22nd International Conference on Ion Beam Analysis
June 14 - 19, 2015 - Opatija, Croatia
IBA 2015

Session 12: Modification and Damage: Contribute lecture O-35

A new protocol to evaluate the charge collection efficiency degradation in semiconductor devices induced by MeV ions

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ATOMKI, Hungary

On behalf of the IAEA coordinated research project CRP-F11016
«Utilization of Ion Accelerators for Studying and Modelling Ion Induced Radiation Defects in Semiconductors and Insulators"

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:

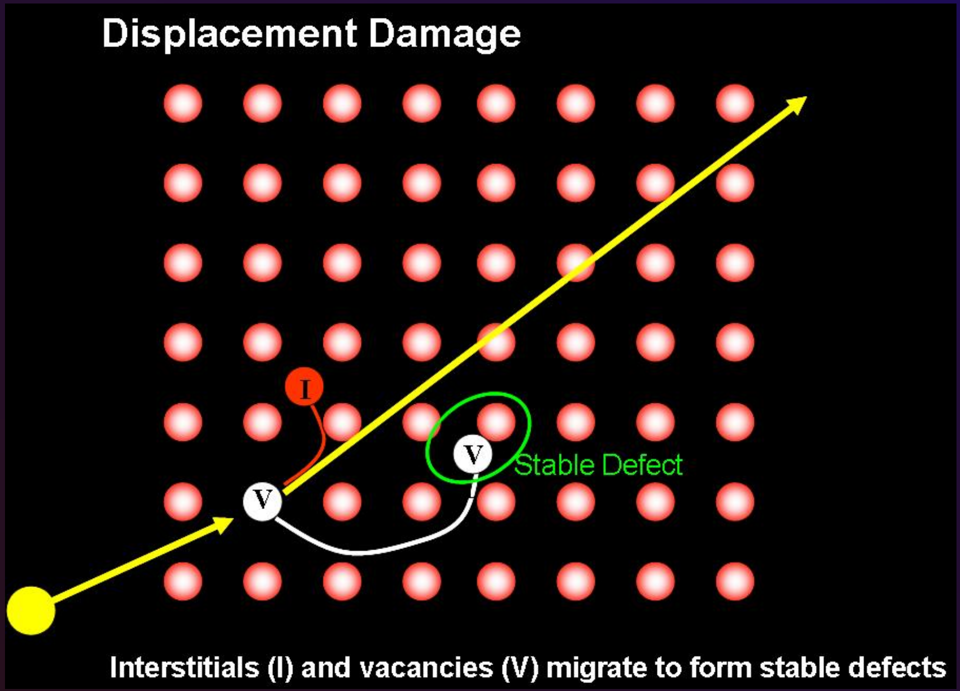
- Transient ionization. This effect produces electron-hole pairs; particle detection with semiconductors is based on this effect.

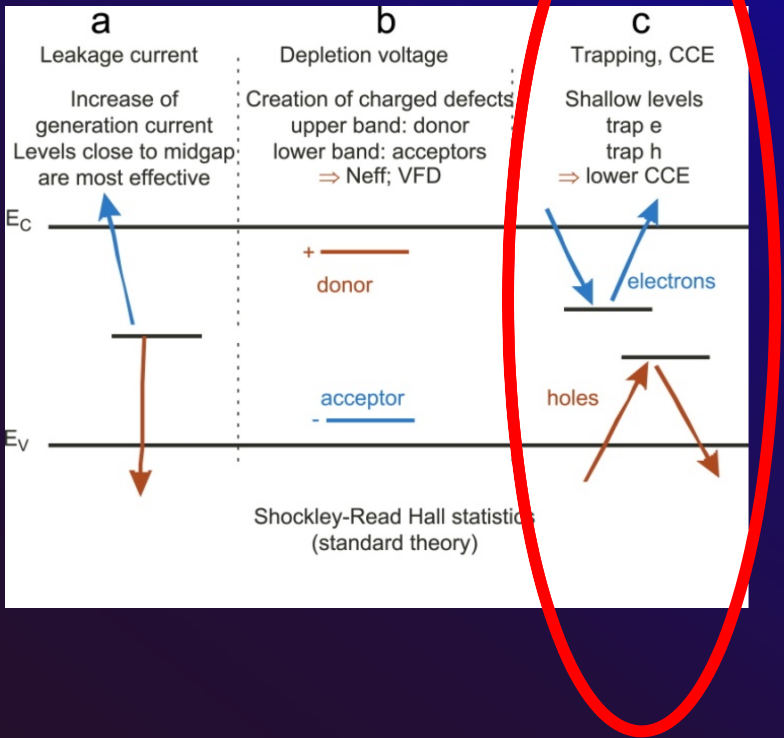
-Long term ionization. In insulators, the material does not return to its initial state, if the electrons and holes produced are fixed, and charged regions are induced.

- **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

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

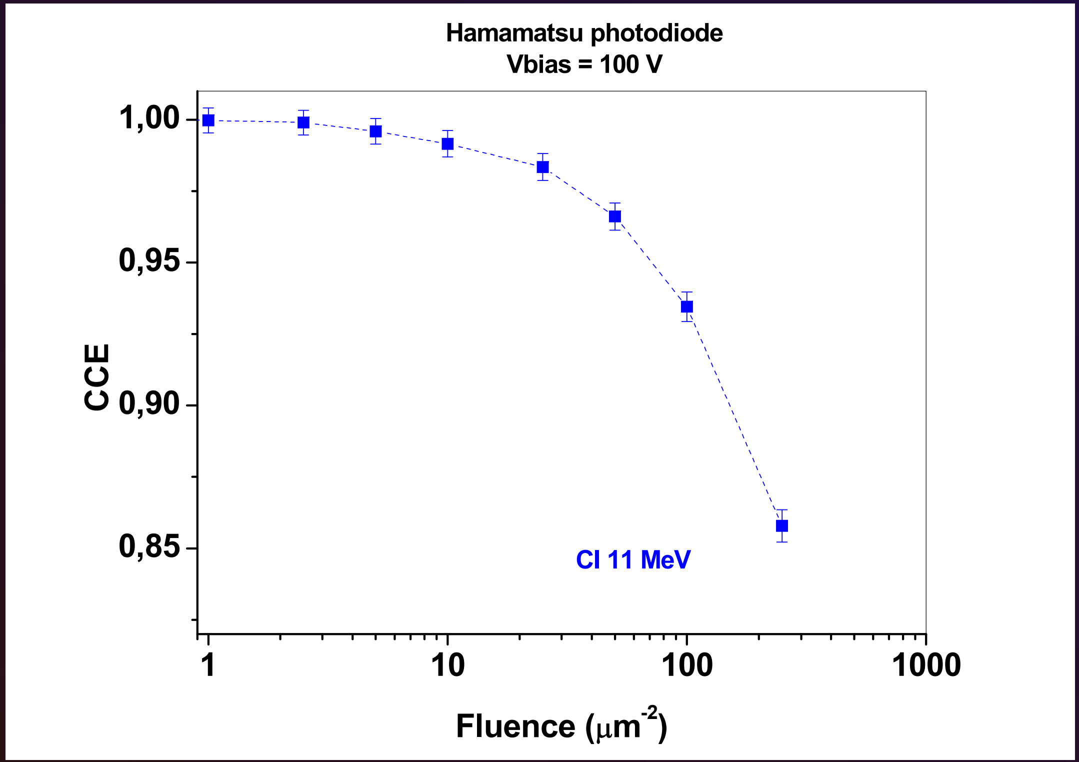
NIEL approach:

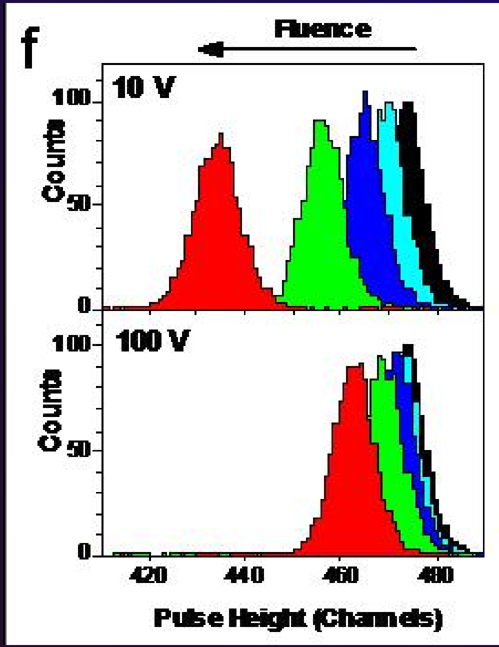
measurement of K_{ed} only for one particle (at one specific energy) → K_{ed} can be estimated for all the particles and energies

CCE degradation induced by ion irradiation

Is a function of the damaging ion fluence

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

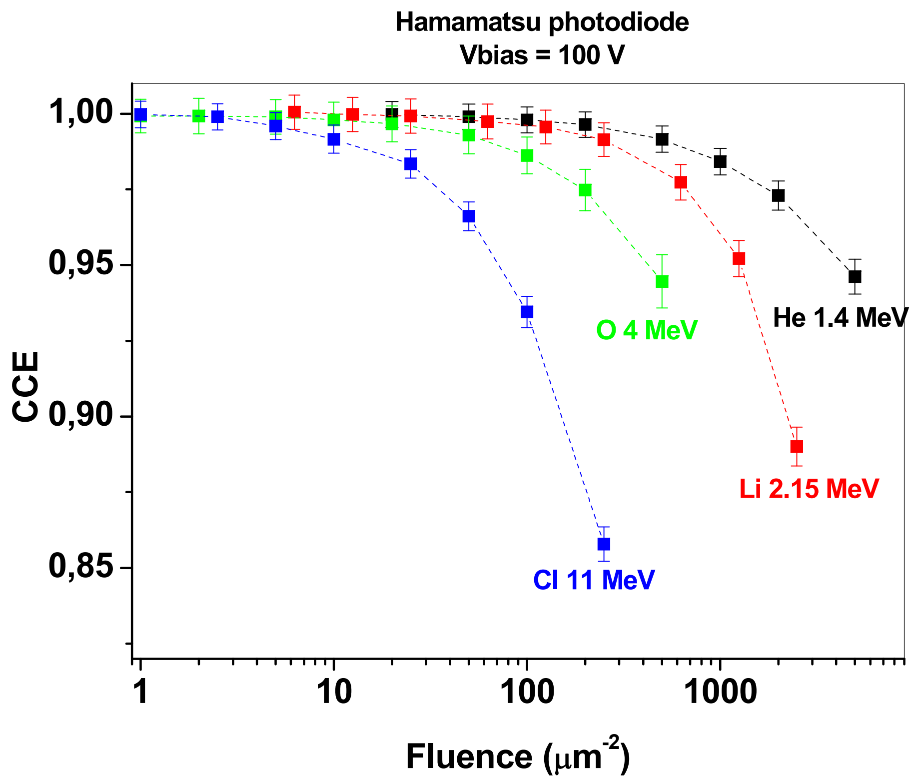




CCE degradation induced by ion irradiation

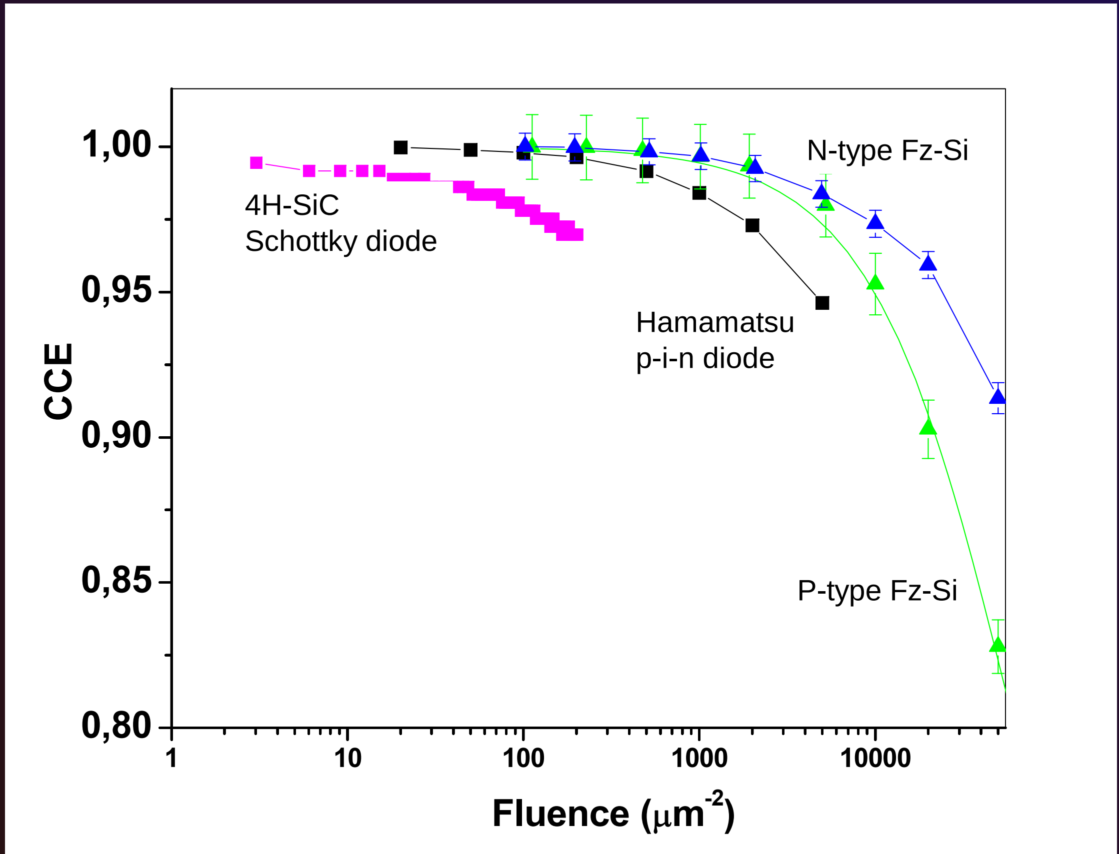
Is a function of the ion energy and mass

