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The Abdus Salam International Centre for Theoretical Physics

Joint ICTP-IAEA Advanced Workshop on Single Ion Technologies for Bio-medical and Materials Sciences

30 June – 4 July 2025

Single Ion Detection III
Assessment of radiation hardness of semiconductors

Ettore Vittone

Physics Department, Torino University – Italy

www.solid.unito.it

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

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

Leipzig Univ.

NUS

Delhi Univ.

Torino Univ.

CAN

Surrey Univ.

Malesian Nuclear Agency

SANDIA

Ruđer Bošković Inst.

Helsinki Univ.

ANSTO

JAEA-Kyoto Univ.

COOPERATION AND MUTUAL UNDERSTANDING LEAD TO GROWTH AND GLOBAL ENRICHMENT

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 semiconductor devices induced by ionizing radiation

Three main types of effects:

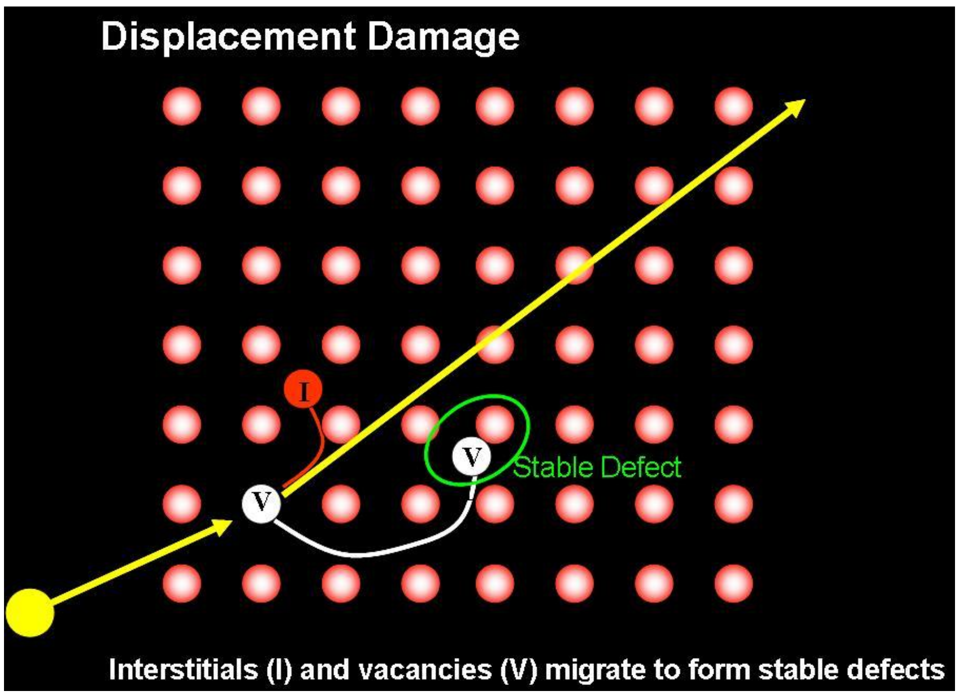
- **Transient ionization.** **This effect produces electron-hole pairs;** ***particle detection with semiconductors is based on this effect.***

