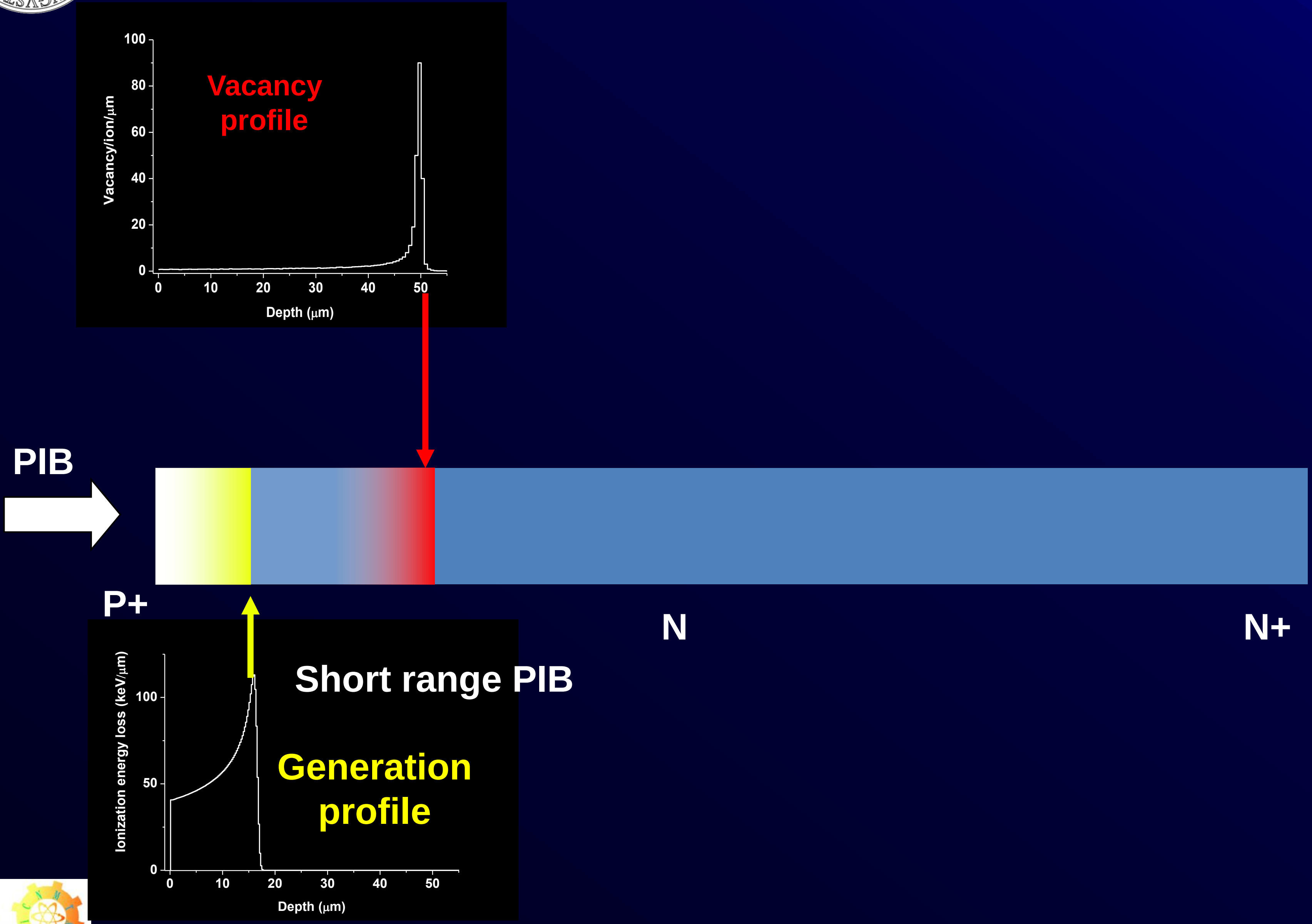
Variable DIB

Fixed PIB

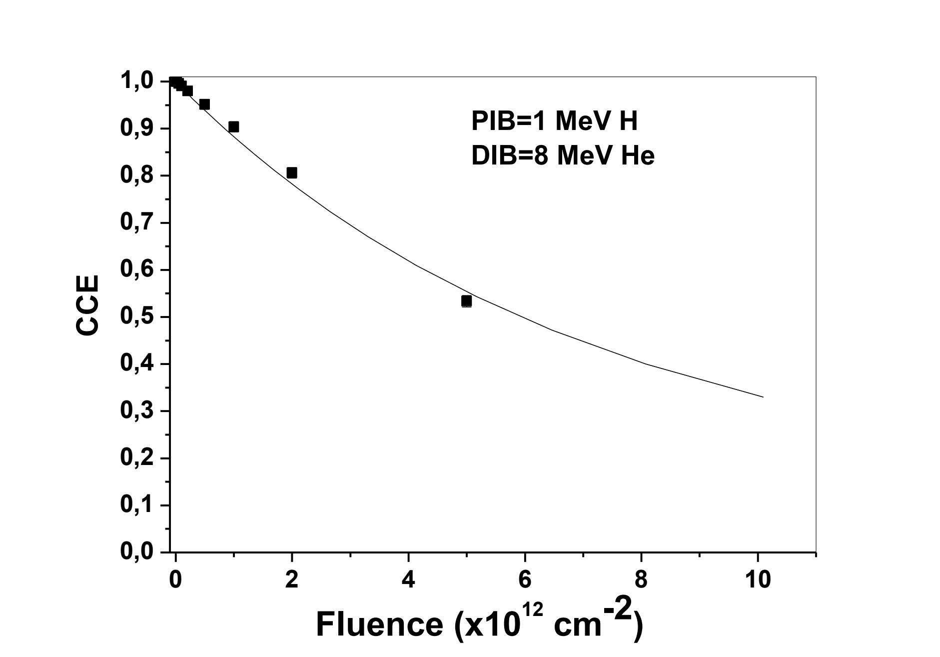
FIXED V_{bias}

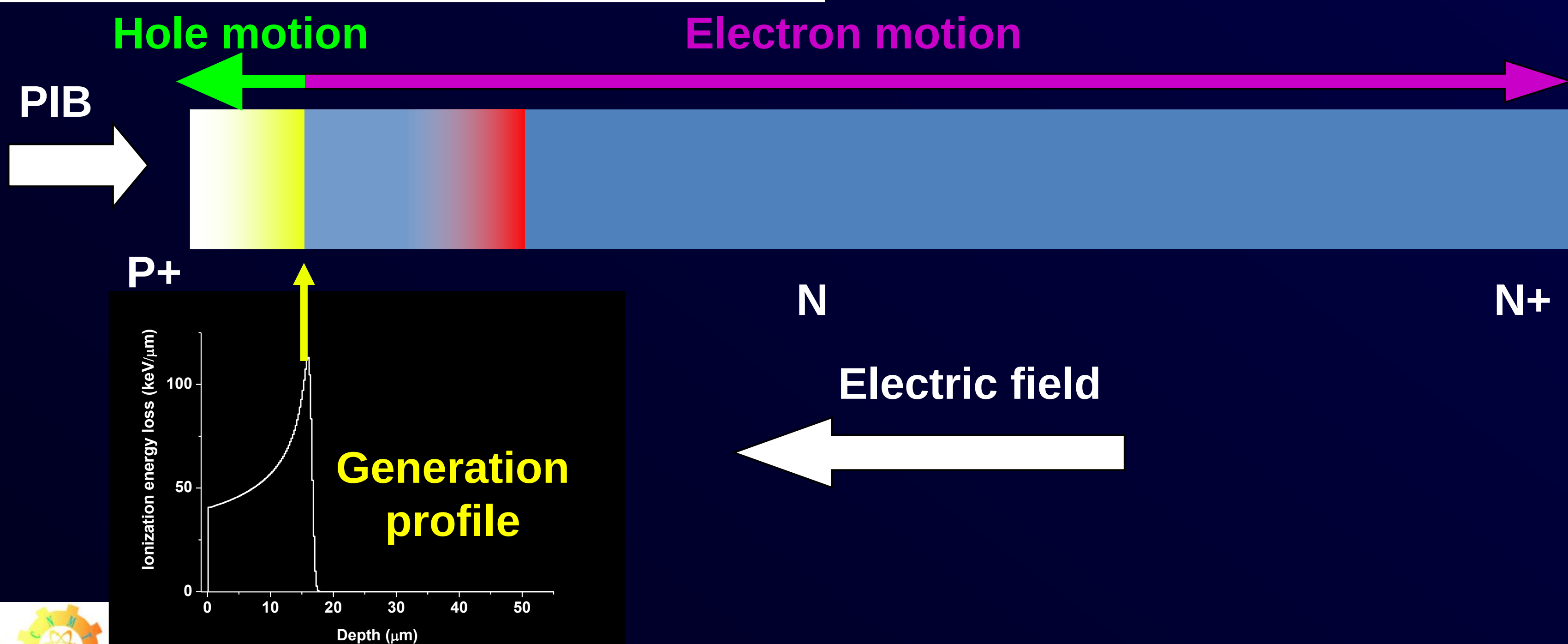

Vacancy profile
Vacancy/ion/µm
Depth (µm)
0
10
20
30
40
50
0
20
40
60
80
100

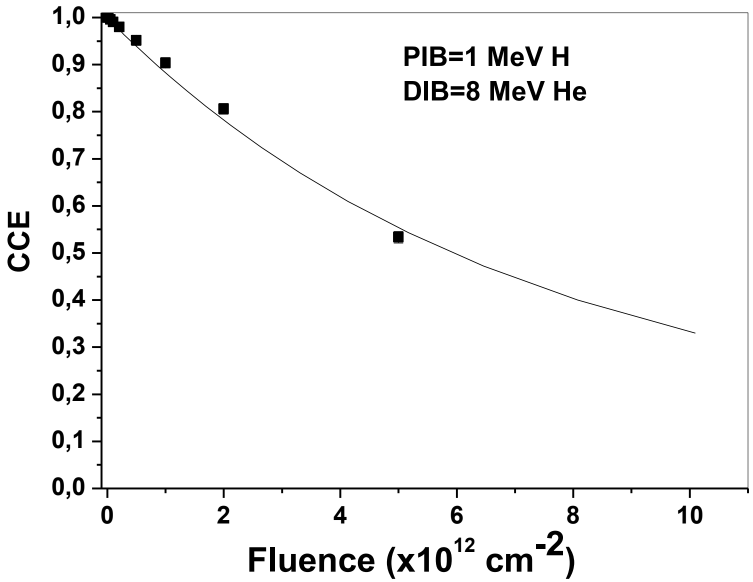

DIB
P+
N
N+

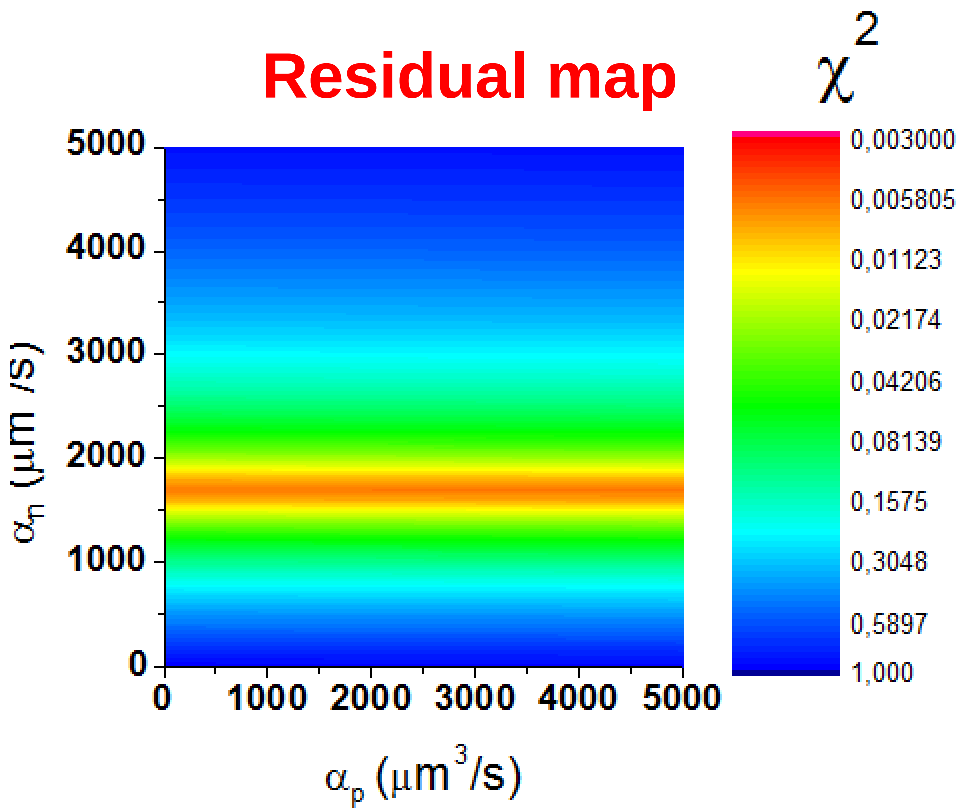


Vacancy profile
Vacancy/ion/µm
Depth (µm)
PIB
P+
N