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



CCE degradation induced by ion irradiation

Is a function of the material and/or device

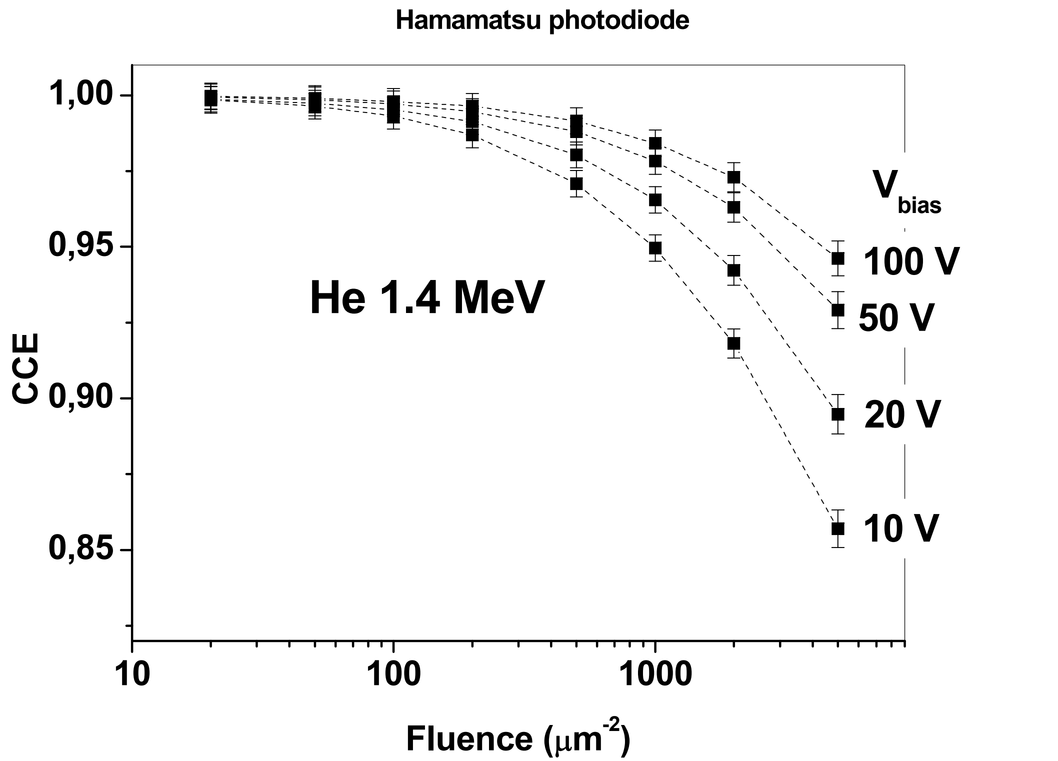


$$\eta = \frac{Y}{Y_0} = 1 - K \cdot \Phi = 1 - K_{ed} \cdot D_d$$

CCE degradation induced by ion irradiation

Is a function of the polarization state of the device

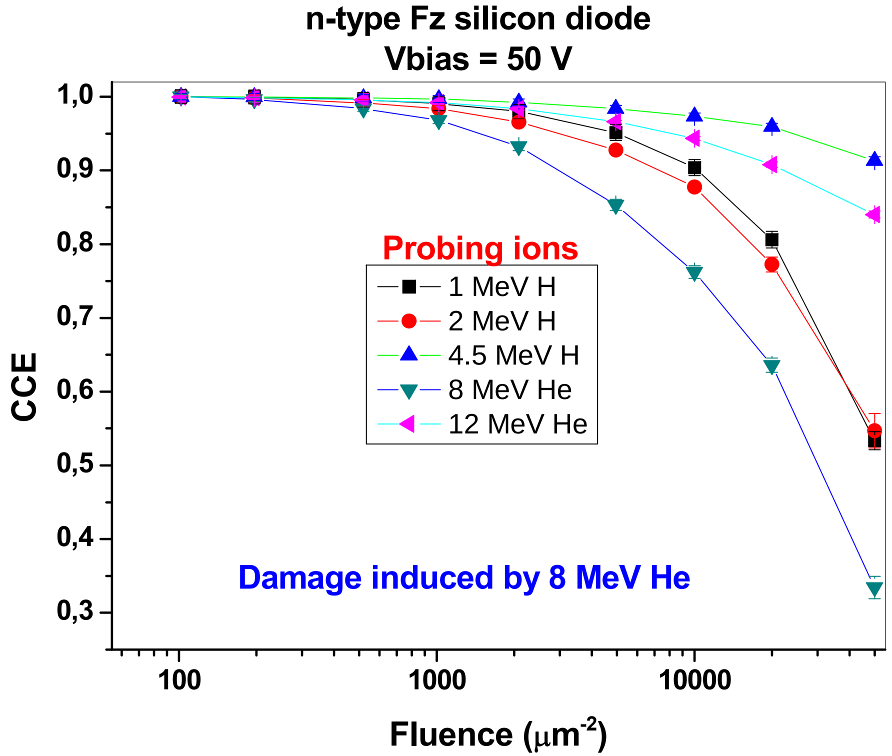
$$\eta = \frac{Y}{Y_0} = 1 - K(V_{bias}) \cdot \Phi = 1 - K_{ed} \cdot D_d$$



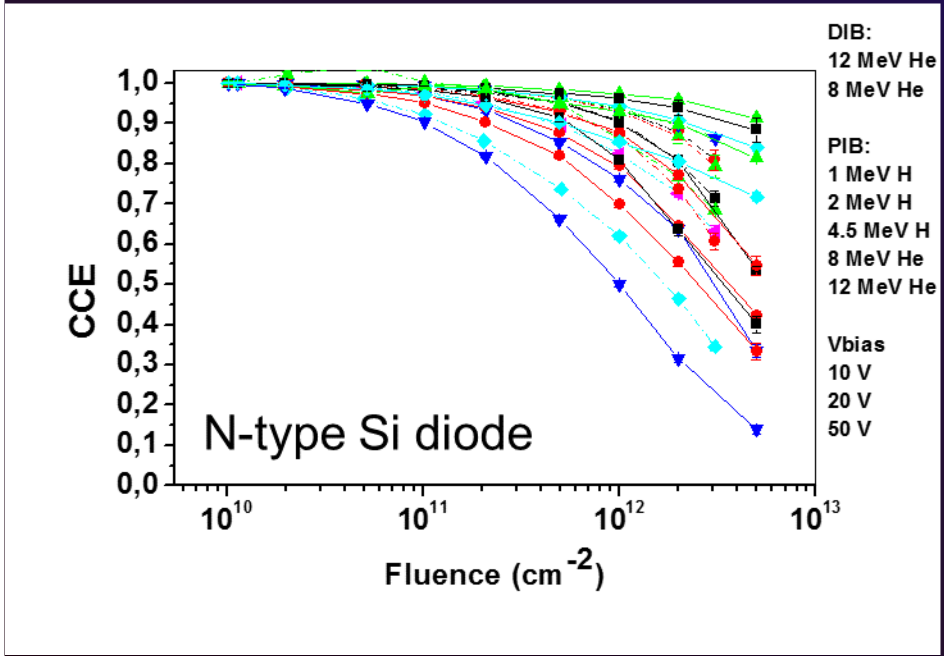
CCE degradation induced by ion irradiation

Is a function of the ion used to measure the CCE

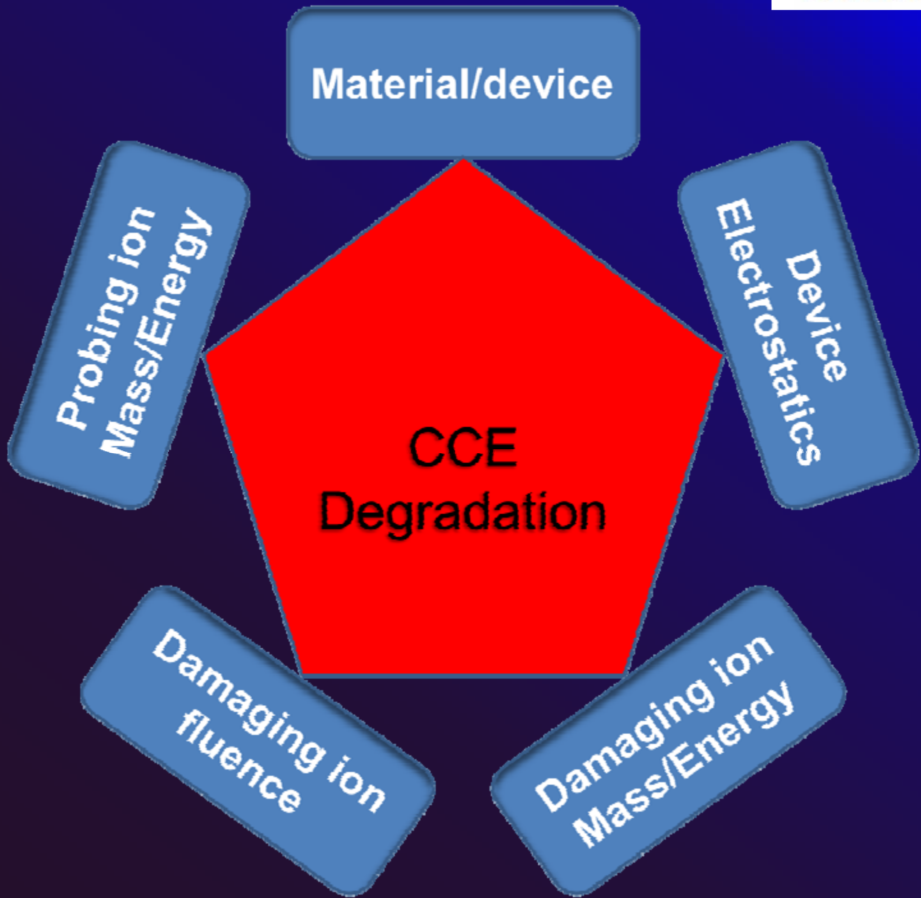
$$\eta = \frac{Y}{Y_0} = 1 - K(V_{bias}, \text{Ion probe}) \cdot \Phi = 1 - K_{ed} \cdot D_d$$



Summary



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
N-type Si diode
Fluence (cm^{-2})



Material/device
Probing ion Mass/Energy
Device Electrostatics
CCE Degradation
Damaging ion fluence
Damaging ion Mass/Energy

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
International Atomic Energy Agency

- ANSTO Australia
- SANDIA 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.

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Model for charge pulse formation (IBIC theory)

1D
↓
Fully depleted device
↓
No diffusion
↓
Ramo Theorem

Ionization profile

Gunn's weighting field

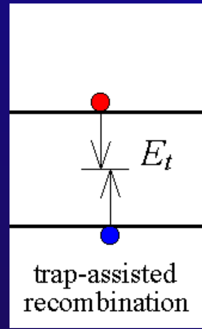
$$Q_S = q \cdot \int_0^d dx \cdot \Gamma(x) \begin{Bmatrix} \displaystyle\int_x^d dy \cdot \frac{\partial F(y)}{\partial V_S} \cdot \exp\left[-\int_x^y dz \left(\frac{1}{v_p \cdot \tau_p} \right) \right] + \\ \displaystyle\int_0^x dy \cdot \frac{\partial F(y)}{\partial V_S} \cdot \exp\left[-\int_y^x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

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

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

Fluence

Capture coefficient

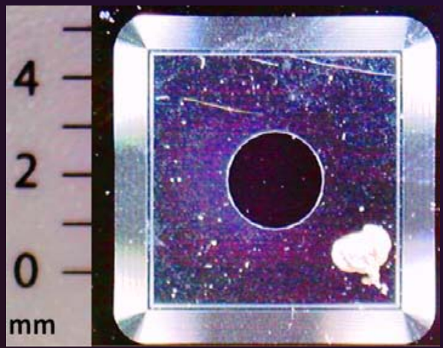
Vacancy Density Profile

The experimental protocol

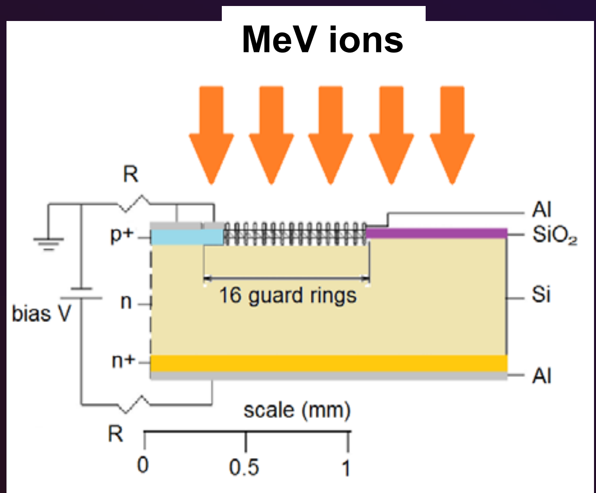
Z. Pastuovic et al., IEEE Trans on Nucl. Sc. 56 (2009) 2457; APL (98) 092101 (2011)

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



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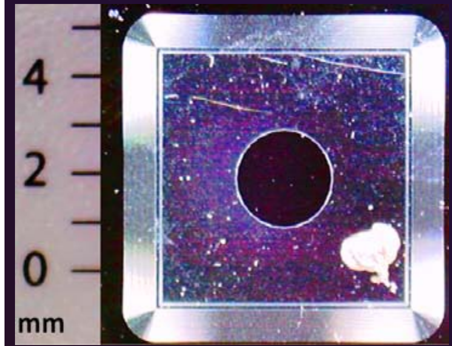
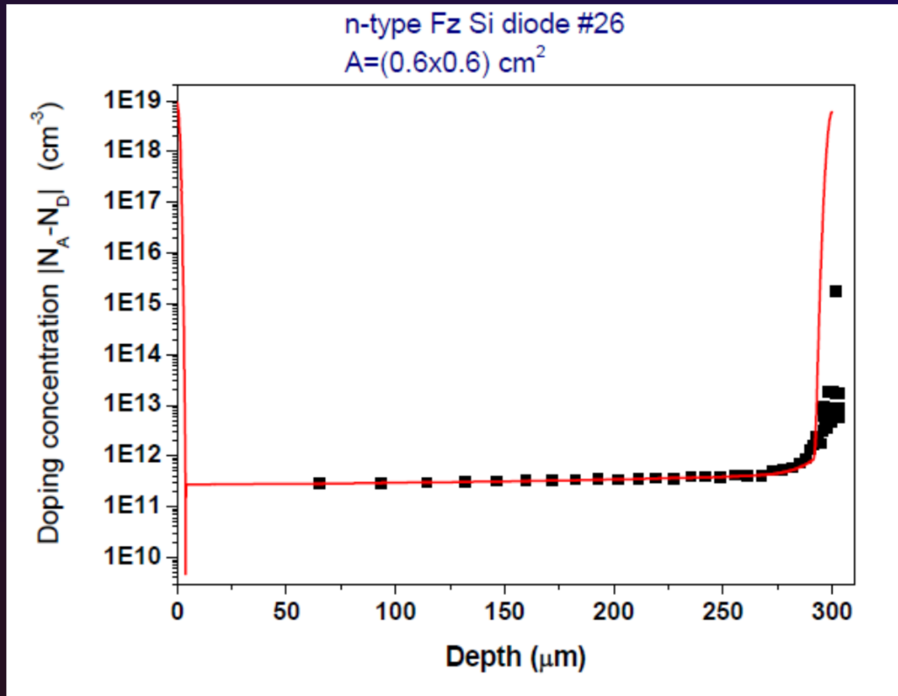
Experimental protocol



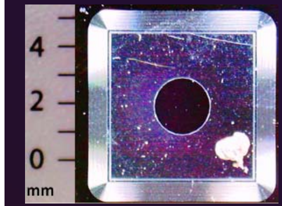
C-V characteristics
Depletion width-voltage