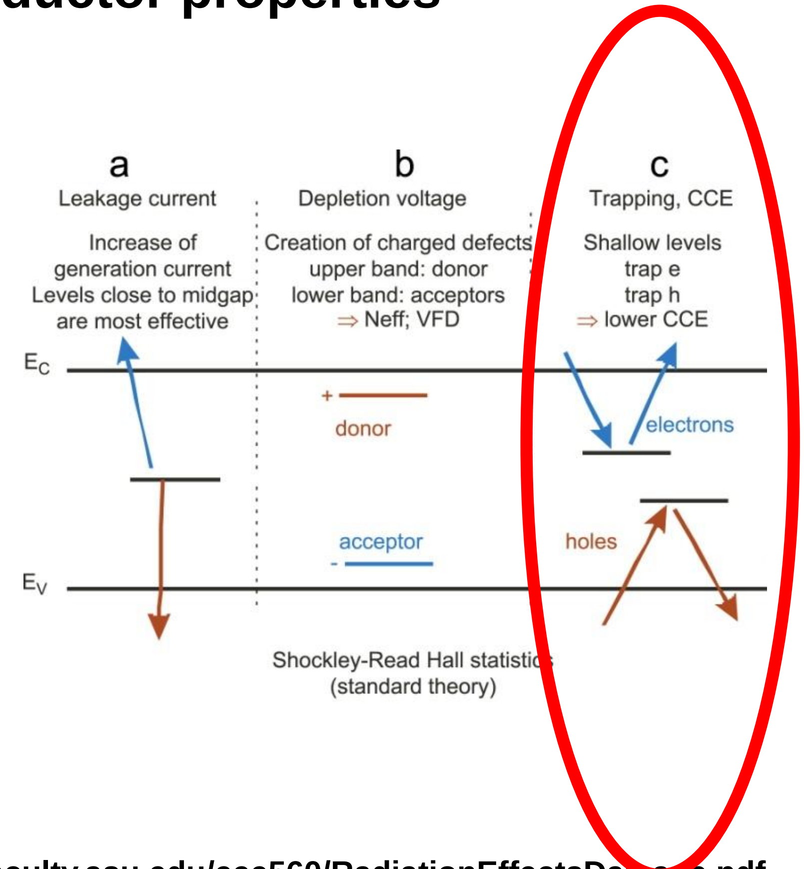
- **Long term ionization.** **In insulators (oxides), the material does not return to its initial state, if the electrons and holes produced are fixed, and charged regions are induced.**

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

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

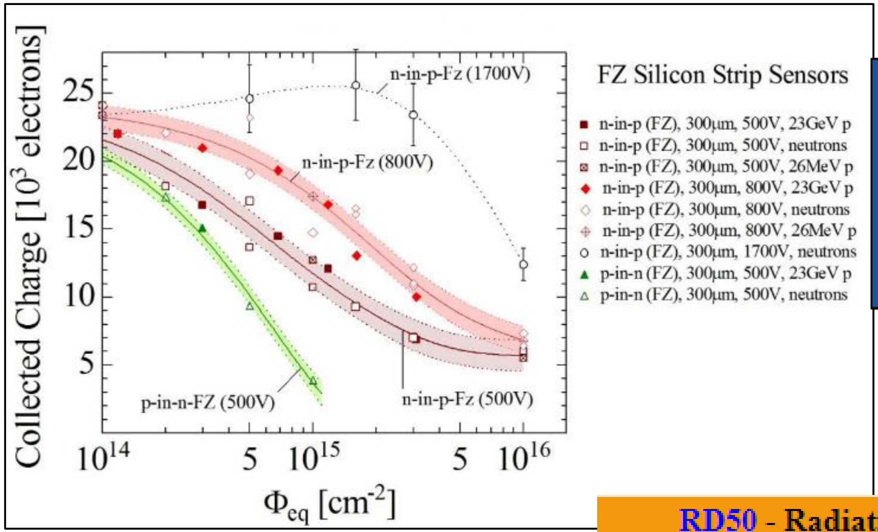
- Displacements. Dislocations of atoms from their normal sites in the lattice, producing less ordered structures, with long term effects on semiconductor properties





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

WHY



RD50 - Radiation hard semiconductor devices for very high luminosity colliders

Nuclear Instruments and Methods in Physics Research A 426 (1999) 1–15

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

G. Lindström*, M. Moll, E. Fretwurst

National Aeronautics and Space Administration

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 is 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

APPLICATIONS

The technology has several potential applications:

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

PUBLICATIONS

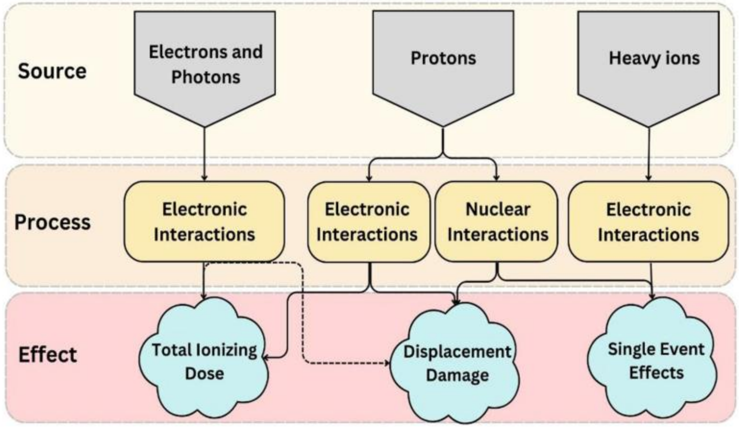
Patent No: 8,159,238; 9,419,558

Patent Pending

Radiation-induced degradation in optoelectronic devices for satellite applications: a review

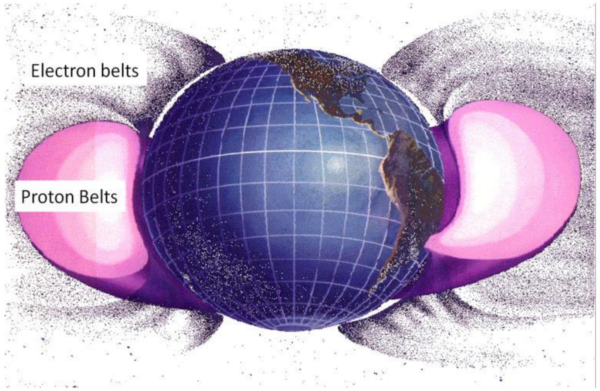
N. N. Sulaiman[1] · N. F. Hasbullah[1] · N. Saidin[1] · Y. Javed[2] · Z. I. Khan[2]

Discover Materials (2025) 5:59



Modeling radiation degradation in solar cells extends satellite lifetime

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



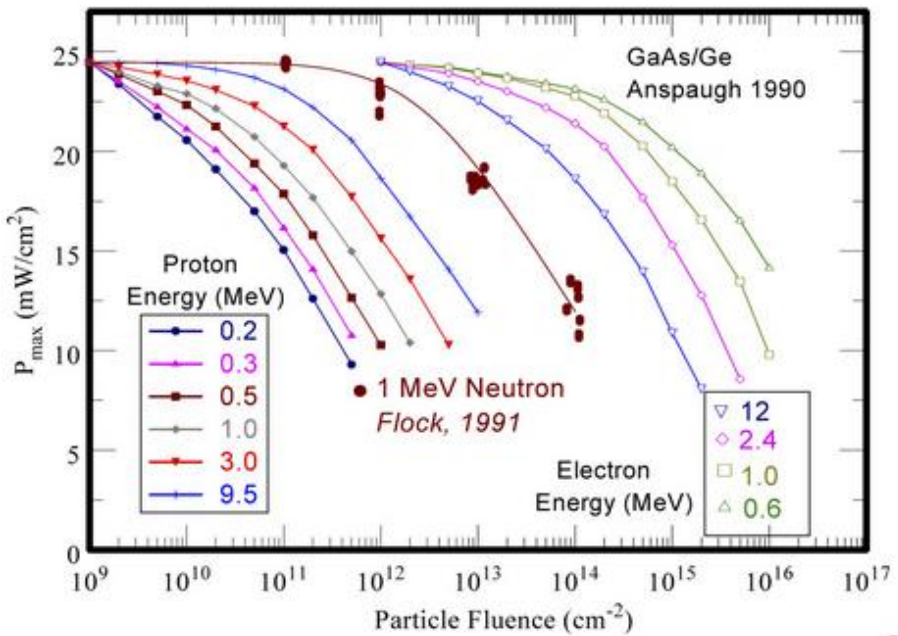


Figure 2. *Measured degradation of a single junction gallium arsenide (GaAs) solar cell under proton, electron,[2] and neutron irradiation.[3] These data can be used to empirically determine the energy dependence of the solar-cell degradation thereby enabling on-orbit performance prediction. P_{max}: Maximum power.*

http://spie.org/x43655.xml

Space environment →
→ wide spectrum of ions (protons) and electrons.