N+
Short range PIB
Generation profile
Ionization energy loss (keV/µm)
Depth (µm)


PIB=1 MeV H
DIB=8 MeV He
CCE
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
0
2
4
6
8
10
Fluence (x10^{12} cm^{-2})

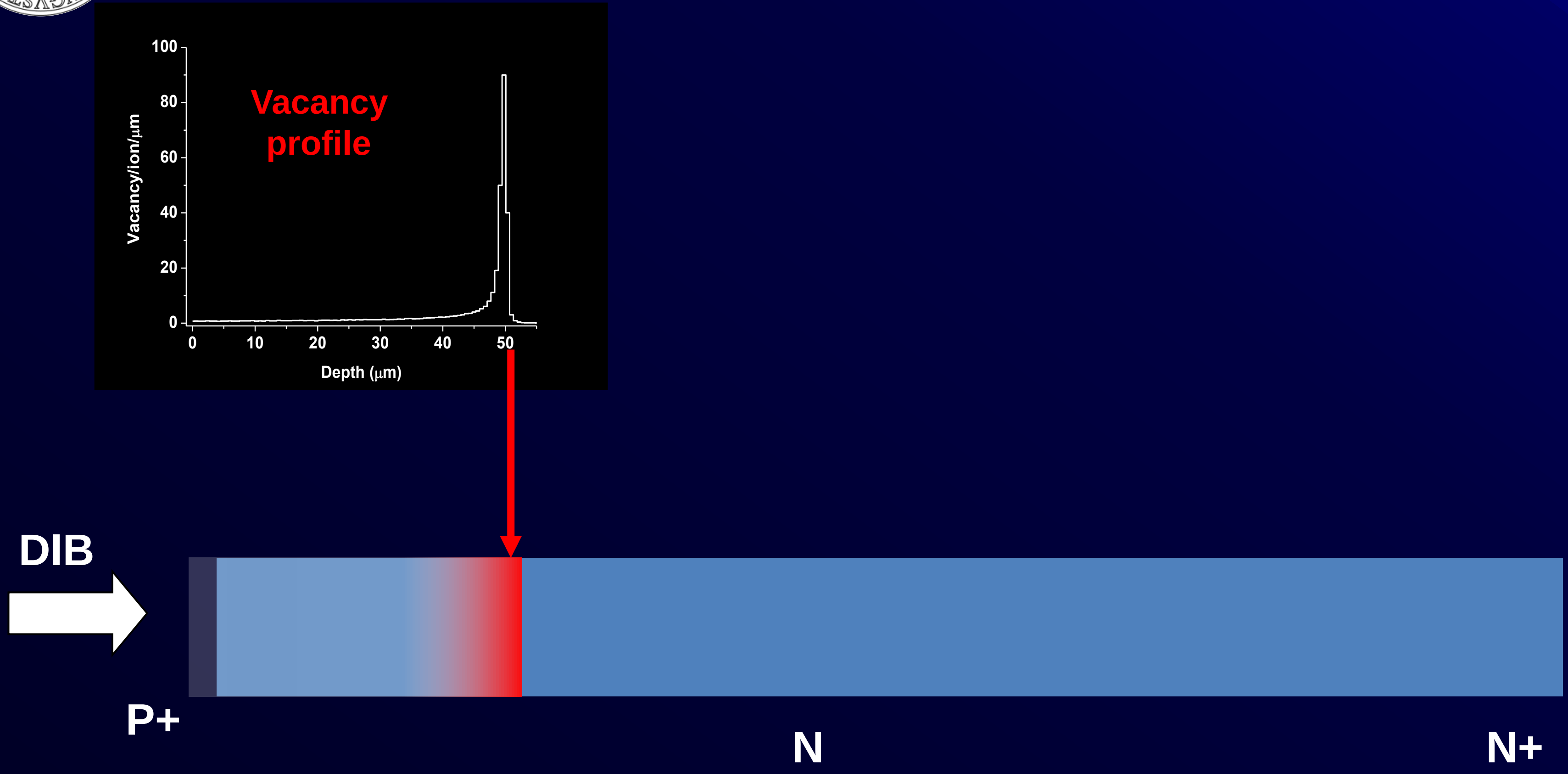

Hole motion
Electron motion
PIB
P+
N
N+
Electric field
Generation profile
Ionization energy loss (keV/μm)
100
50
0
0
10
20
30
40
50
Depth (μm)