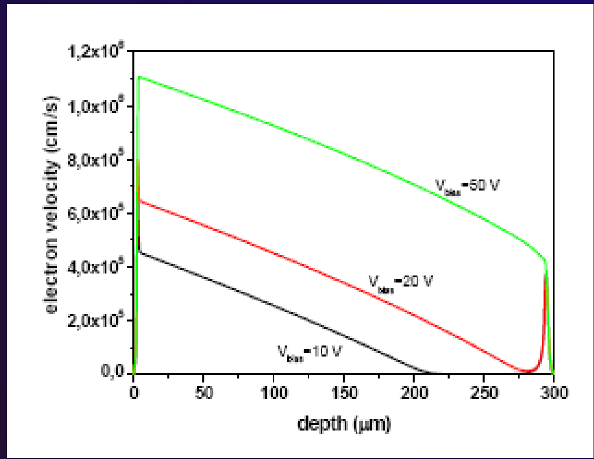


Experimental protocol

✓**Electrical characterization**

Experimental protocol

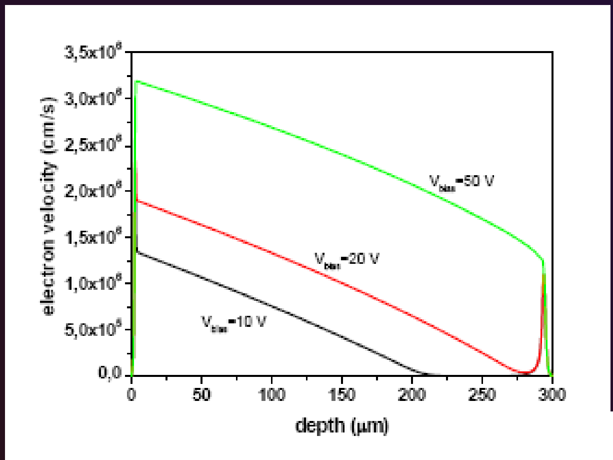




hole drift velocity profiles

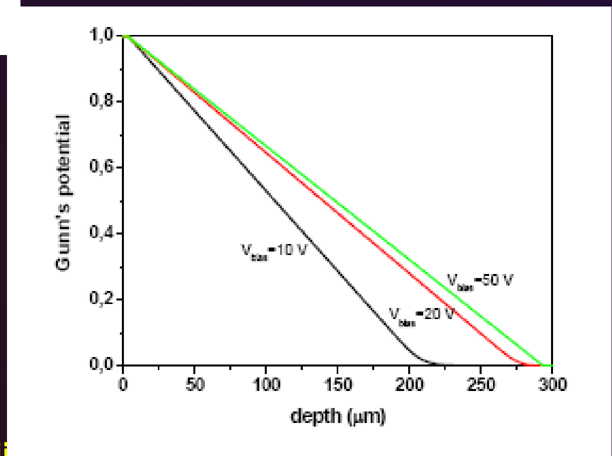
Experimental protocol

✓Electrical characterization
✓Electrostatic modeling

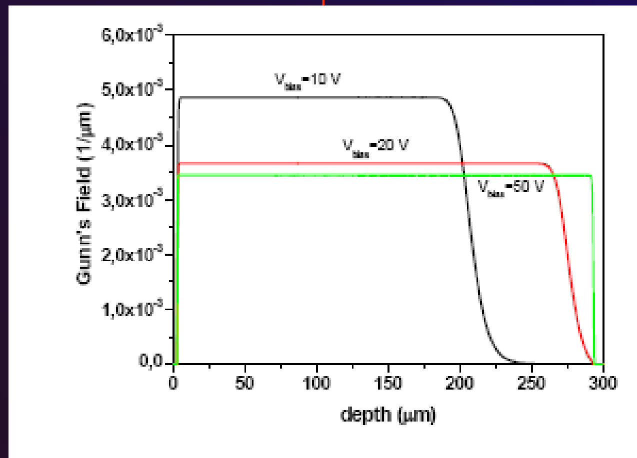


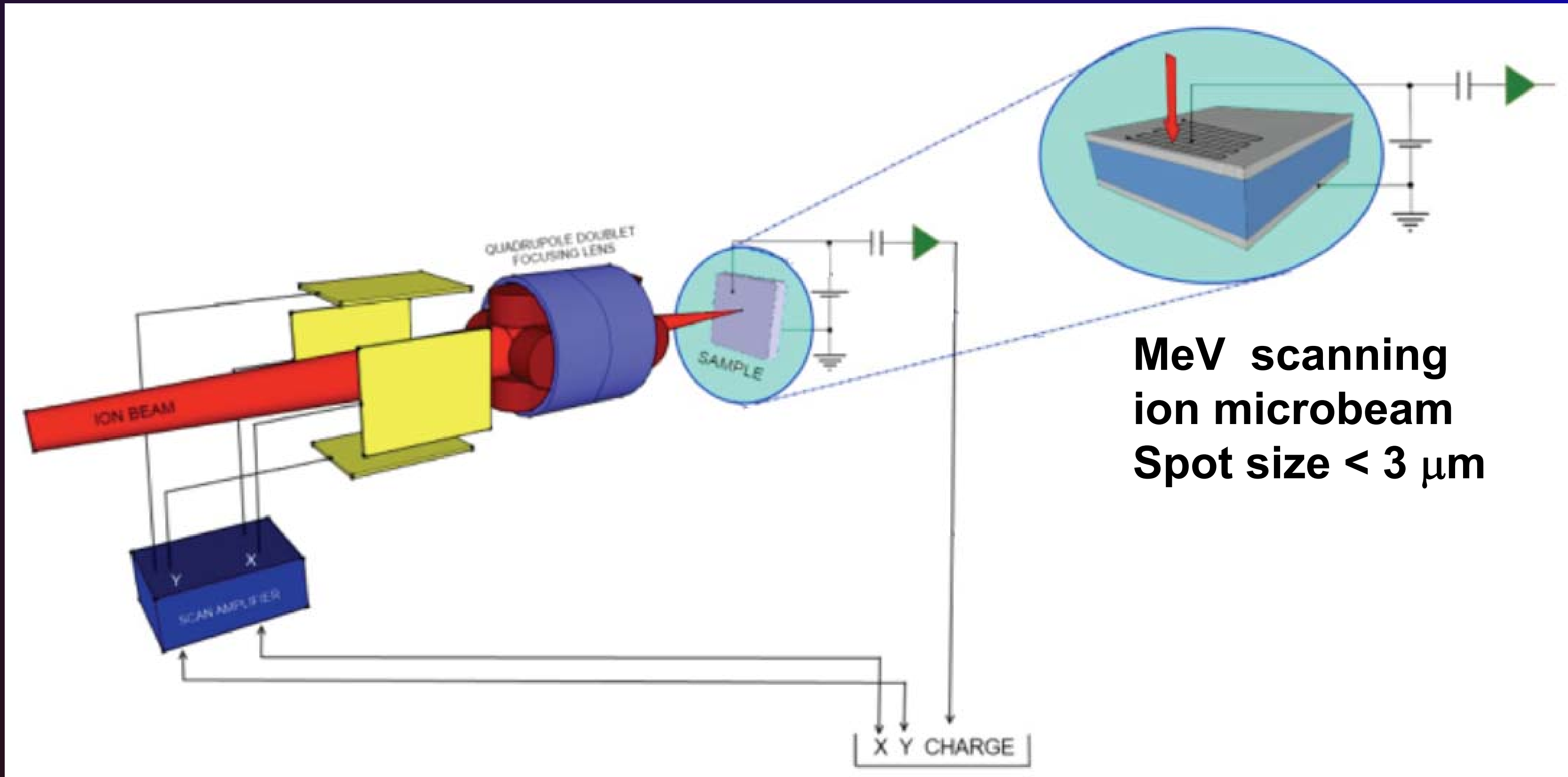
Electron drift velocity profiles

Gunn's weighting potential



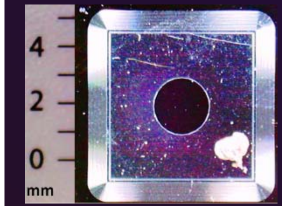
Gunn's weighting field

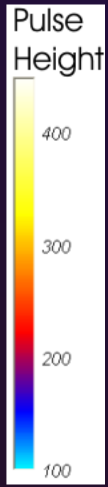


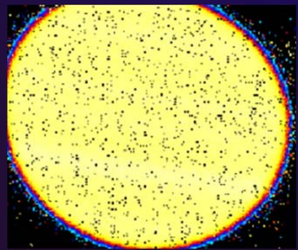


PROBING THE PRISTINE SAMPLE

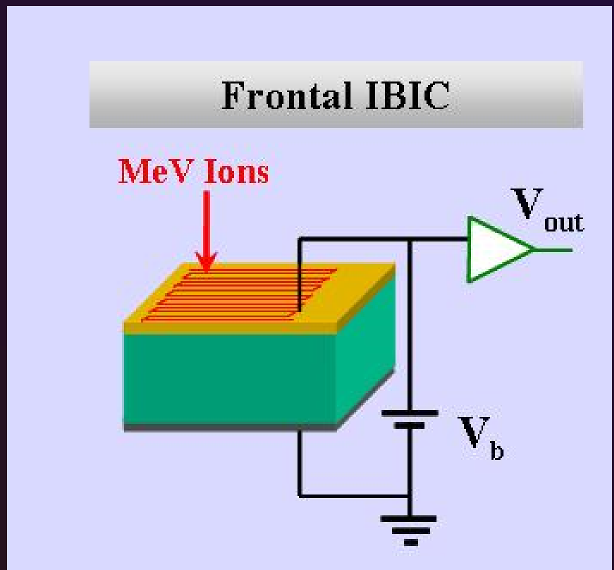
IBIC map on a pristine diode probed with a scanning 1.4 MeV He microbeam;







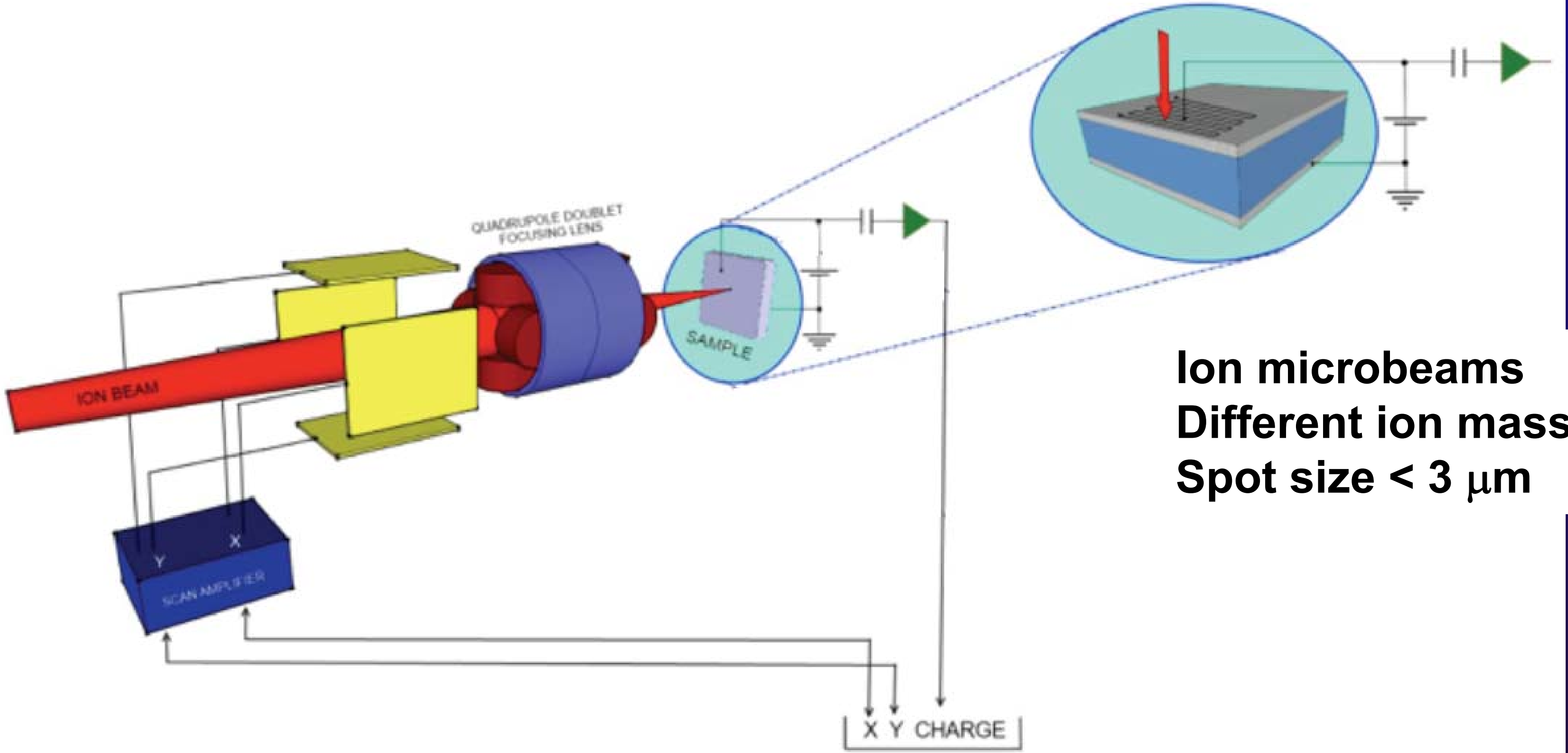
Uniform CCE map



Experimental protocol

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

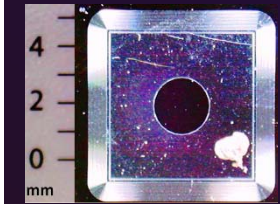
Z. Pastuovic et al., IEEE Trans on Nucl. Sc. 56 (2009) 2457; APL (98) 092101 (2011)



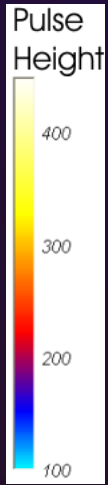
Ion microbeams
Different ion mass/energy
Spot size < 3 μm