To understand the performance of a solar cell in the space radiation environment, it is necessary to know how cell degradation depends on the energy of the irradiating particle.

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 characteristics before irradiation

Particle Fluence

Equivalent damage factor

Displacement dose

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

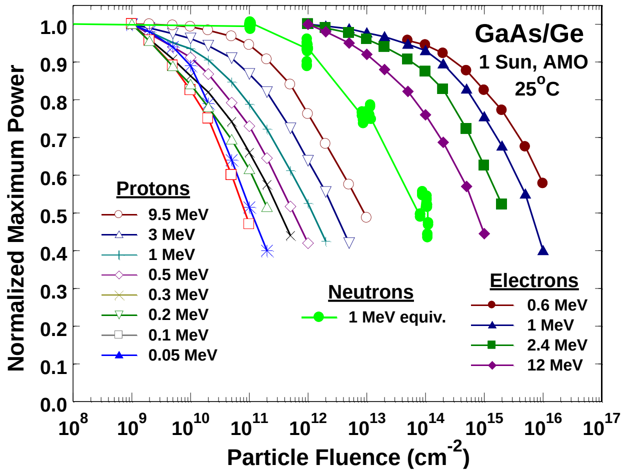
NIEL (Non Ionizing Energy Loss) approach:

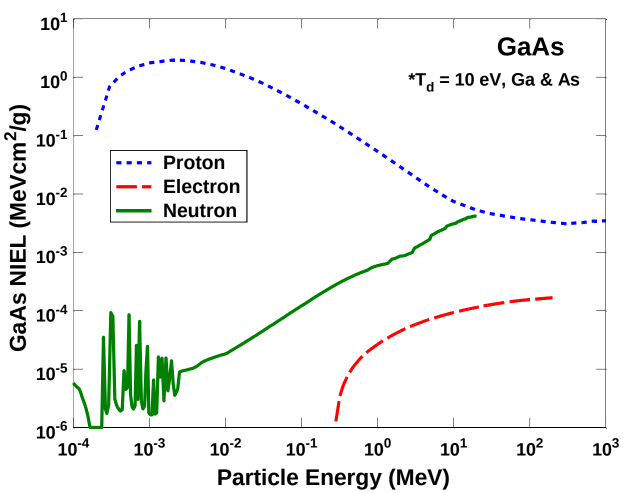
measurement of K_{ed} only for one particle (at one specific energy) → **K_{ed} can be estimated for all the particles and energies**

US Naval Research Laboratory (NRL)