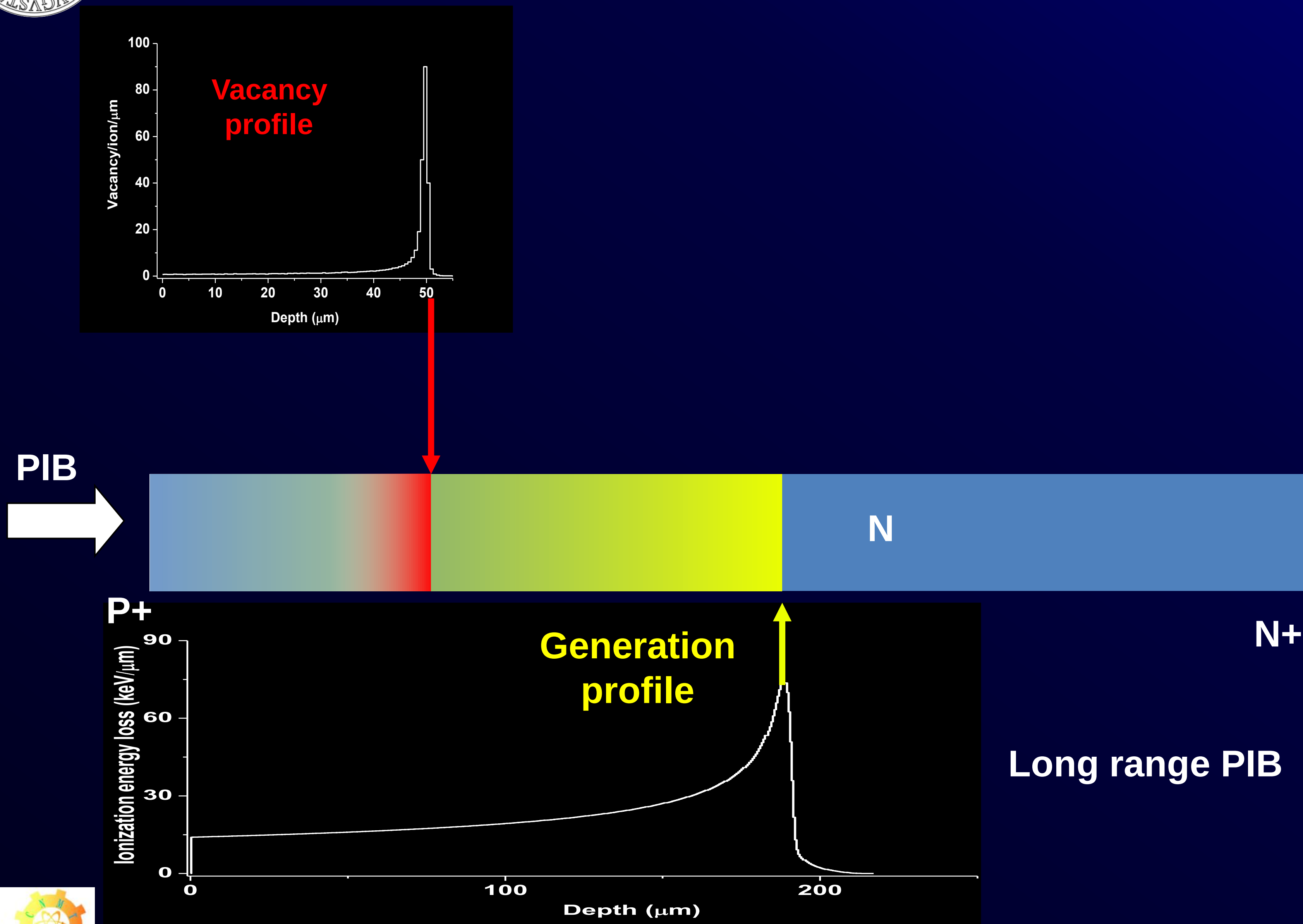




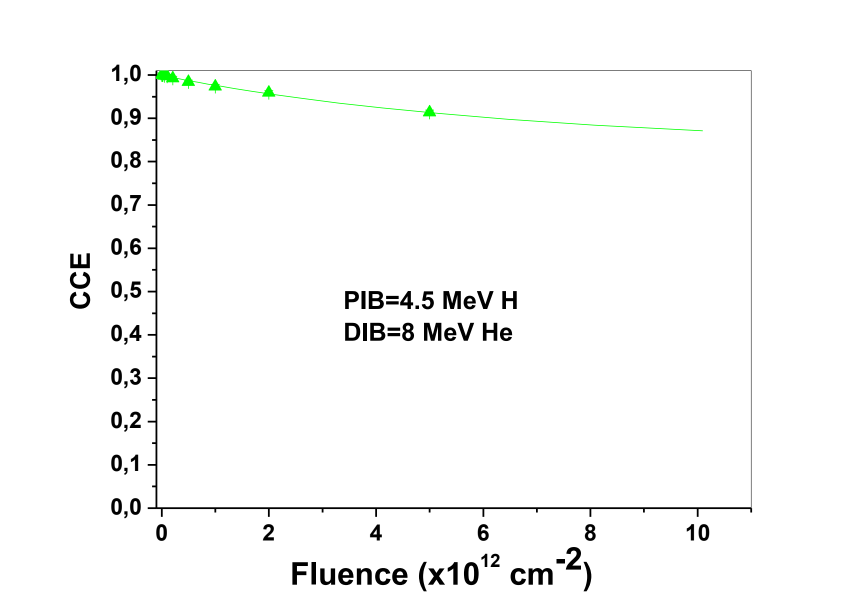
α_n Recombination Coefficient Free parameter

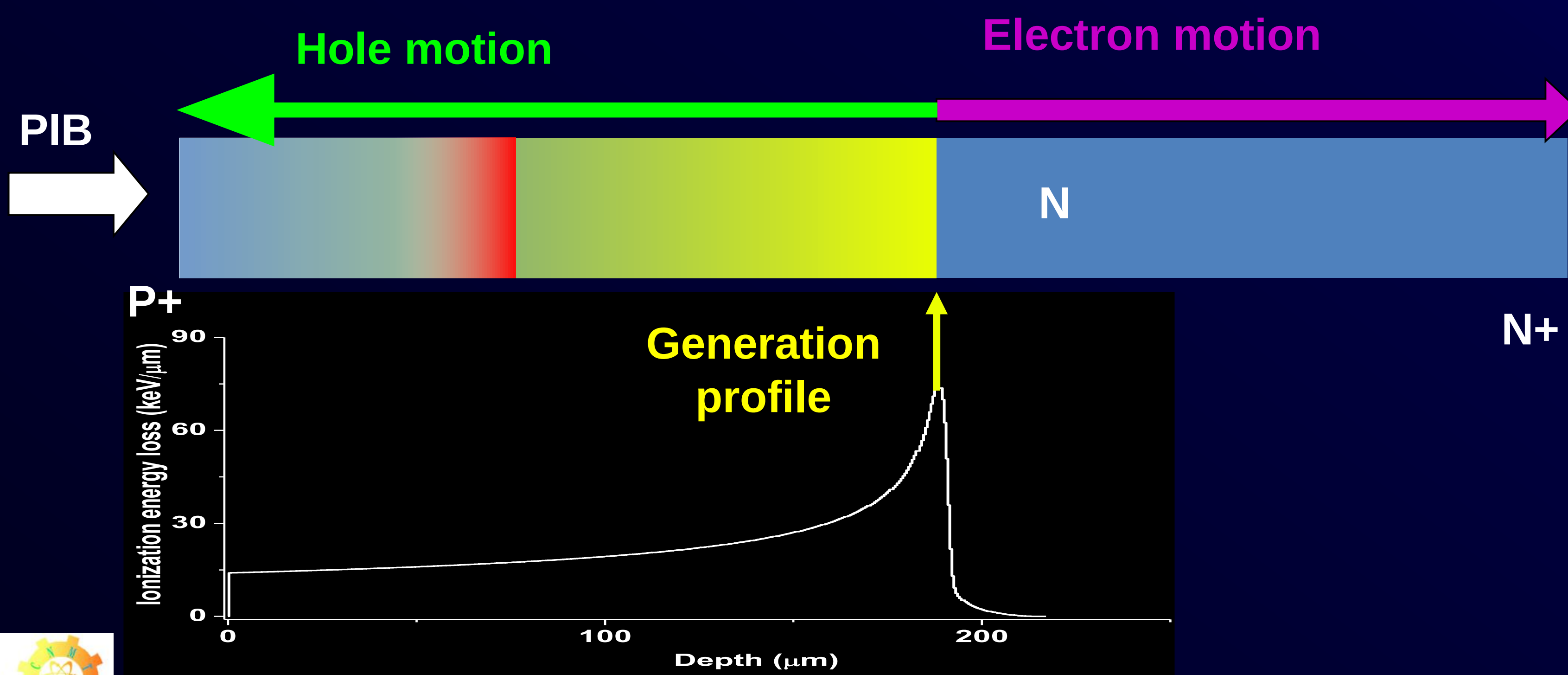
$$Q_S = q \cdot \int_0^d dx \cdot \Gamma(x) \left\{ \int_x^d dy \cdot \frac{\partial F(y)}{\partial V_S} \cdot \exp\left[-\int_x^y dz \frac{1}{v_n} \cdot \left(\frac{1}{\tau_0} + \alpha_n \cdot Vac(x) \cdot \Phi \right) \right] \right\}$$