DAMAGING SELECTED AREAS 100X100 μm^2

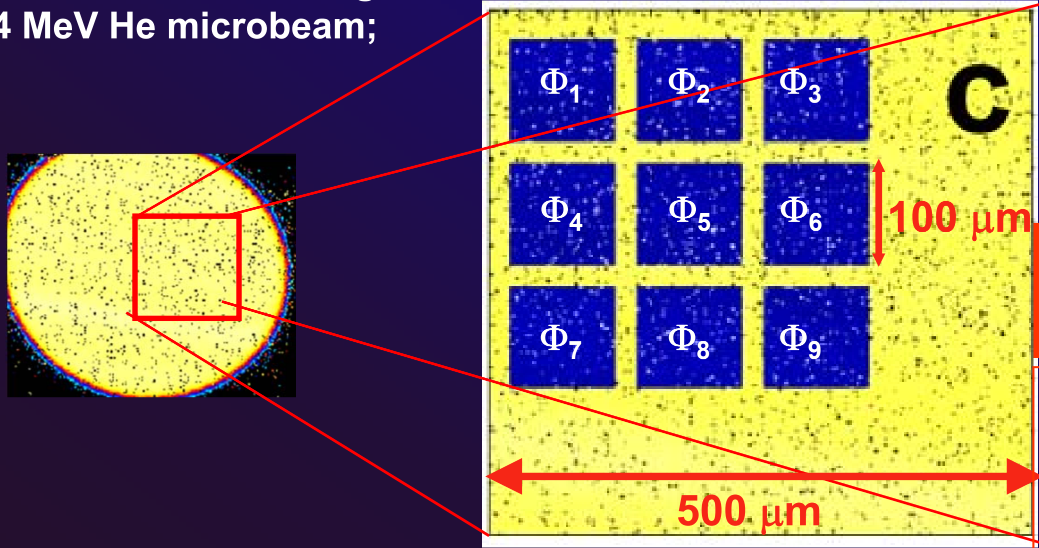
23



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



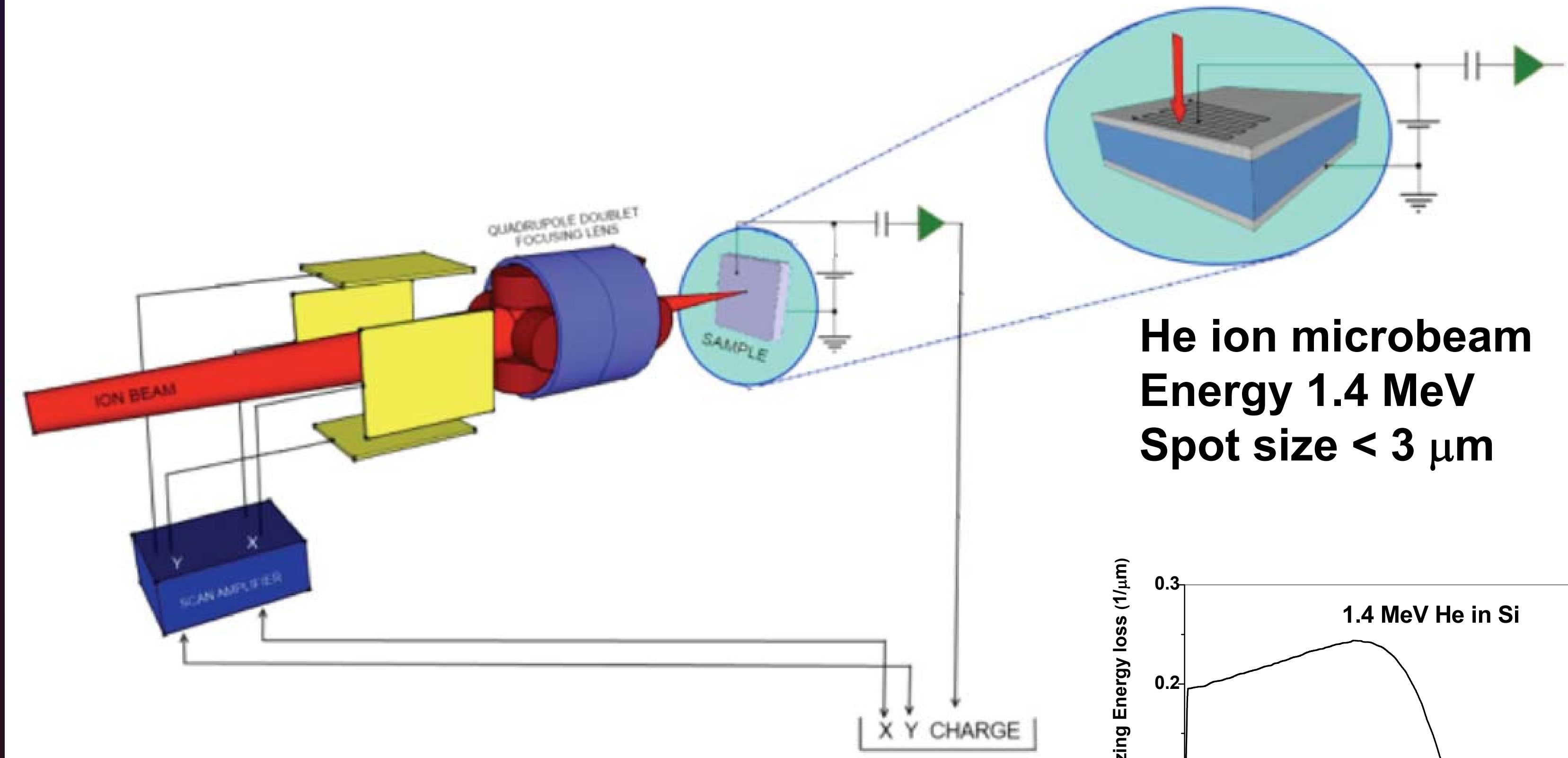
ZOOM in view of the selected area for focused ion beam irradiation at different fluences Φ



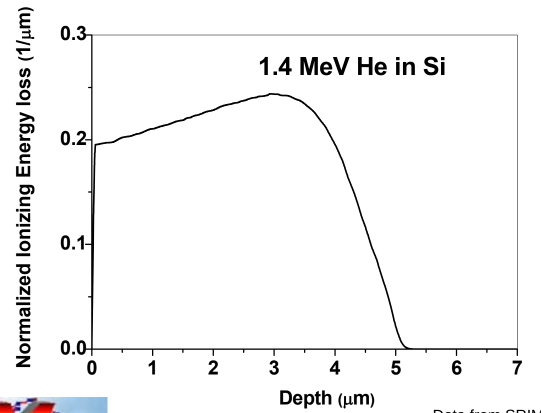
Experimental protocol

- ✓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)



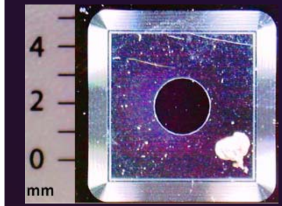
He ion microbeam
Energy 1.4 MeV
Spot size < 3 μm

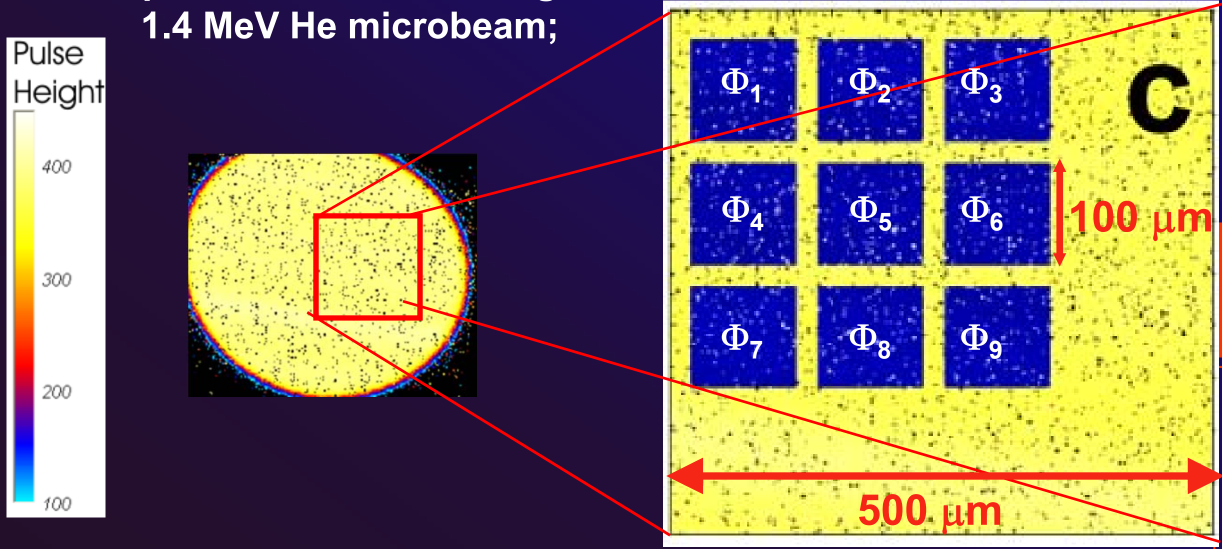


Data from SRIM

PROBING DAMAGED AREAS

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





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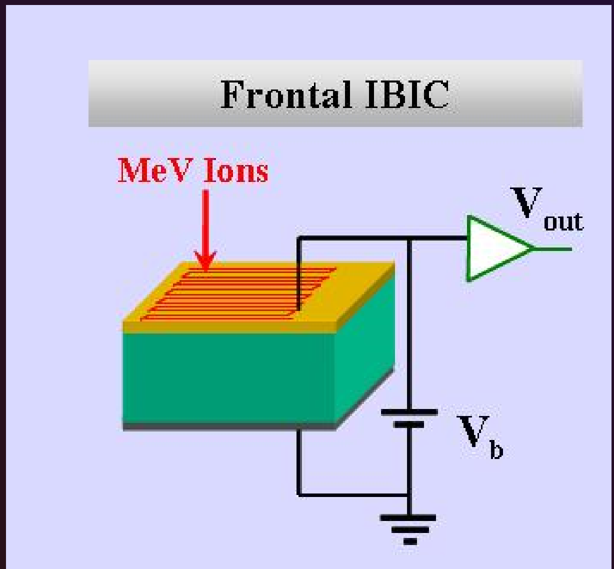
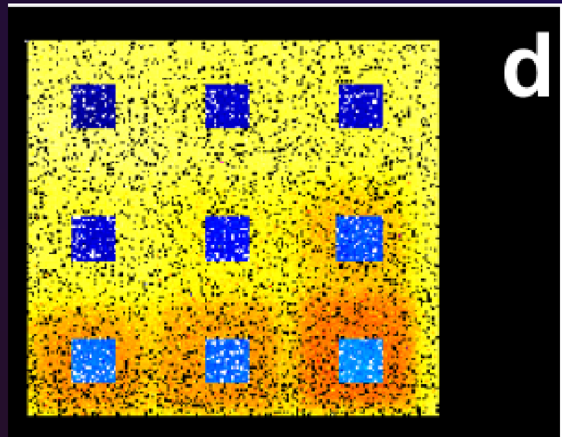
- ✓IBIC map of irradiated regions

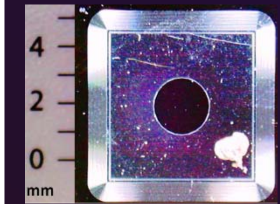


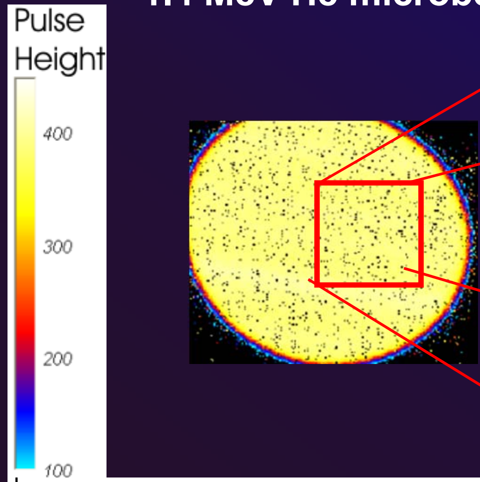


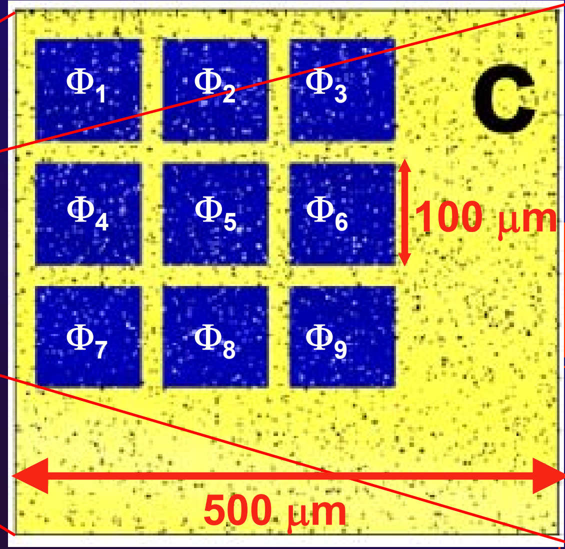
a measured 2D distribution of the IBIC signal amplitude after irradiation

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;







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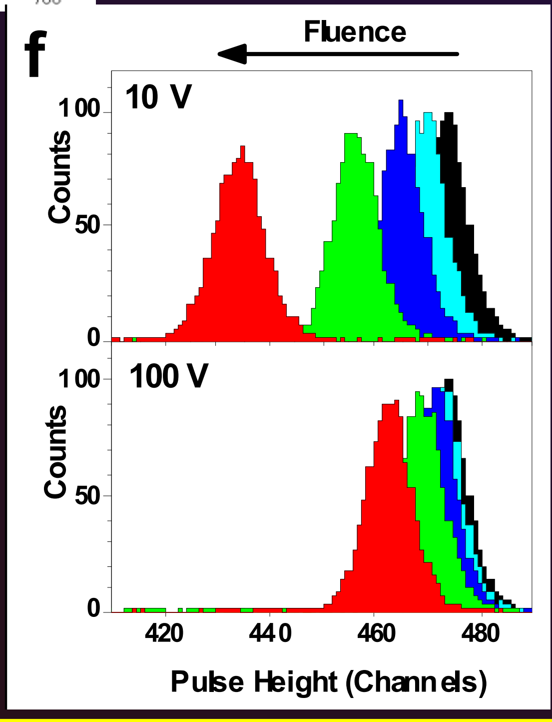
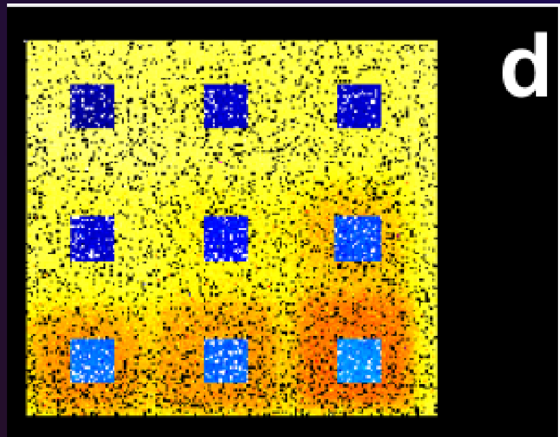


IBIC spectra (bias voltage = 10 V and 100 V) from the central regions of four of the areas shown in Fig. c



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IBIC map on a pristine diode
probed with a scanning
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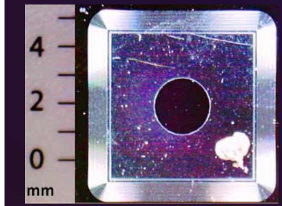