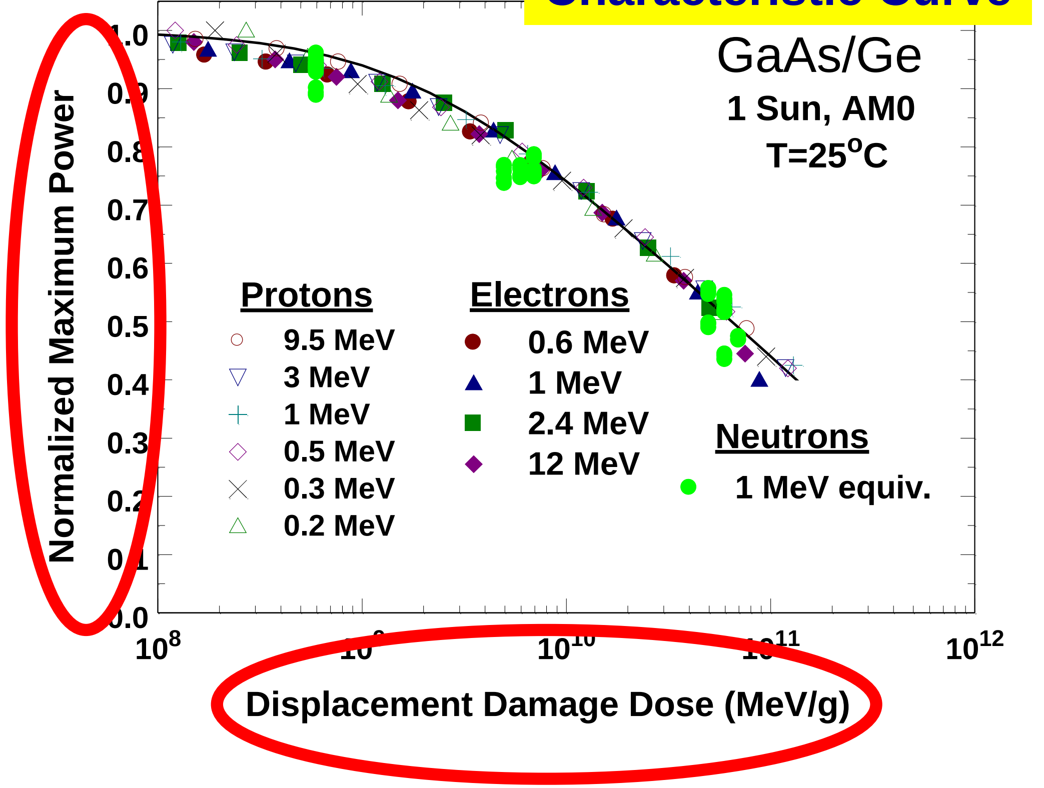
Displacement Damage Dose Method

Measured Data





Characteristic Curve



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

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 characteristics before irradiation

Particle Fluence

Equivalent damage factor

Displacement dose

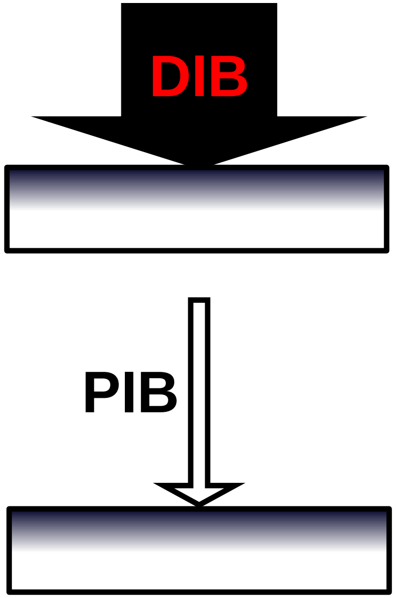
First order: proportionality, independent of the particle, between the damage factor and the particle NIEL