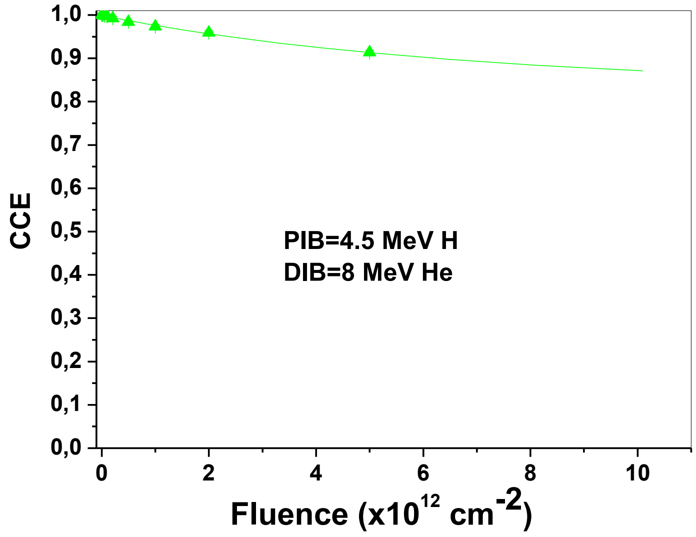

Vacancy profile
Vacancy/ion/µm
100
80
60
40
20
0
0
10
20
30
40
50
Depth (µm)
DIB
P+
N
N+

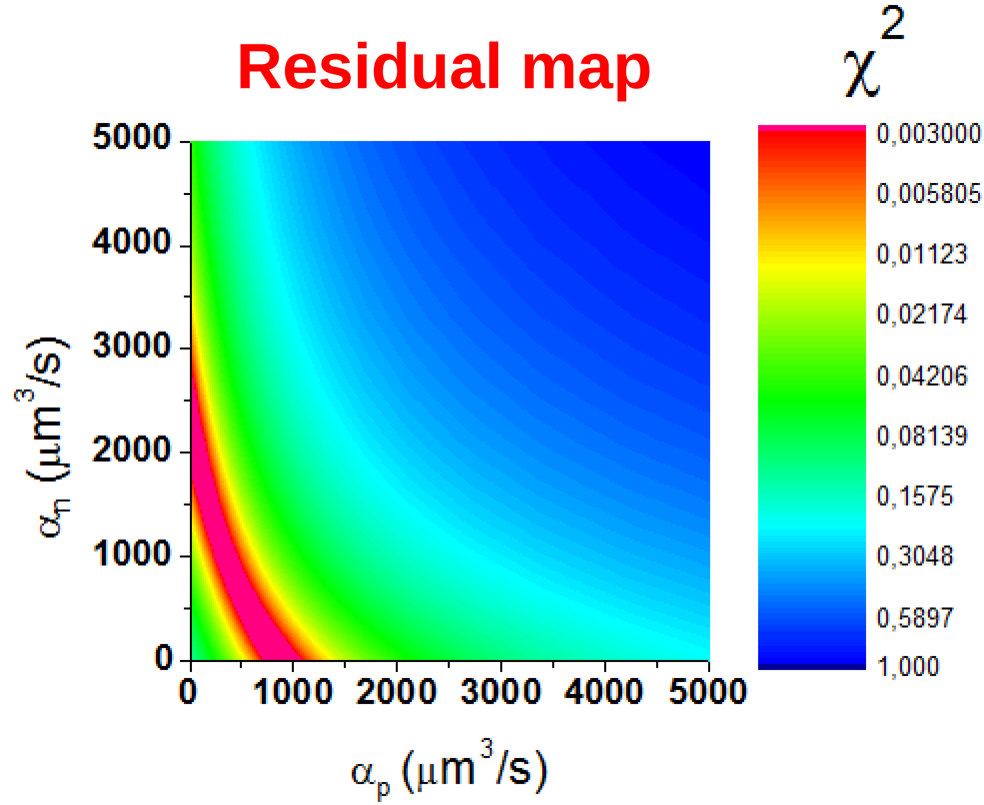


Vacancy profile
Vacancy/ion/µm
Depth (µm)
PIB
N
P+
N+
Generation profile
Ionization energy loss (keV/µm)
Depth (µm)
Long range PIB


CCE
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
0
2
4
6
8
10
PIB=4.5 MeV H
DIB=8 MeV He
Fluence (x10^12 cm^-2)


Hole motion
Electron motion
PIB
N
P+
N+
Generation profile
Ionization energy loss (keV/µm)
90
60
30
0
100
200
Depth (µm)



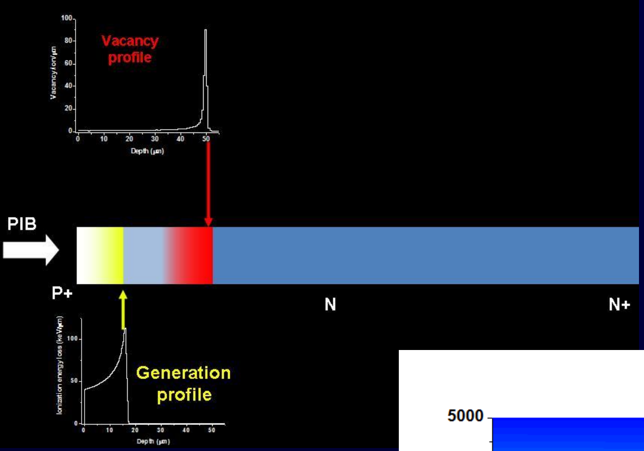


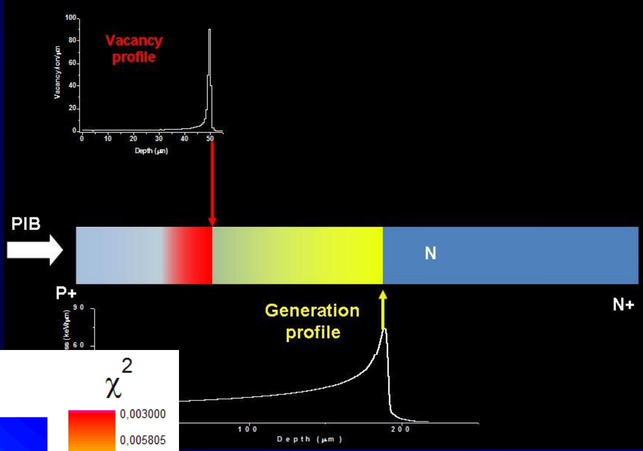
α_n, α_p

Recombination Coefficients

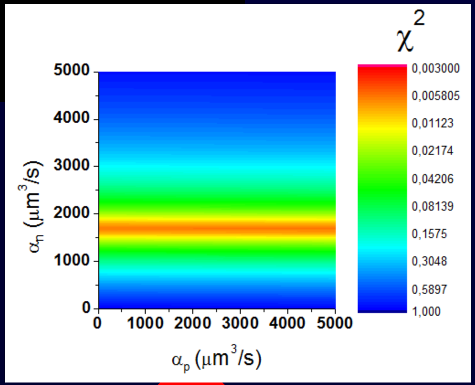
Free parameters

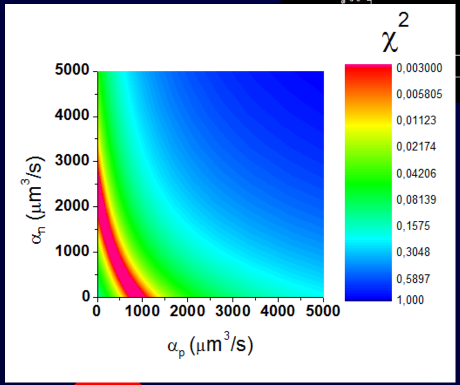
$$Q_S = q \cdot \int_0^d dx \cdot \Gamma(x) \left\{ \begin{array}{l} \displaystyle\int_0^x dy \cdot \frac{\partial F(y)}{\partial V_S} \cdot \exp\left[-\int_y^x dz \frac{1}{v_p} \cdot \left(\frac{1}{\tau_0} + \alpha_p \cdot Vac(x) \cdot \Phi \right) \right] + \\ \displaystyle\int_x^d dy \cdot \frac{\partial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