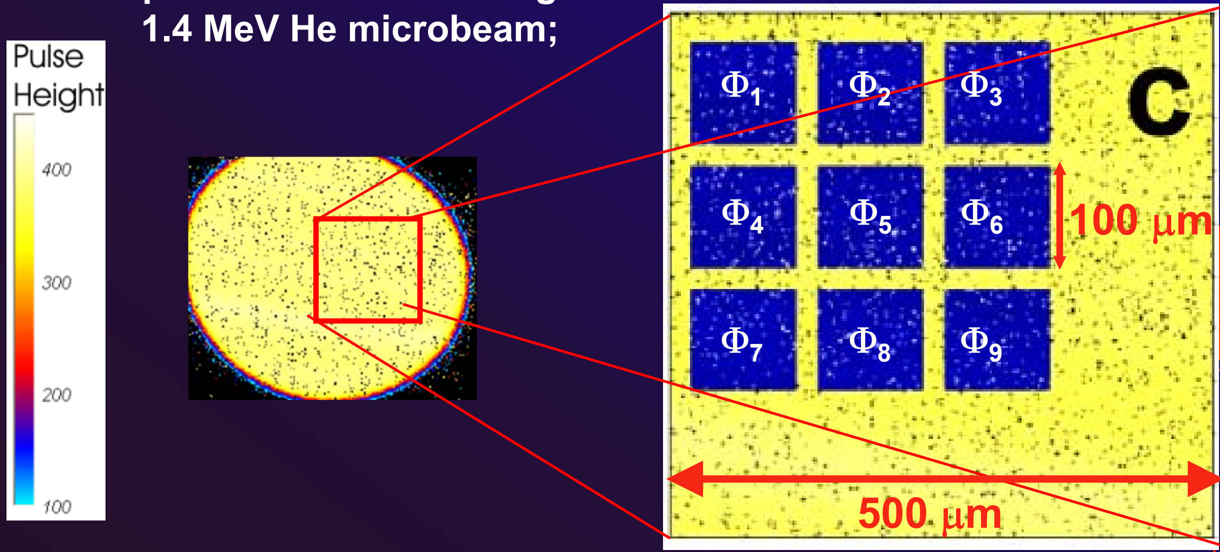

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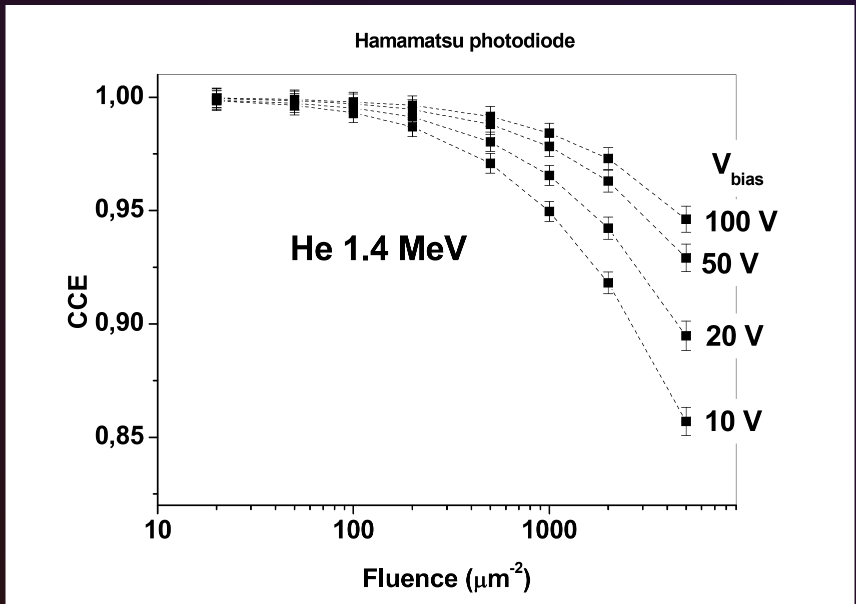
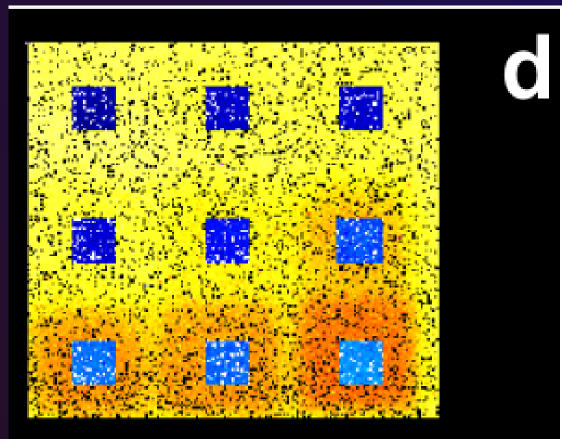
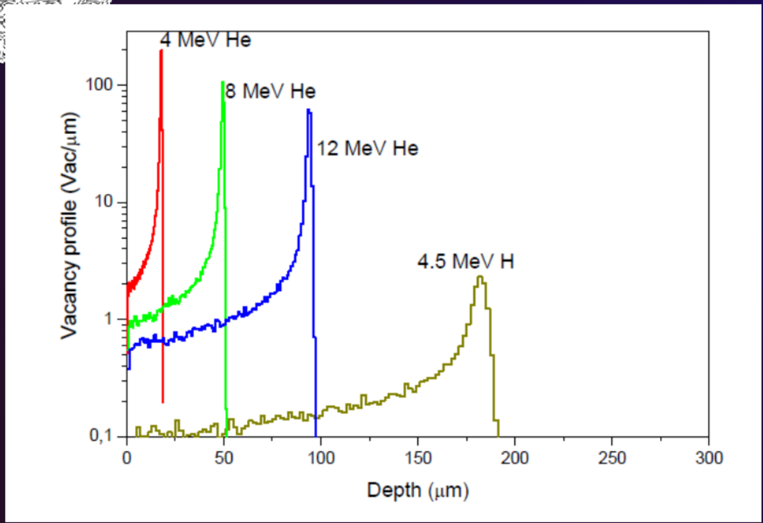




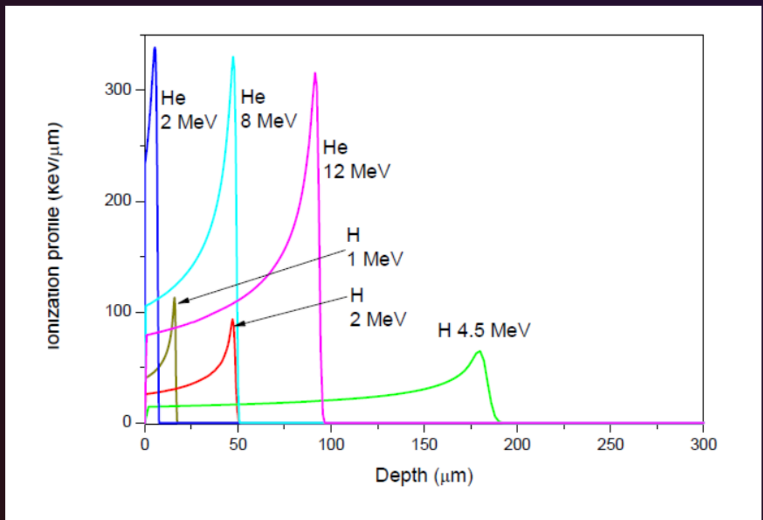
a measured 2D distribution of the IBIC signal amplitude after irradiation

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

DIB: Vacancy profiles



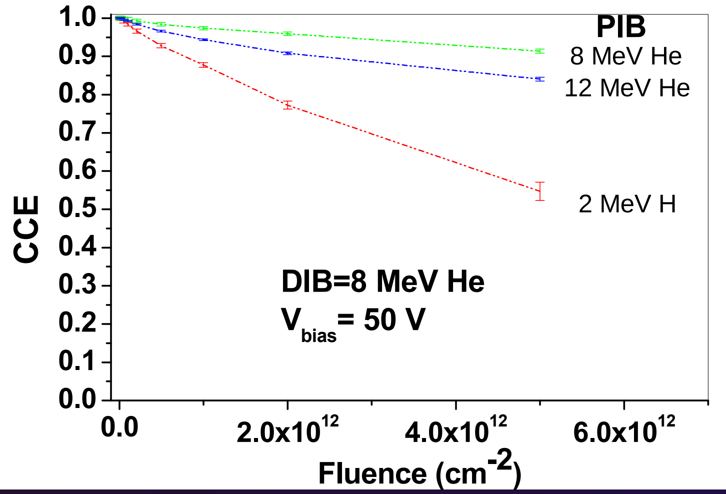
PIB: Ionization profiles



PIB = Probing ion beam
DIB = Damaging ion beam

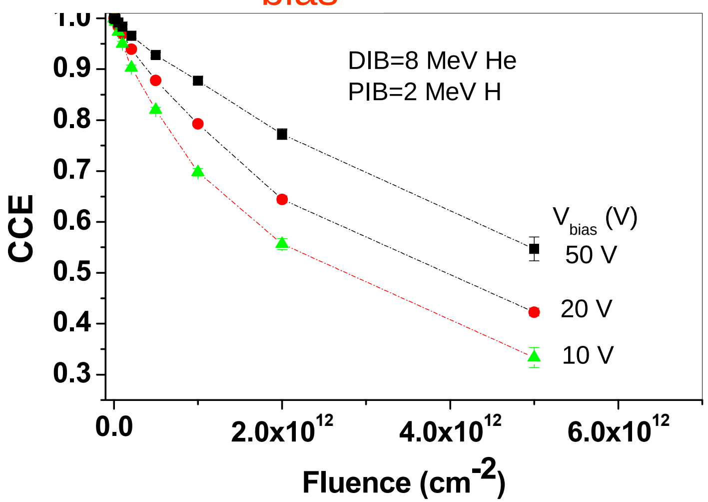
PIB\DIB	He 4 MeV	He 8 MeV	He 12 MeV	H 4.5MeV	H 17MeV
H 1 MeV Bias (V)					
H 2 MeV Bias (V)		(ANSTO) 10,20,50	(ANSTO) 10,20,50		
H 4.5 MeV Bias (V)		(ANSTO) 10,20,50	(ANSTO) 10,20,50		
He 2 MeV Bias (V)	(SNL) 10,50	(SNL) 10,50		(SNL) 10,50	
He 4 MeV Bias (V)		(ANSTO) 10,20,50	(ANSTO) 10,20,50		(CNA) 0-38
He 8 MeV Bias (V)		(ANSTO) 10,20,50	(ANSTO) 10,20,50		
He 12 MeV Bias (V)			(ANSTO) 10,20,50		