MeV Ion beams

to induce the damage ⟶ DIB=DAMAGING IONS

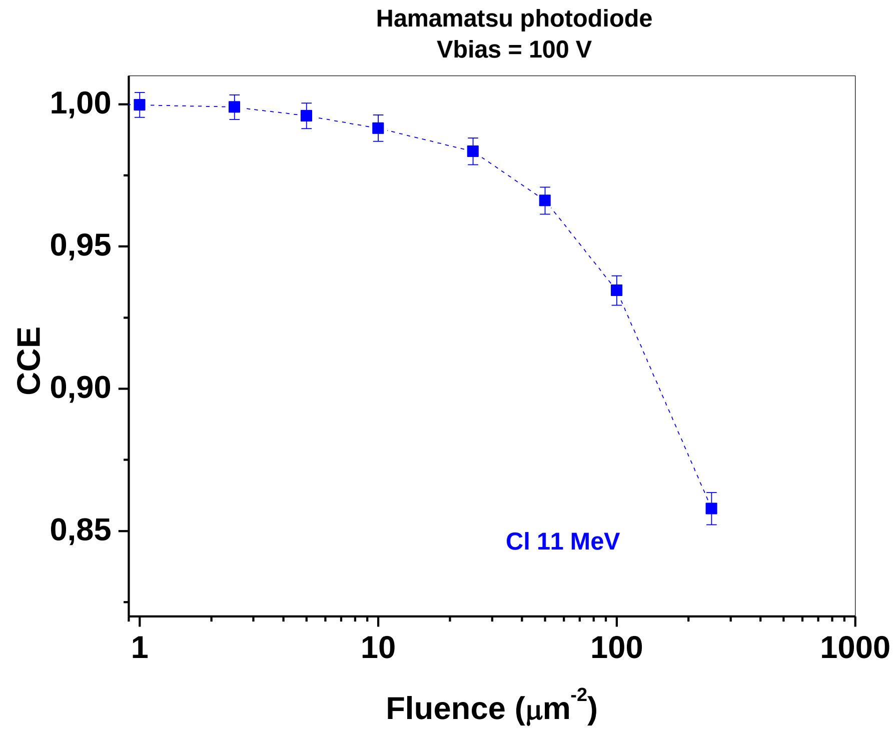
And

to probe the damage ⟶ PIB=PROBING IONS

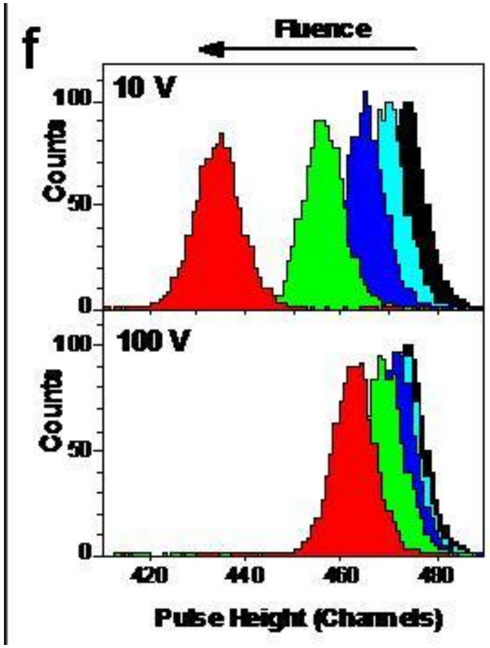


CCE degradation induced by ion irradiation

Is a function of the damaging ion fluence



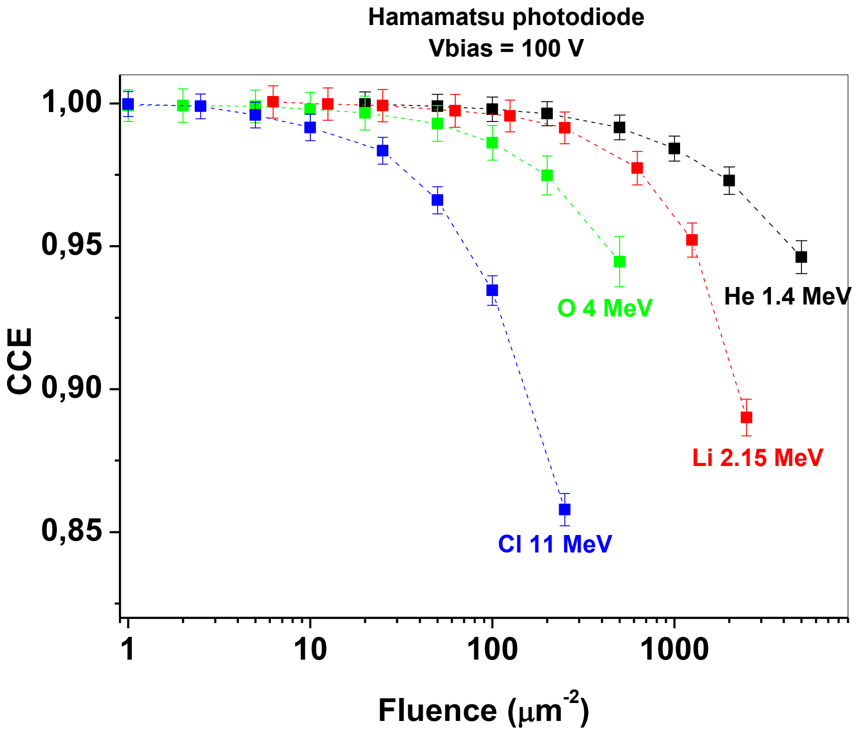
$$\eta = \frac{Y}{Y_0} = 1 - K \cdot \Phi = 1 - K_{ed} \cdot D_d$$