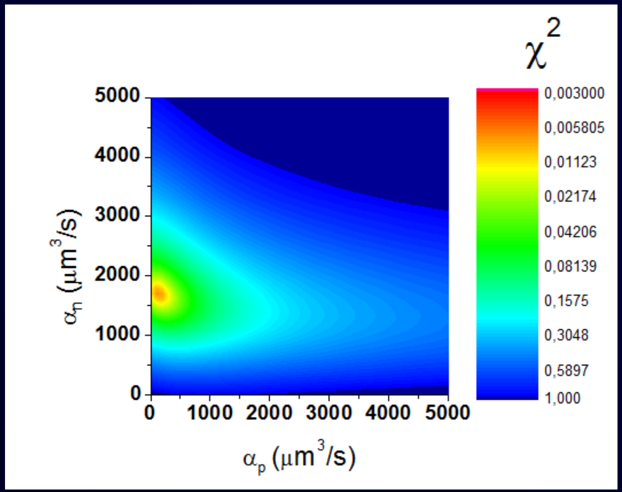


Short range PIB





Long range PIB

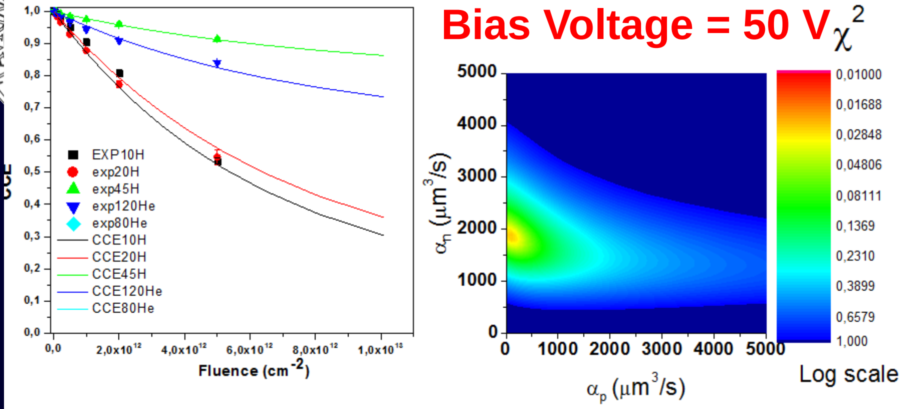


Bias Voltage = 50 V

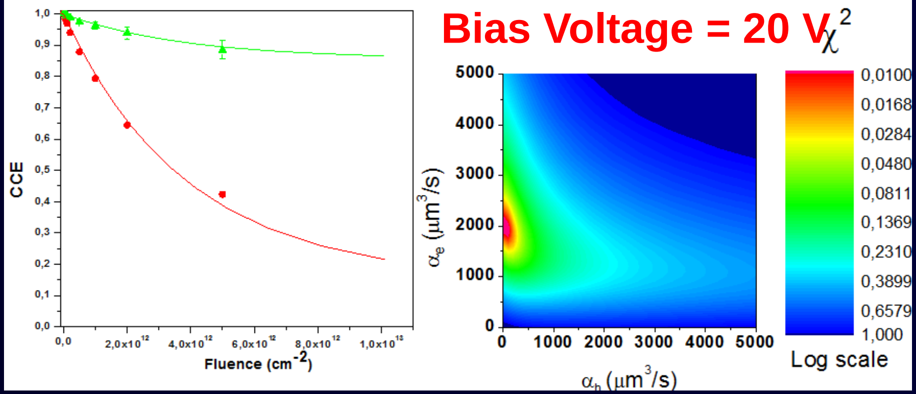
α_n=1700 $\mu m^3/s$

α_p=130 $\mu m^3/s$

n-type Fz silicon diode



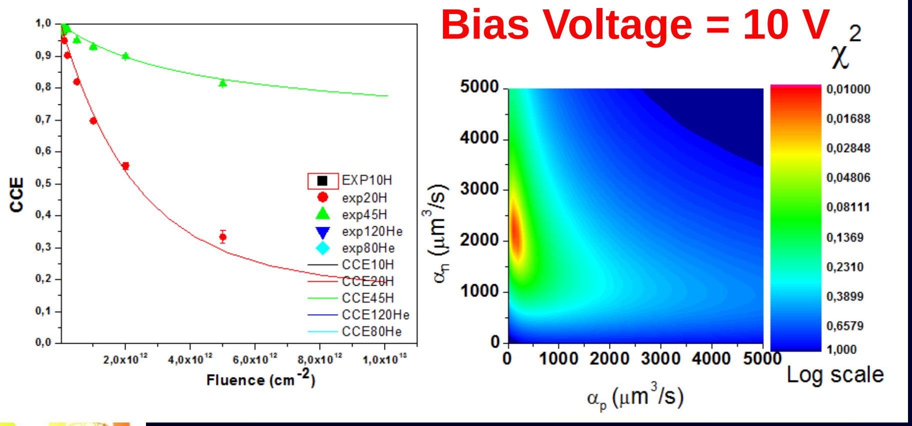
Damaging ions: 8 MeV He
Probing ions: 1,2,4.5 MeV H, 12 MeV He
Bias Voltages: 10,20 50 V