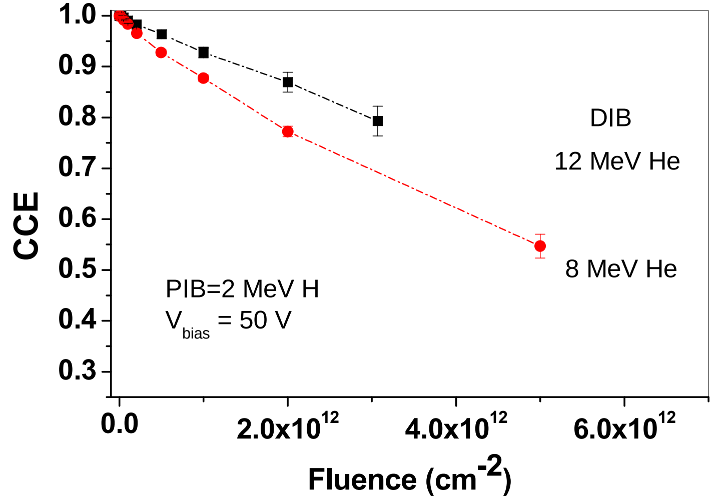
Different bias voltages



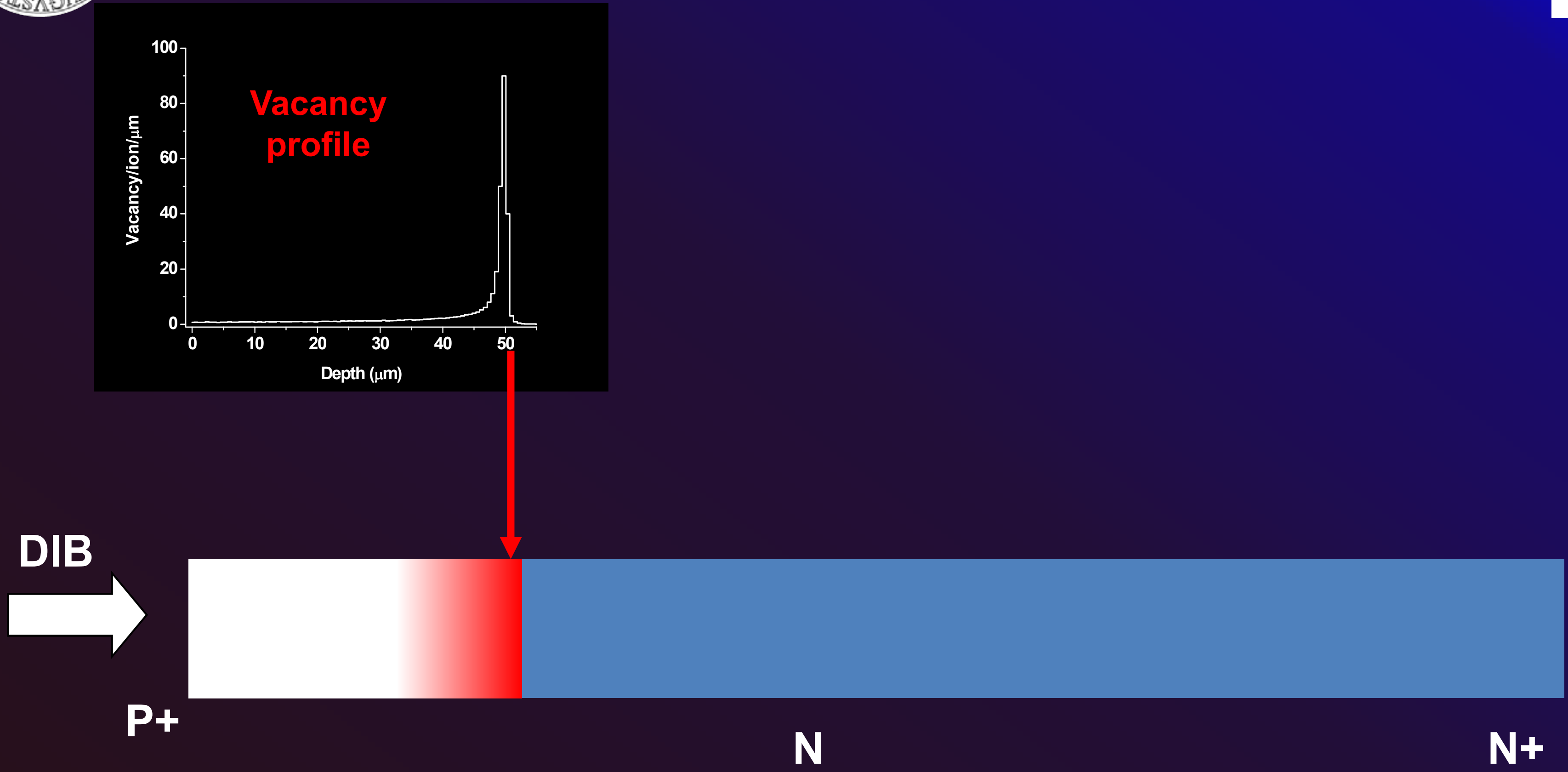
Fixed DIB
Fixed V_{bias}
Variable PIBs

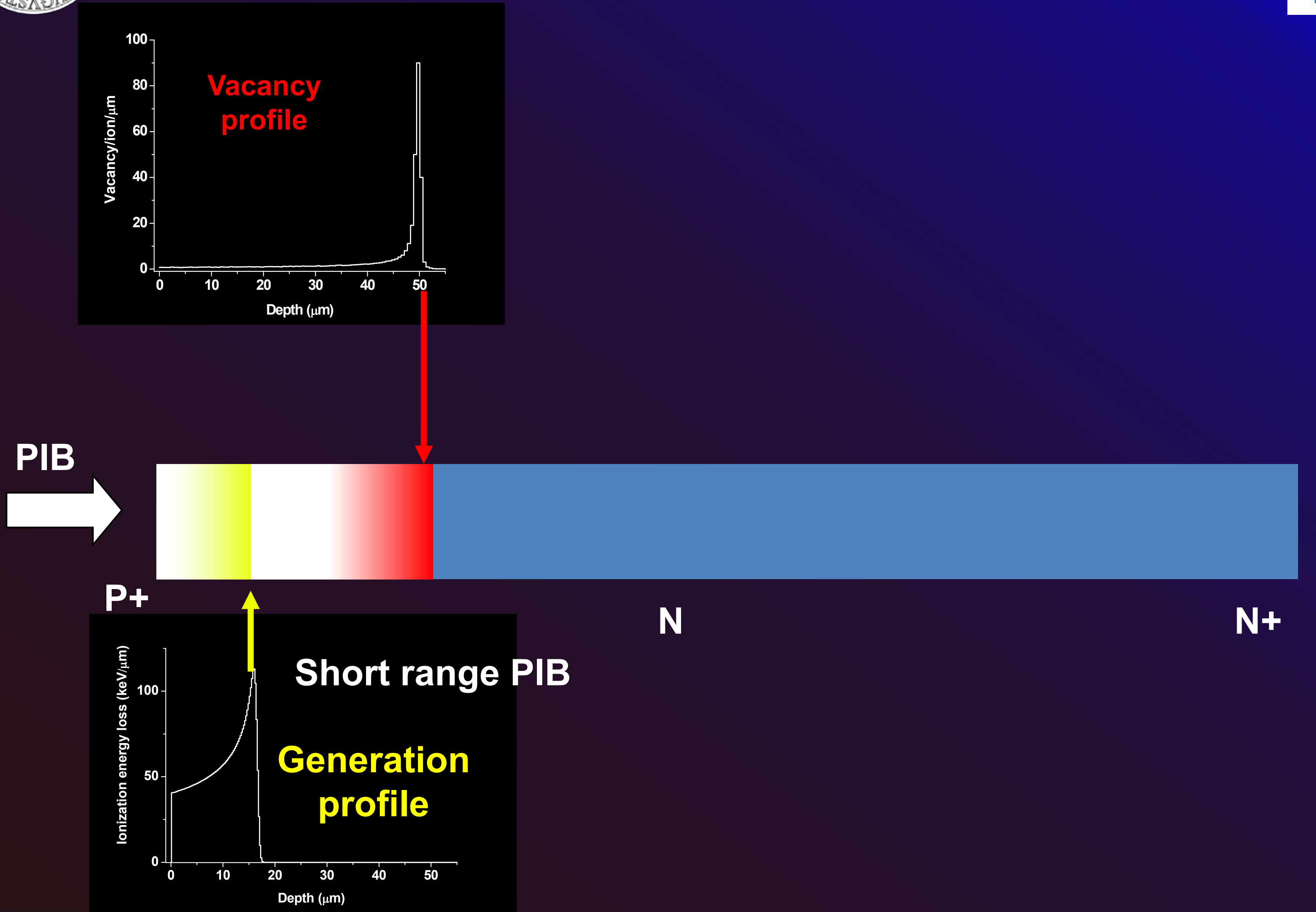
Fixed DIB
Fixed PIB
Variable V_{bias}

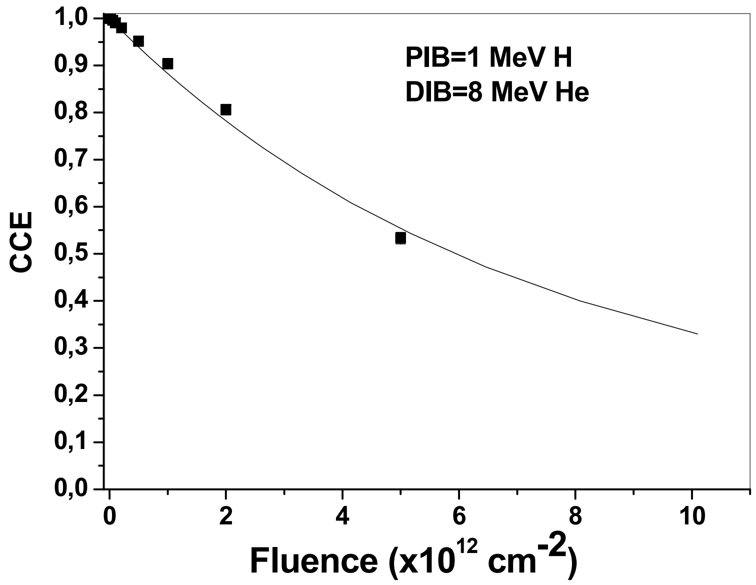


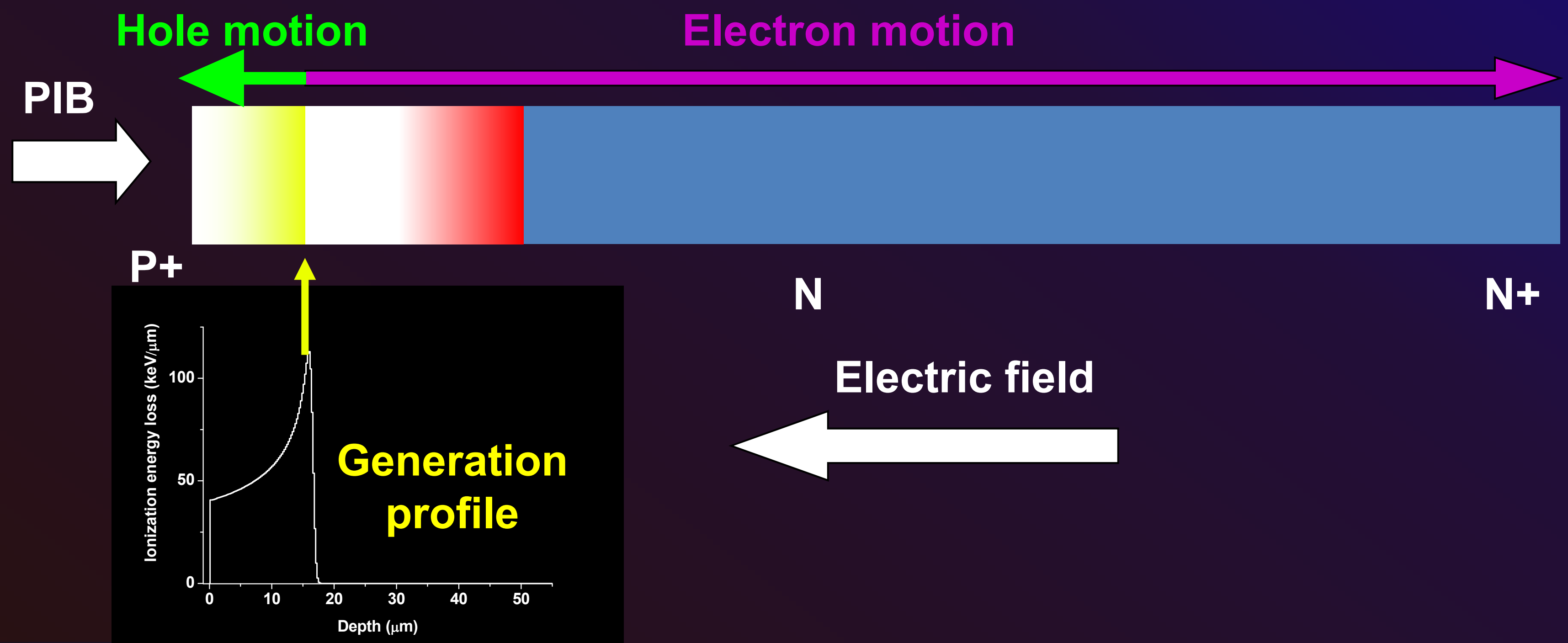


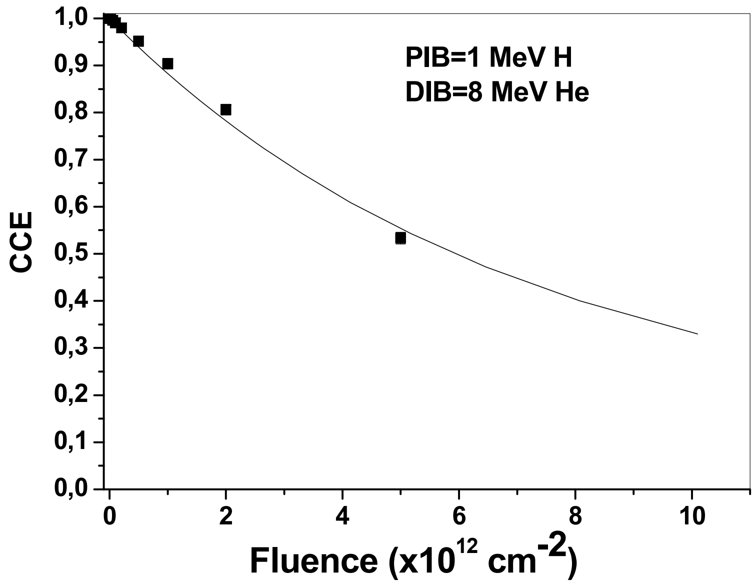
Variable DIB
Fixed PIB
FIXED V_{bias}

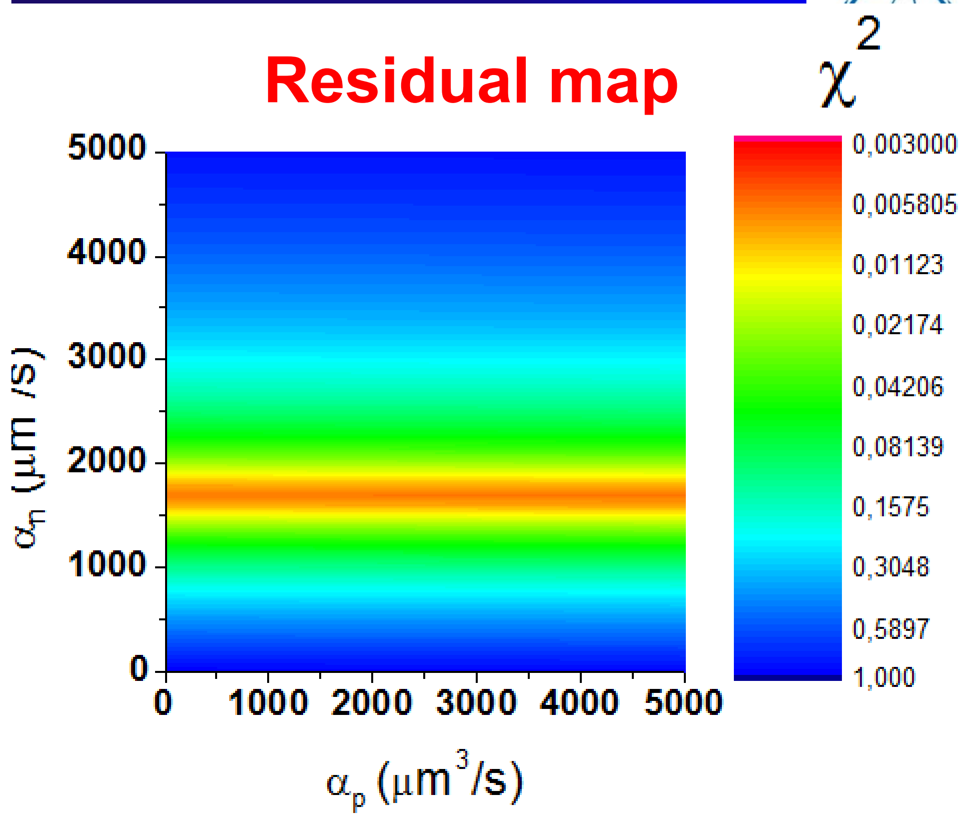

Vacancy profile
Vacancy/ion/µm
100
80
60
40
20
0
0
10
20
30
40
50
Depth (µm)
DIB
P+
N
N+


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


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

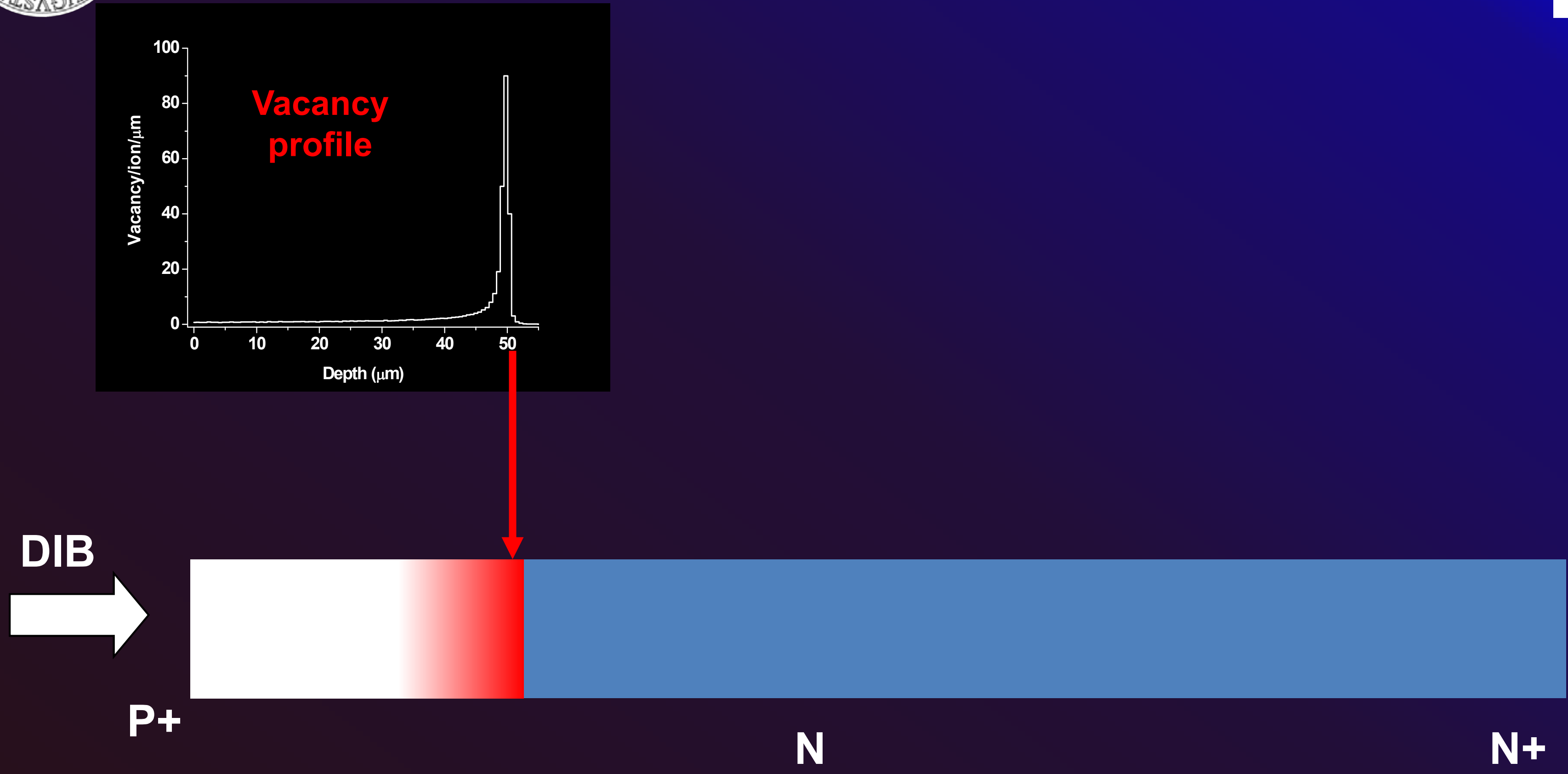

Hole motion
Electron motion
PIB
P+
N
N+
Electric field
Generation profile
Ionization energy loss (keV/μm)
100
50
0
0
10
20
30
40
50
Depth (μm)