Damaging Ion Beam (DIB) = Cl 11 MeV
Probing Ion Beam (PIB) = He 1.4 MeV

CCE degradation induced by ion irradiation

Is a function of the ion energy and mass



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

Damaging Ion Beam (DIB)

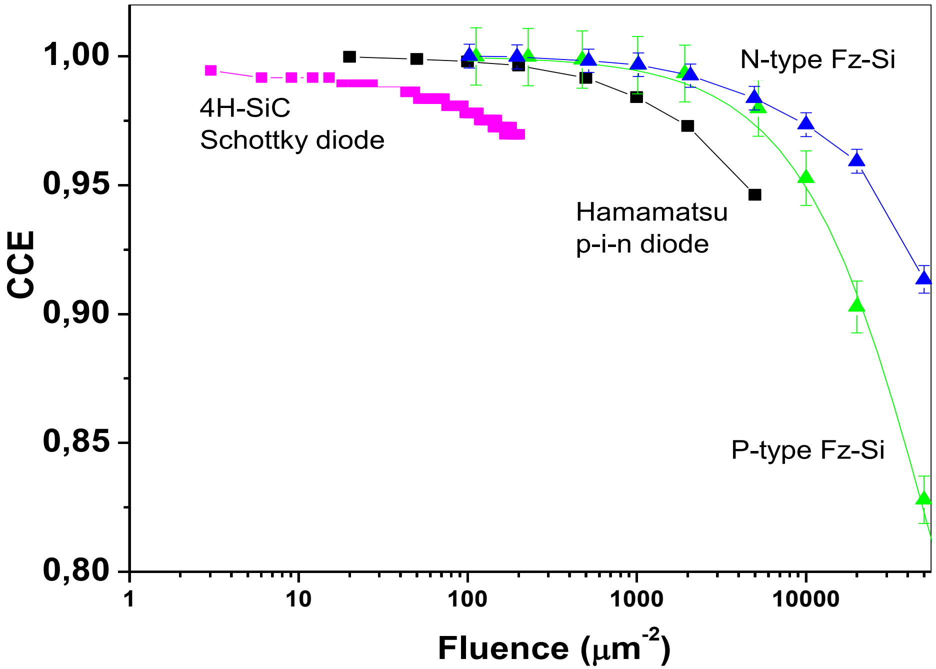
Cl	11 MeV
O	4 MeV
Li	2.15 MeV
He	1.4 MeV