CAPTURE COEFFICIENTS

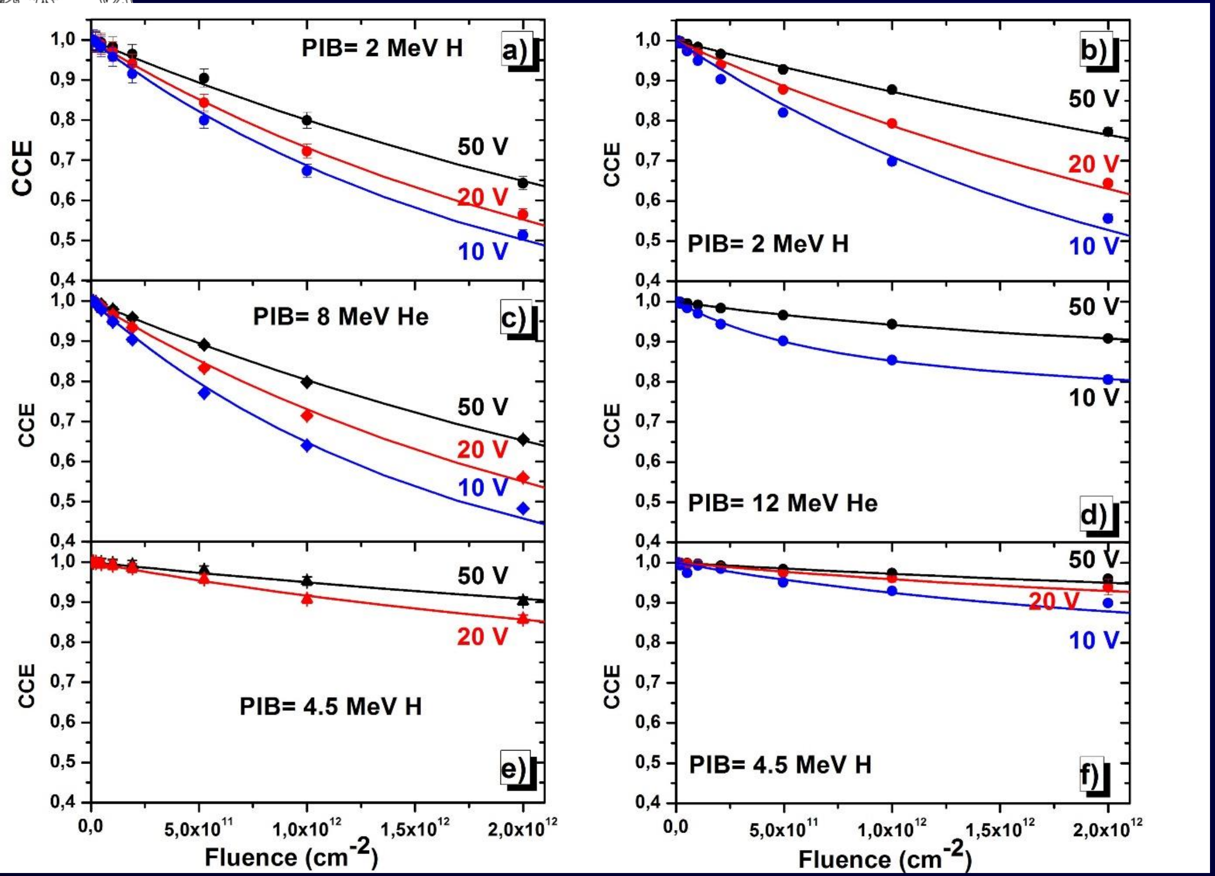
α_n = (2300±600) $\mu m^3/s$

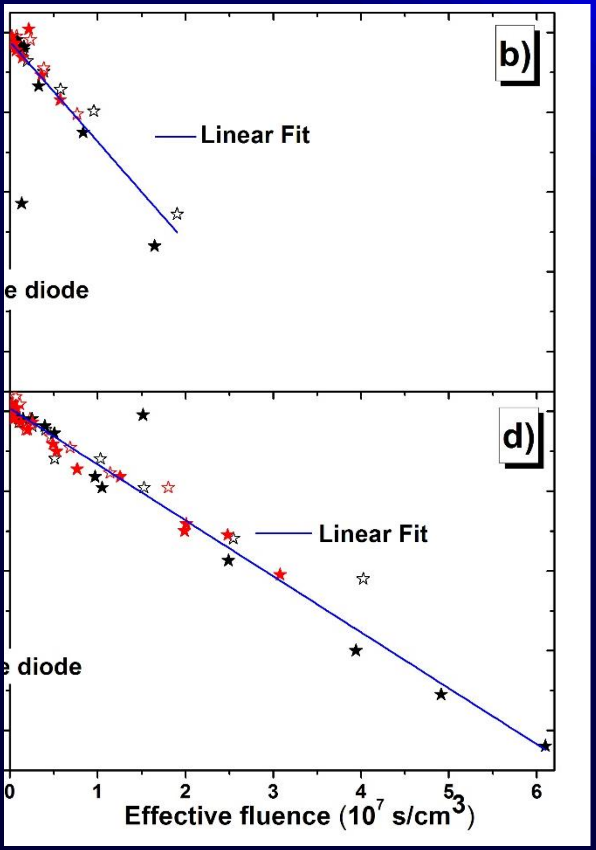
α_p = (70±30) $\mu m^3/s$



DIB: 8 MeV He

DIB: 4 MeV He

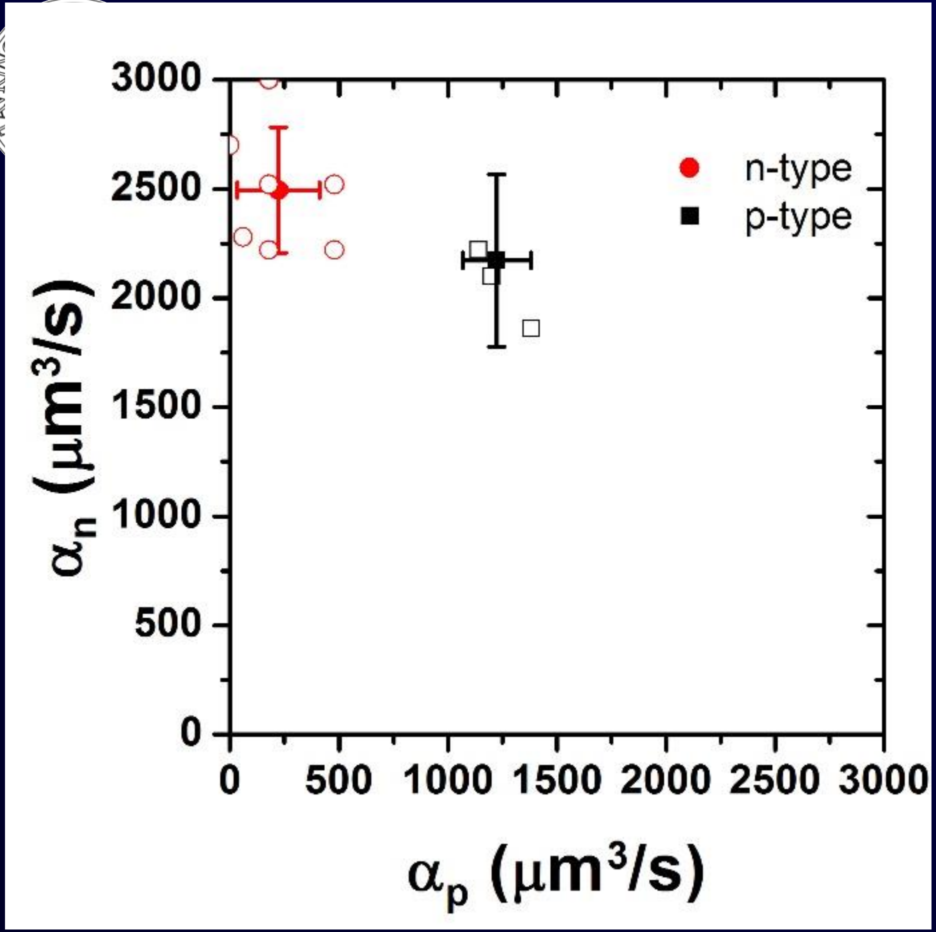




CCE degradation depends from

- **Damaging ion energy and mass**
- **Probing ion energy and mass**
- **Polarization**

The solid lines are the **best fits** obtained by means of our model considering
Different PIBs
Different DIBs (8 MeV, 4 MeV)
Different polarizations (10,20,50 V)



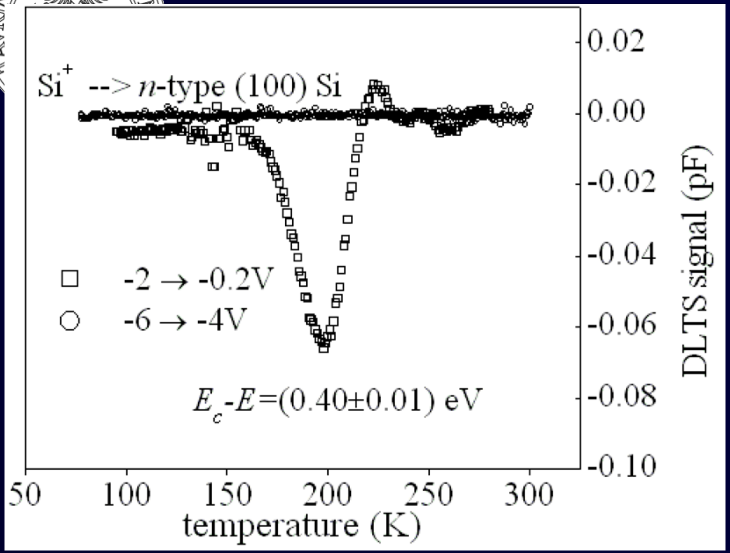
Fz silicon diode
Capture coefficient

Recombination coefficient

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

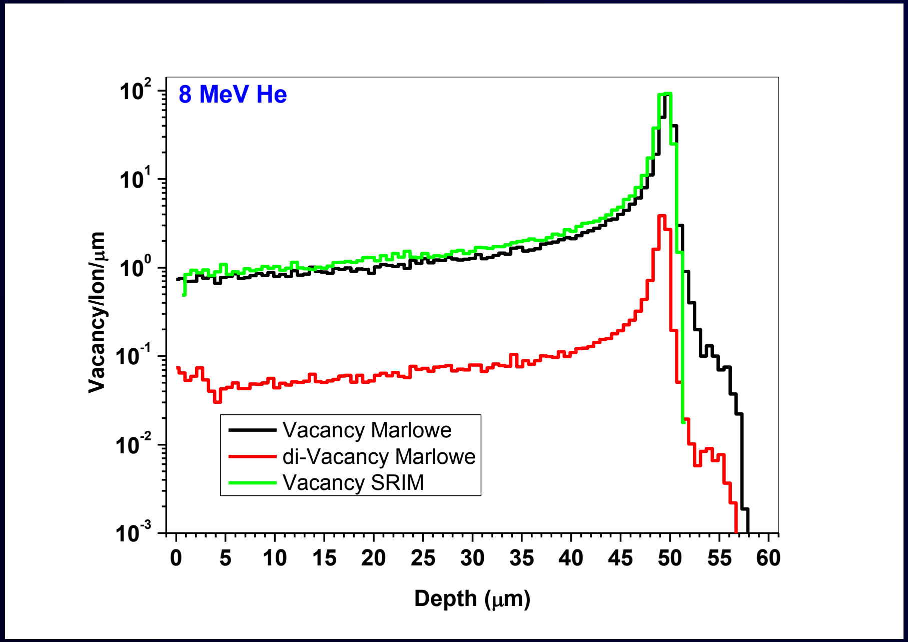
Final measurement of the recombination coefficients;
n-type diode: $\alpha_p=(210\pm160)\mu m^3/s$; $\alpha_n=(2500\pm300)\mu m^3/s$;
p-type diode: $\alpha_n=(2200\pm300)\mu m^3/s$; $\alpha_p=(1310\pm90)\mu m^3/s$;
Open marks: dispersion of the combination of the fitting parameters.