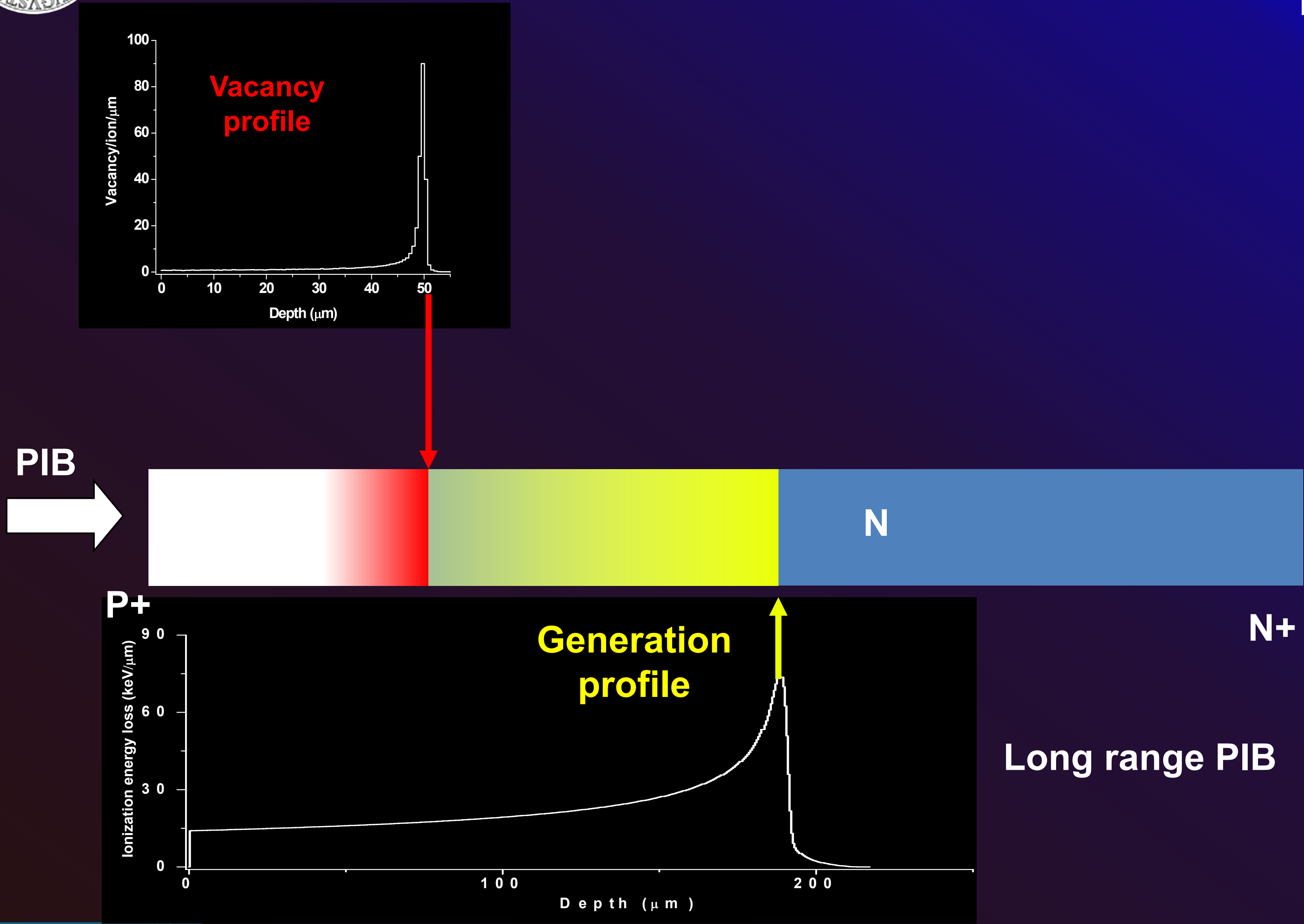




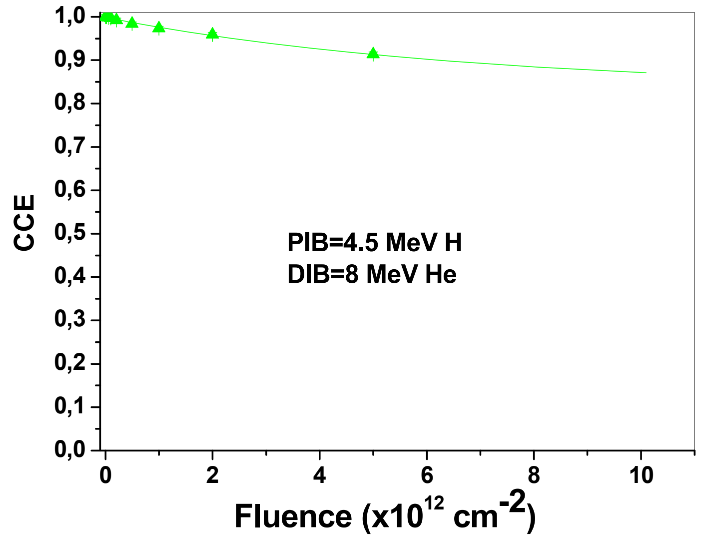
α_n Free parameter

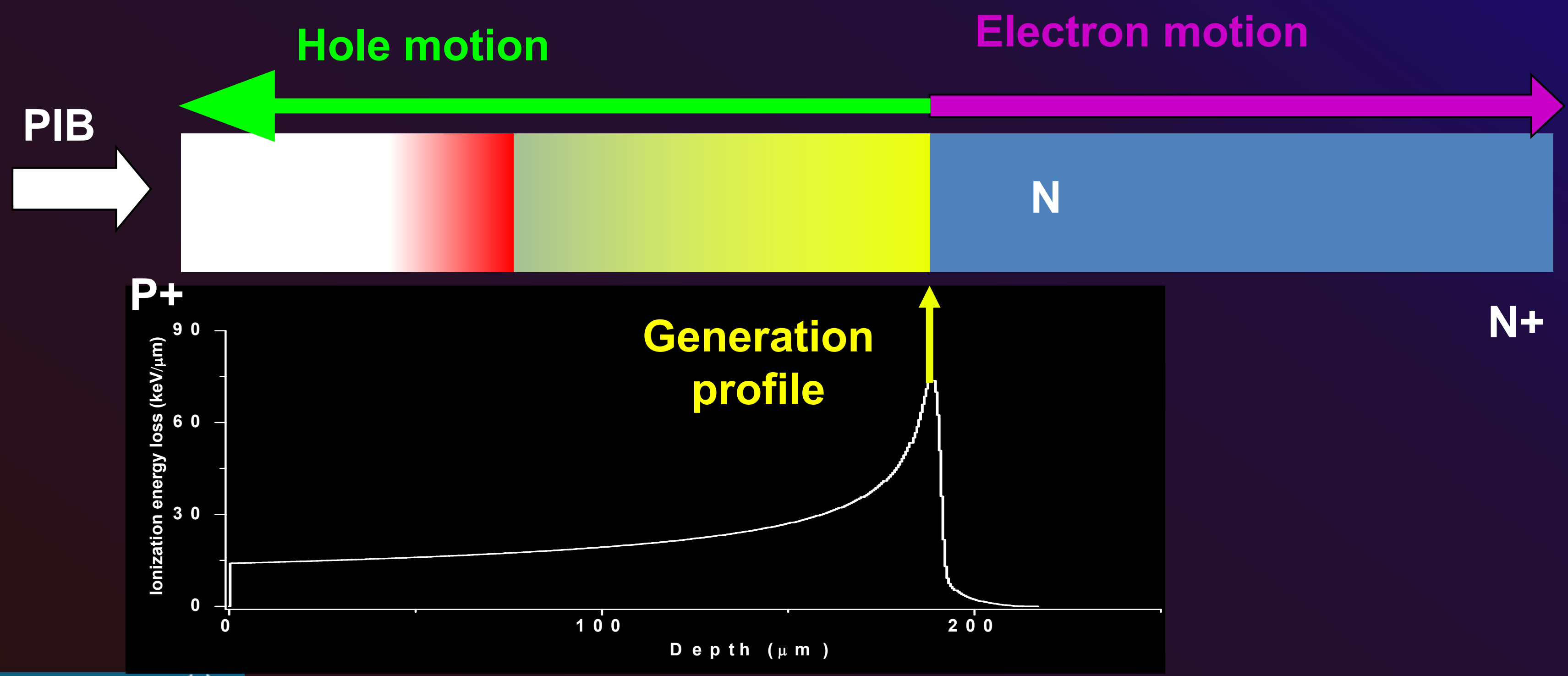
$$Q_S = q \cdot \int_0^d dx \cdot \Gamma(x) \left\{ \int_x^d dy \cdot \frac{\partial F(y)}{\partial V_S} \cdot \exp\left[-\int_x^y dz \frac{1}{v_n} \cdot \left(\frac{1}{\tau_0} + \alpha_n \cdot Vac(x) \cdot \Phi \right) \right] \right\}$$

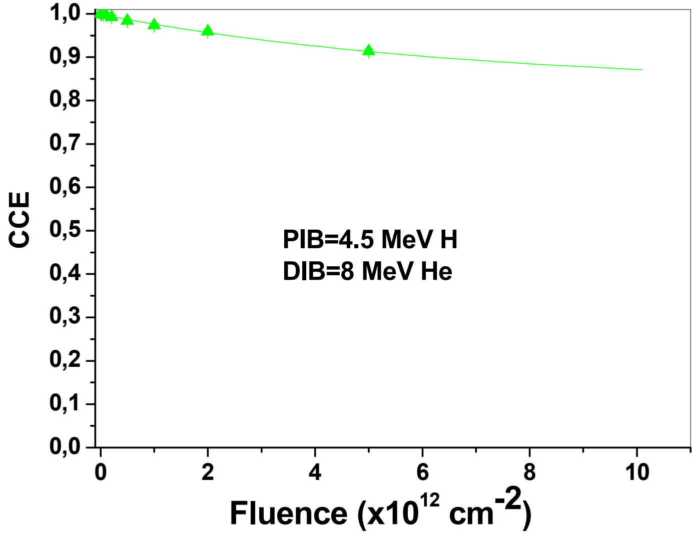

Vacancy profile
Vacancy/ion/µm
100
80
60
40
20
0
0
10
20
30
40
50
Depth (µm)
DIB
P+
N
N+



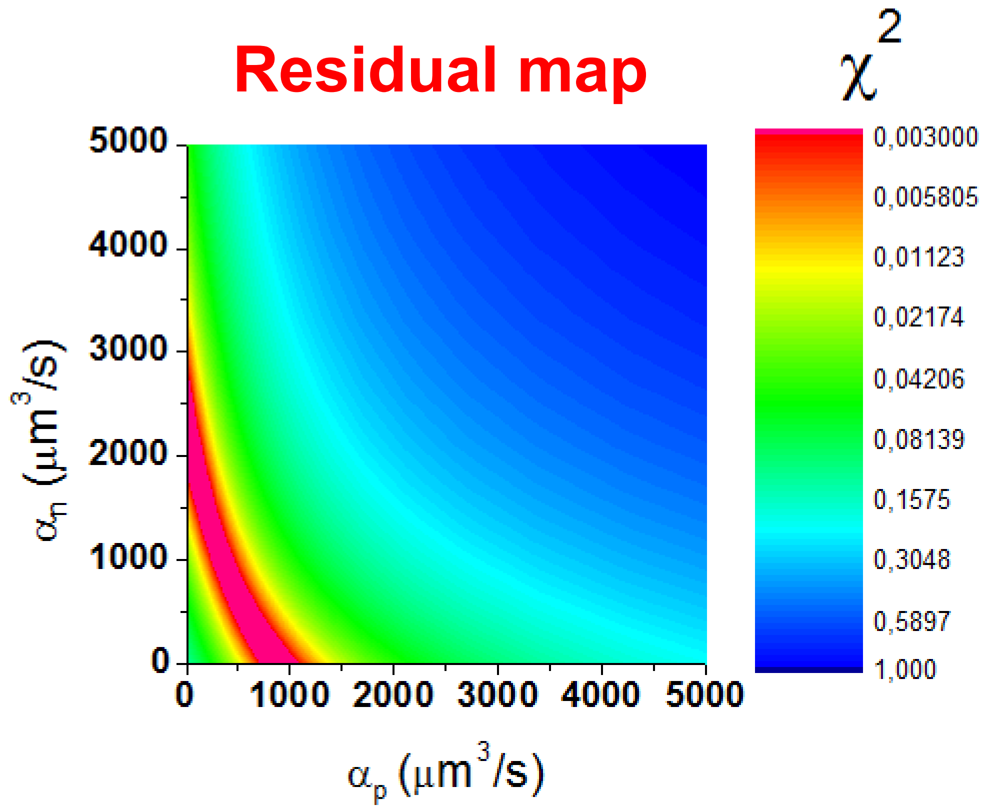
Long range PIB


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

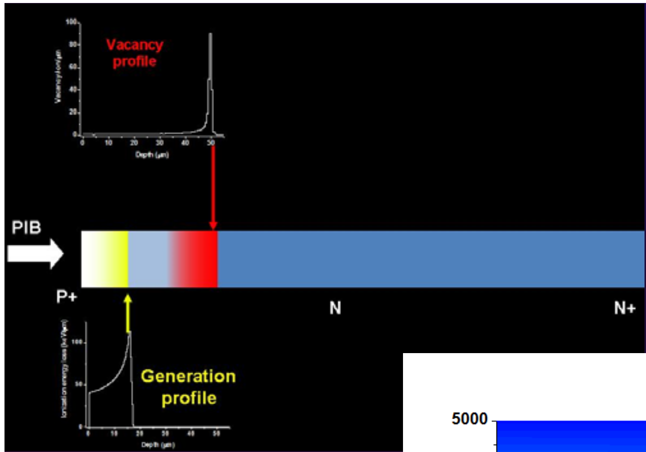

Hole motion
Electron motion
PIB
N
P+
N+
Generation
profile
90
60
30
0
Ionization energy loss (keV/µm)
0
100
200
Depth (µm)

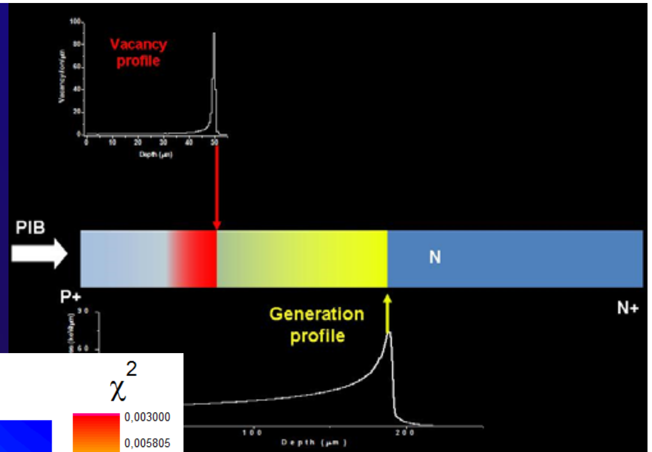


Residual map

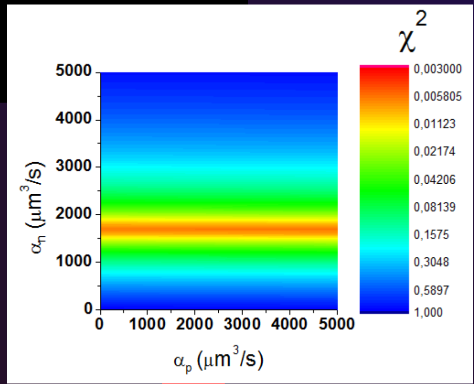


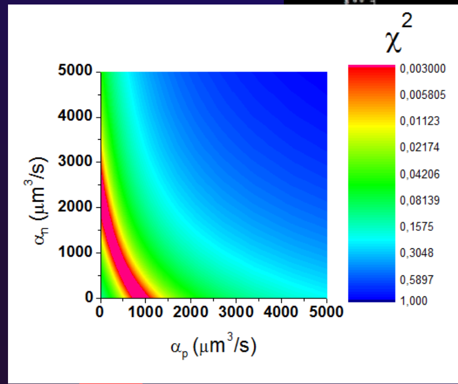
$$Q_S = q \cdot \int_0^d dx \cdot \Gamma(x) \left\{ \int_0^x dy \cdot \frac{\partial F(y)}{\partial V_S} \cdot \exp\left[-\int_y^x dz \frac{1}{v_p} \cdot \left(\frac{1}{\tau_0} + \alpha_p \cdot Vac(x) \cdot \Phi \right) \right] + \int_x^d dy \cdot \frac{\partial F(y)}{\partial V_S} \cdot \exp\left[-\int_x^y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





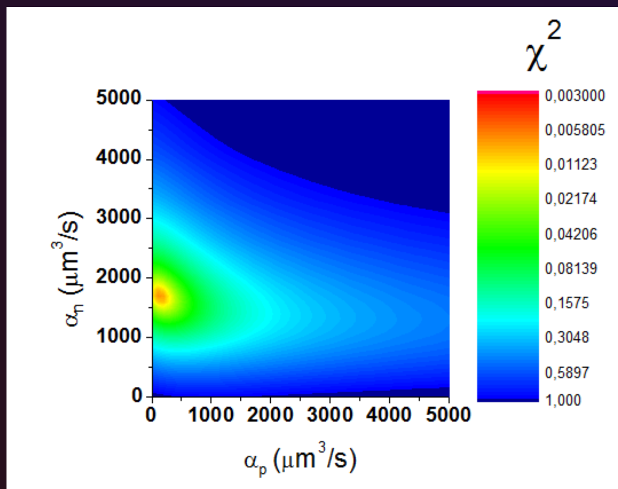
Short range PIB





Long range PIB

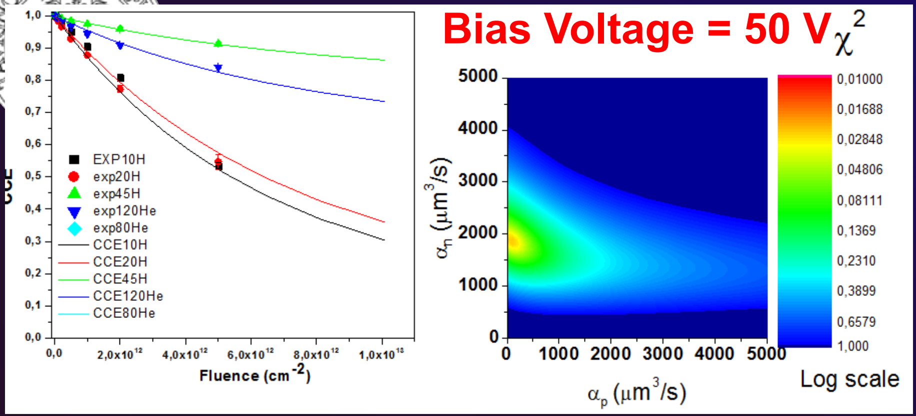
Bias Voltage = 50 V

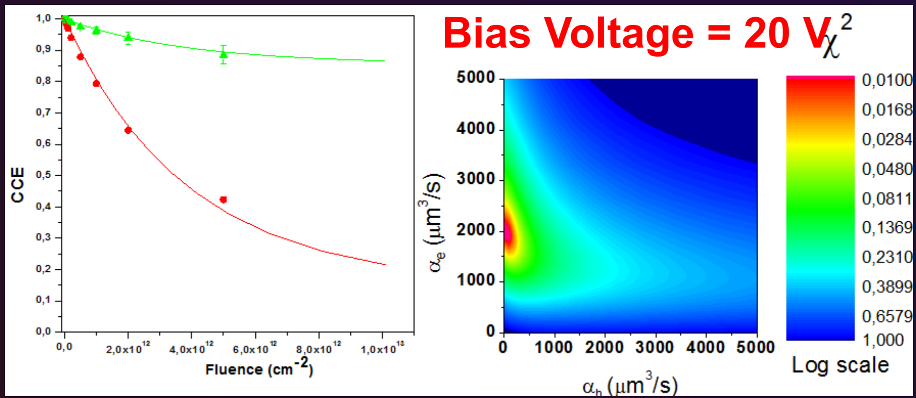


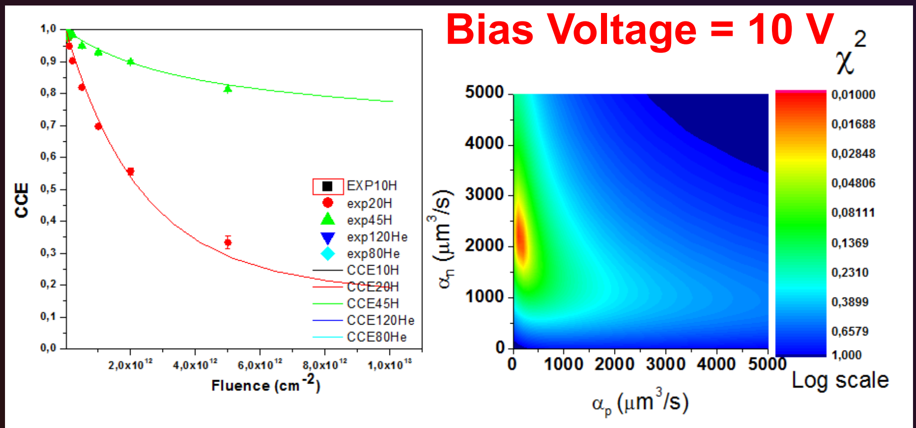
α_n=1700 $\mu m^3/s$

α_p=130 $\mu m^3/s$

n-type Fz silicon diode







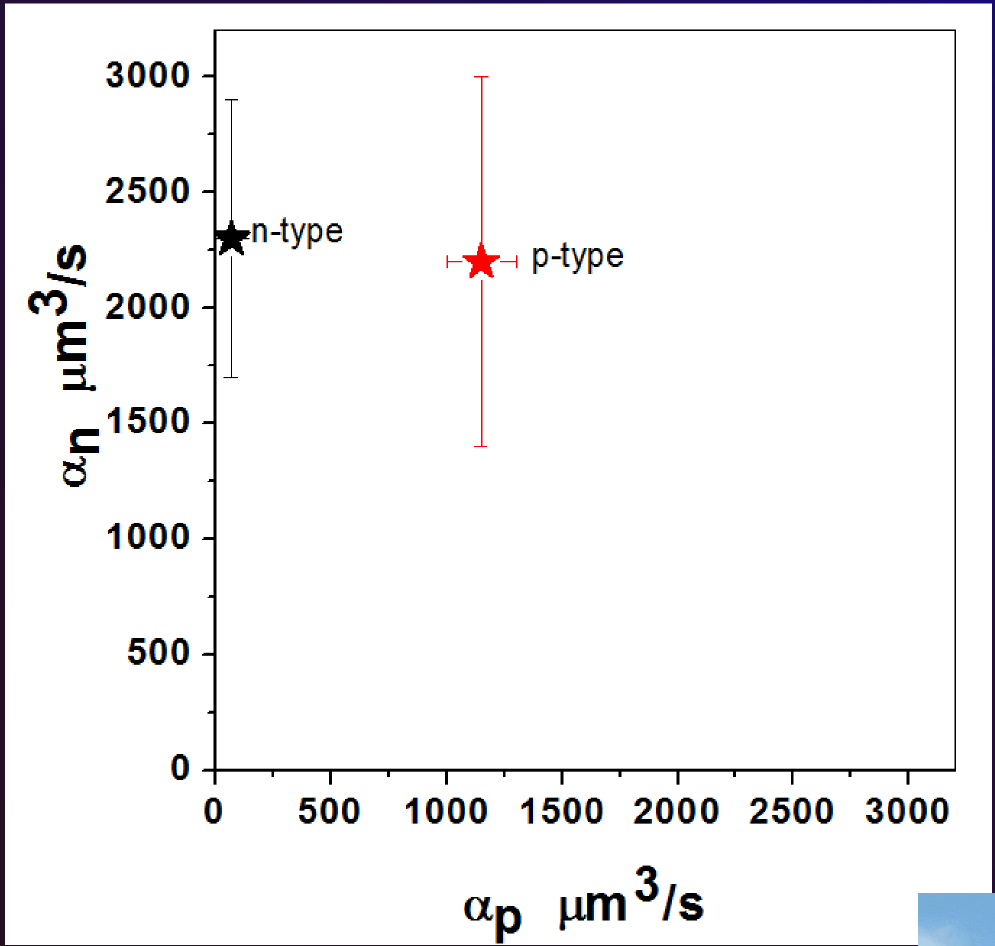
Damaging ions: 8 MeV He
Probing ions: 1,2,4.5 MeV H, 12 MeV He
Bias Voltages: 10,20 50 V

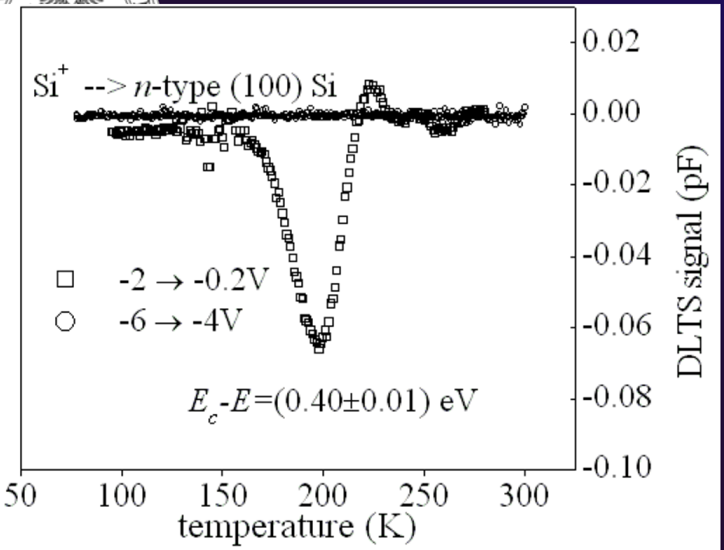
CAPTURE COEFFICIENTS

α_n = (2300±600) $\mu m^3/s$

α_p = (70±30) $\mu m^3/s$

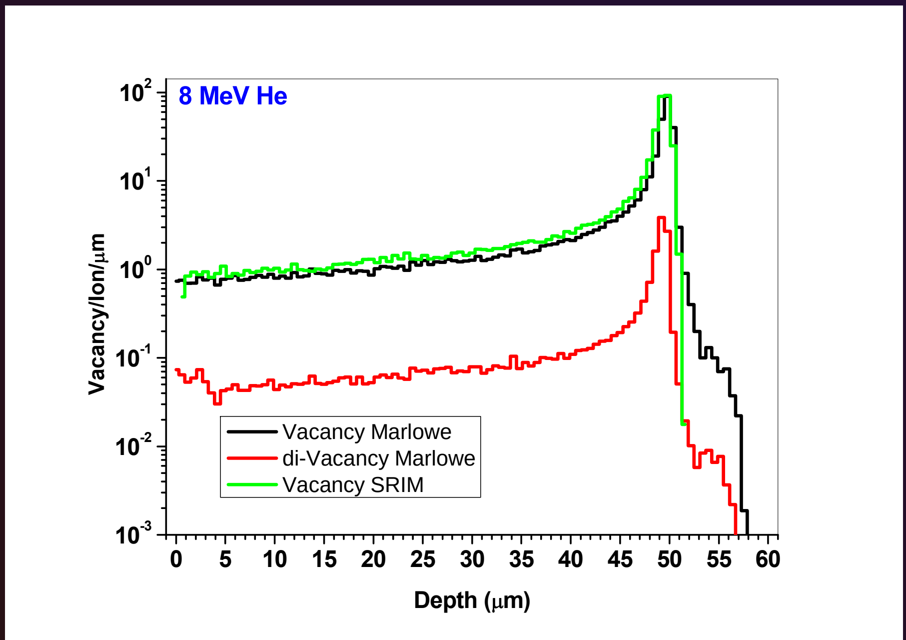
Fz silicon diode
Capture coefficient





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

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

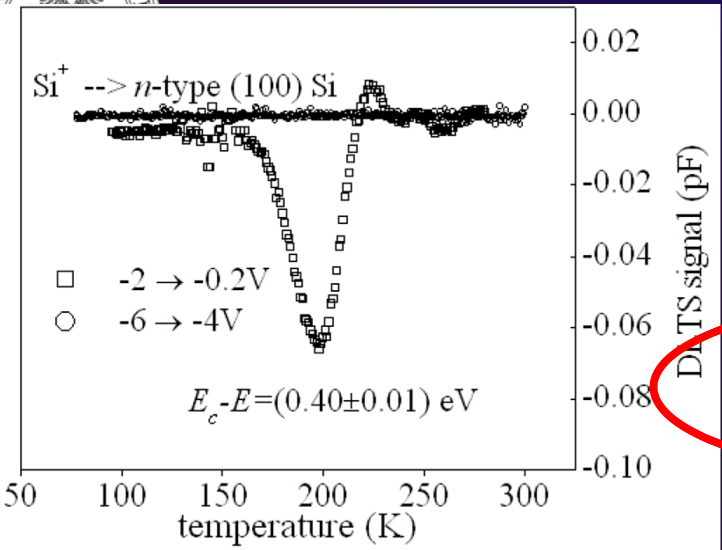


From MARLOWE simulation

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

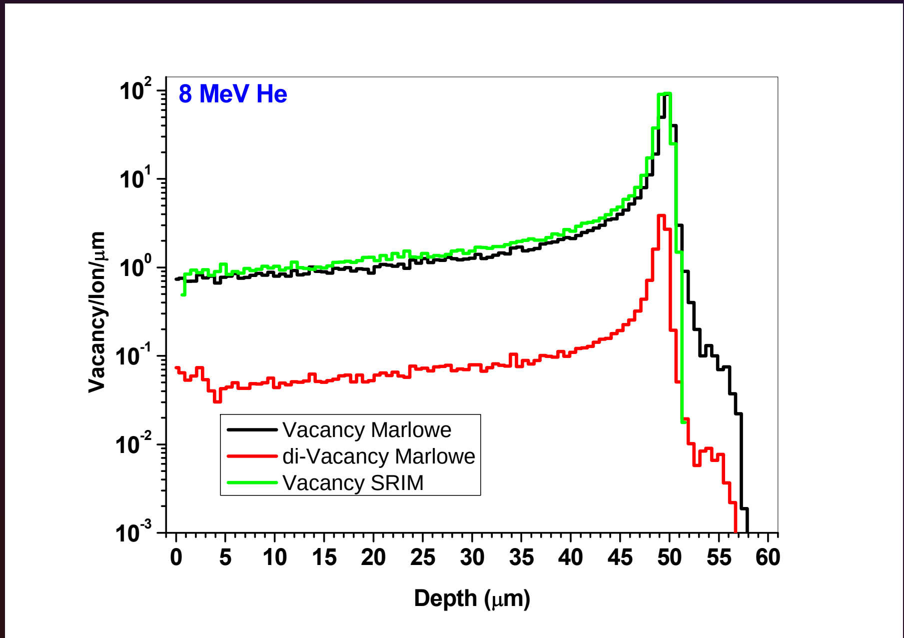
$\alpha_n = v_{th} \cdot \sigma_n$

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



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

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

Limits of applicability

Basic Hypotheses

DIB : low level of damage

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

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

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