E. Vittone, Z. Pastuovic, M.B.H. Breese, J. Garcia Lopez, M. Jaksic, J. Raisanen, R. Siegele, A. Simon, G. Vizkelethy, "Charge collection efficiency degradation induced by MeV ions in semiconductor devices: Model and experiment ", Nuclear Instruments and Methods in Physics Research B 372 (2016) 128–142



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

$\sigma_n \approx 5 \cdot 10^{-15}\ cm^2$

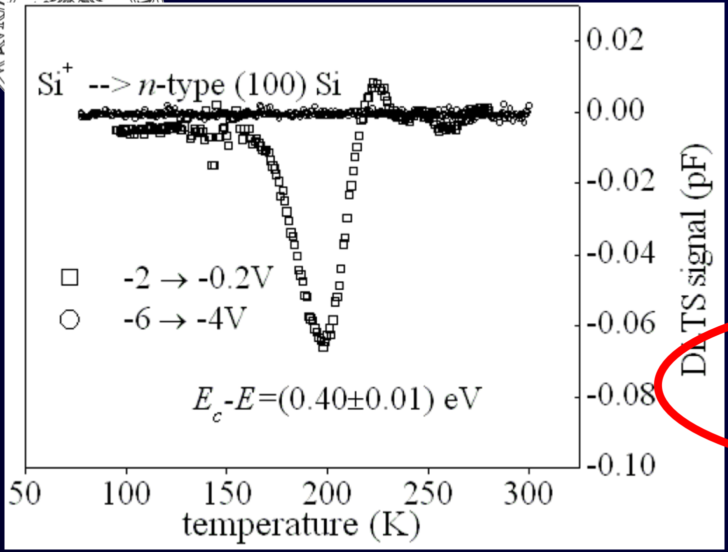


From MARLOWE simulation

$$\frac{Divacancy}{Vacancy} \approx 26$$

$$\alpha_n = v_{th} \cdot \sigma_n$$

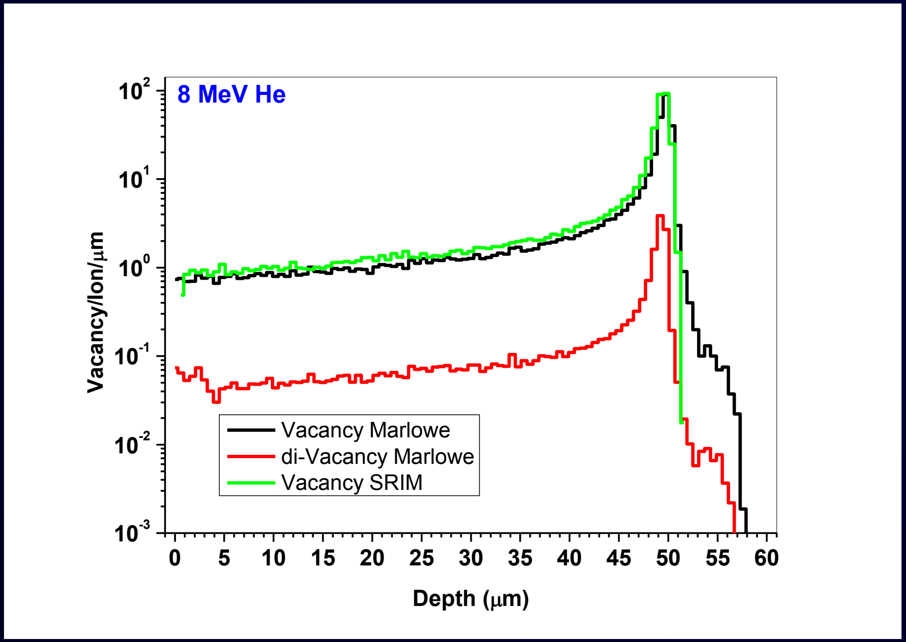
$$\sigma_n \approx (5.3 \pm 1.4) \cdot 10^{-15}\ cm^2$$



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

$\sigma_n \approx 5 \cdot 10^{-15}$ cm²

From MARLOWE simulation



$$\frac{Divacancy}{Vacancy} \approx 26$$

$$\alpha_n = v_{th} \cdot \sigma_n$$

$$\sigma_n \approx (5.3 \pm 1.4) \cdot 10^{-15} \text{ cm}^2$$

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

CONCLUSIONS

An experimental protocol has been proposed to study the radiation hardness of semiconductor devices

Under the assumption of low damage level,
the CCE degradation of a semiconductor device induced by ions of different mass and energy can be interpreted by means of a model based on
- **The Shockley-Ramo-Gunn theorem for the charge pulse formation**
- **The Shockley-Read-Hall model for the trapping phenomena**

If the generation occurs in the depletion region, an analytical solution of the adjoint equation can be calculated.

Adjusted NIEL scaling can be derived from the general theory in the case of constant vacancy profile.

The model leads to the evaluation of the capture coefficient.
For n-type Fz-Si it is in good agreement with DLTS data

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

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

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

IAEA CRP collaboration
"Charge collection efficiency degradation induced by MeV ions in semiconductor devices: Model and experiment ",
Nuclear Instruments and Methods in Physics Research B 372 (2016) 128–142

IAEA Coordinate Research Programme (CRP) F11016 (2011-2015)
"Utilization of ion accelerators for studying and modeling of radiation induced defects in semiconductors and insulators"

Acknowledgements

A. SIMON

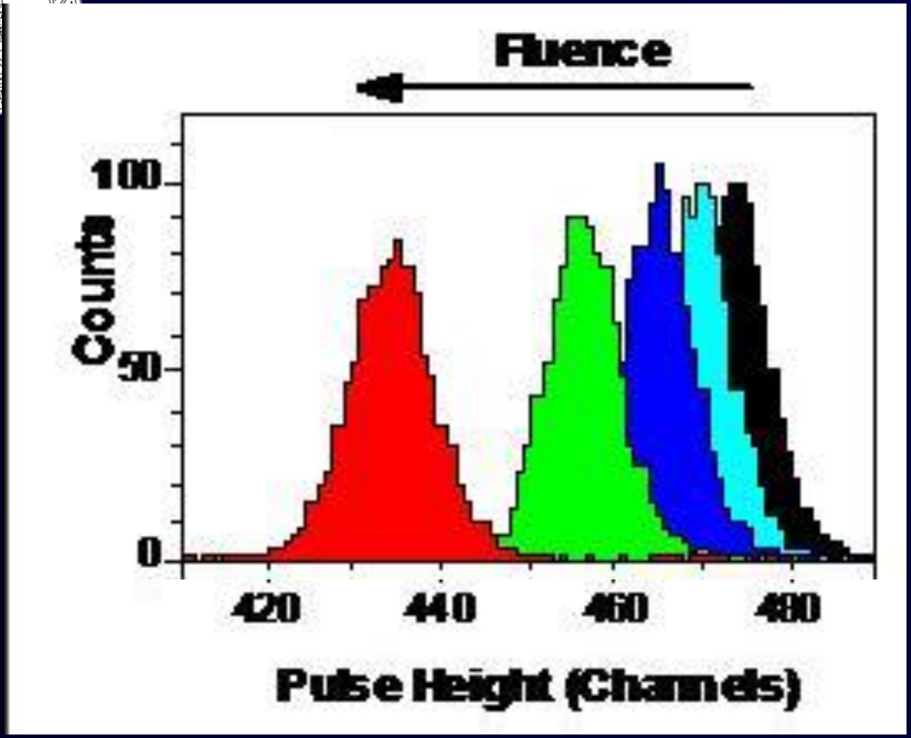
M. JAKSIC, V. GRILJ, N. SKUKAN

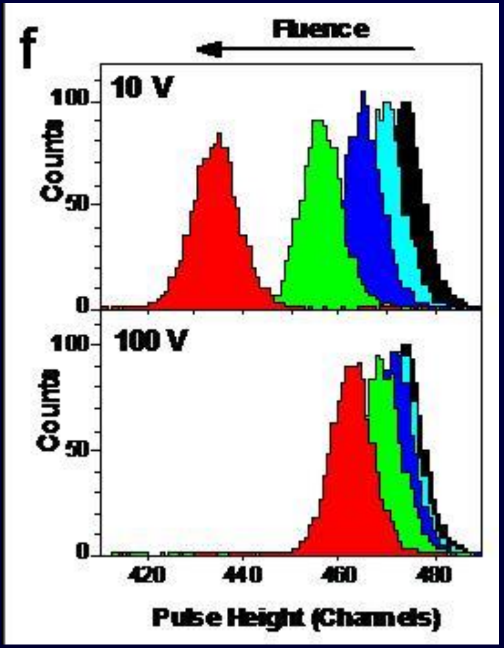
G. VIZKELETHY

J. GARCIA LOPEZ

J. RAISANEN

Z. PASTUOVIC, R. SIEGELE

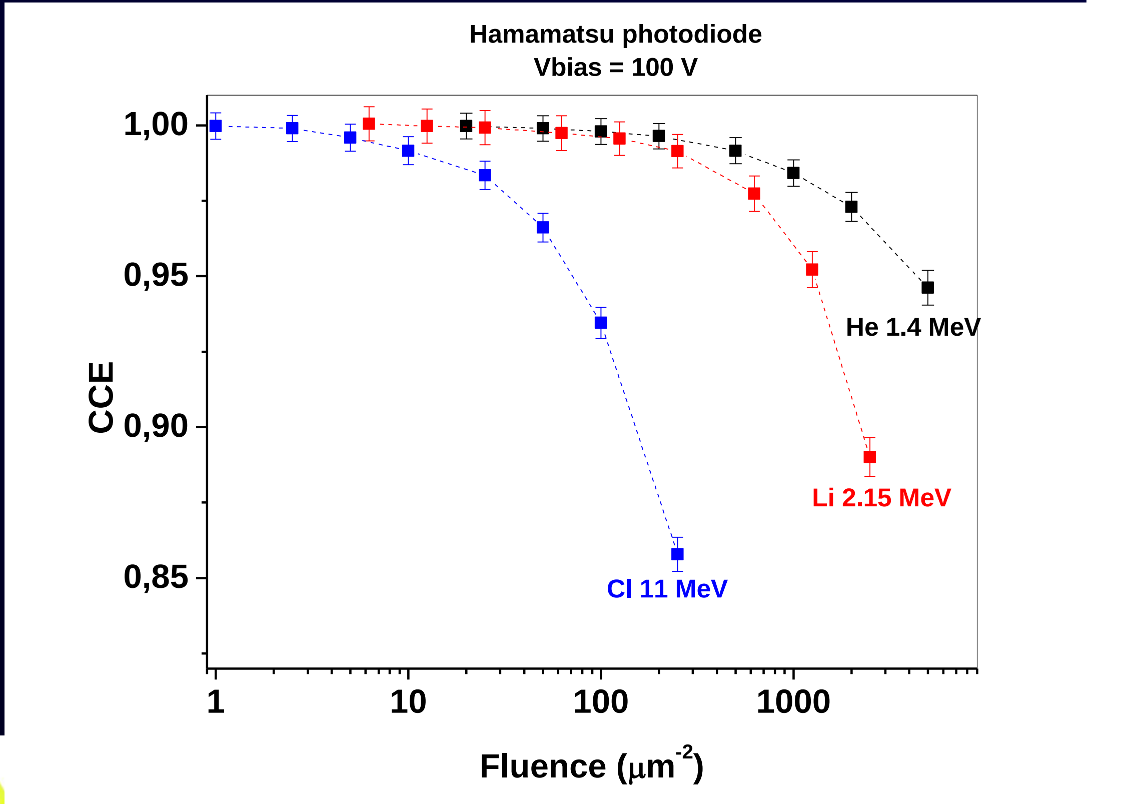

Fluence
100
50
0
Counts
420
440
460
480
Pulse Height (Channels)


f
Fluence
10 V
100 V
100
50
0
Counts
420
440
460
480
Pulse Height (Channels)

CCE degradation induced by ion irradiation

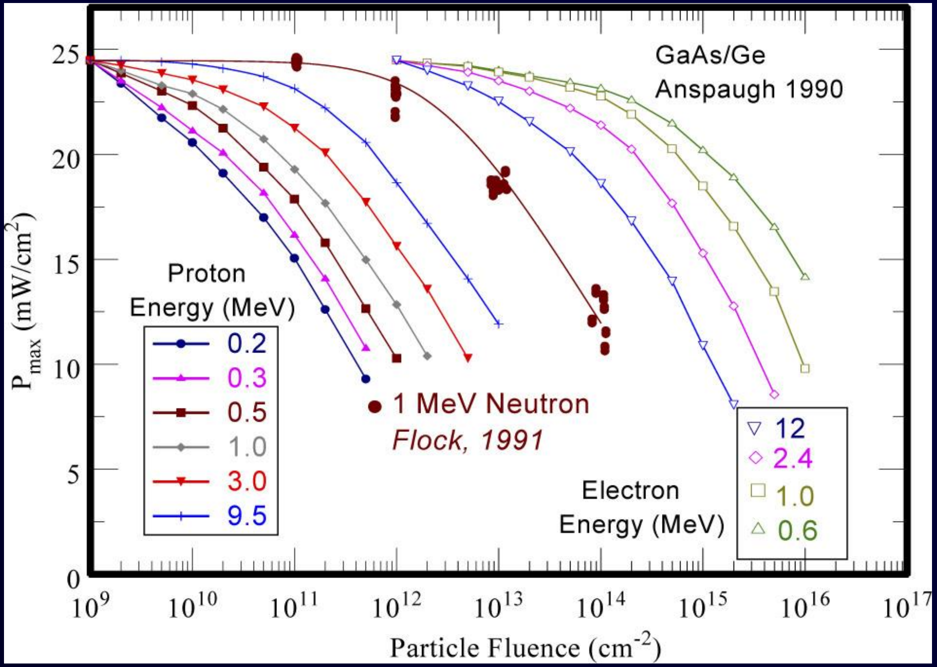
Is a function of the ion energy and mass

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

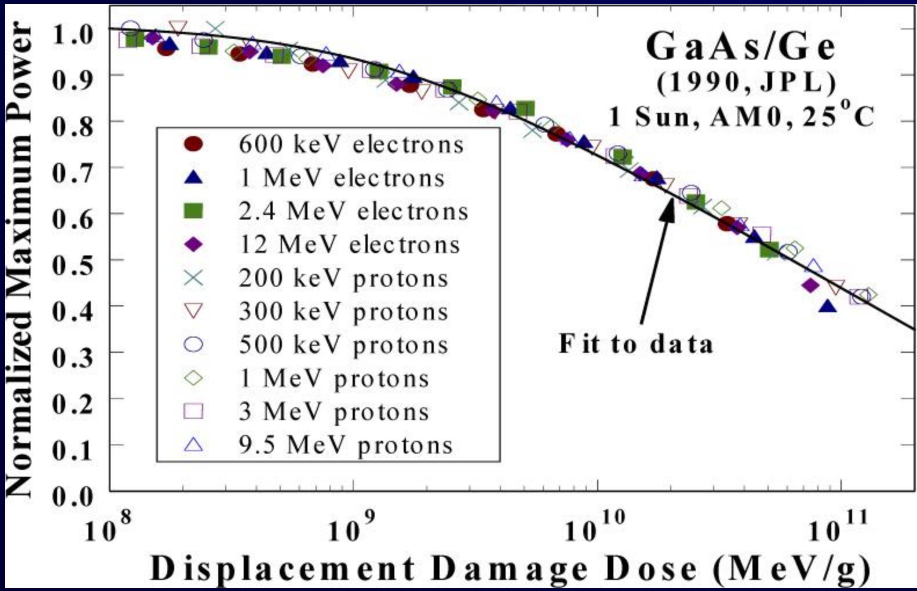


Modeling radiation degradation in solar cells extends satellite lifetime

Robert J. Walters, Scott Messenger, Cory Cress, Maria Gonzalez Serguei Maximenko



Normalized maximum power degradation of GaAs/Ge solar cells as a function of particle fluences.



Normalized maximum power degradation of GaAs/Ge solar cells as a function of displacement damage dose. The effects of the many different particles and energies can be reduced to a single, charactgerization curve

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 46, NO. 6, DECEMBER 1999