Probing Ion Beam (PIB) = He 1.4 MeV

CCE degradation induced by ion irradiation

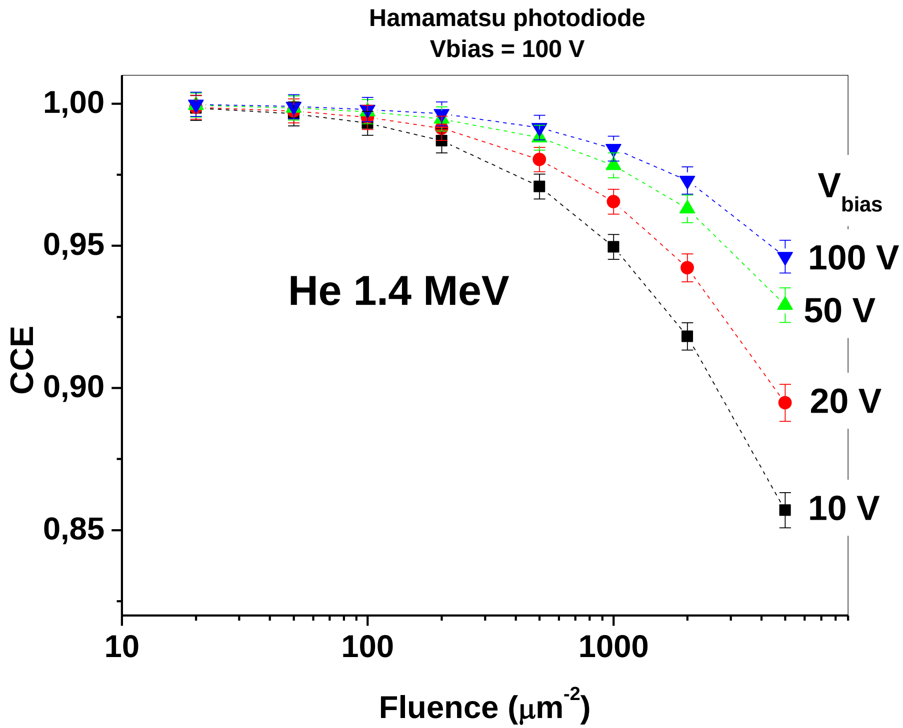
Is a function of the material and/or device

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



CCE degradation induced by ion irradiation

Is a function of the polarization state of the device



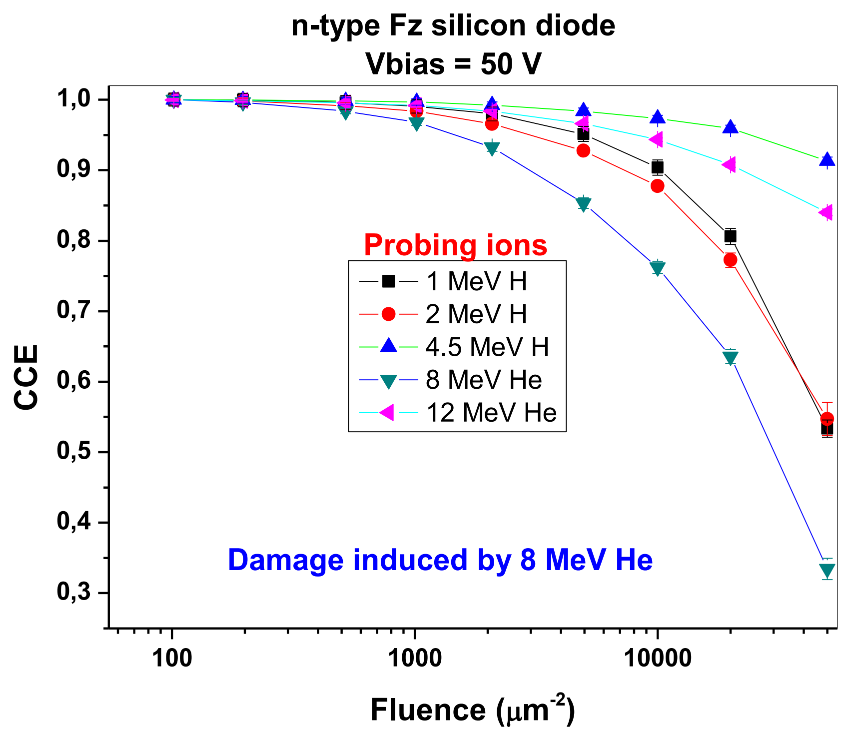
$$\eta = \frac{Y}{Y_0} = 1 - K(V_{bias}) \cdot \Phi = 1 - K_{ed} \cdot D_d$$

Damaging Ion Beam (DIB) = He 1.4 MeV
Probing Ion Beam (PIB) = He 1.4 MeV

CCE degradation induced by ion irradiation

Is a function of the probing ions (PIB)

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



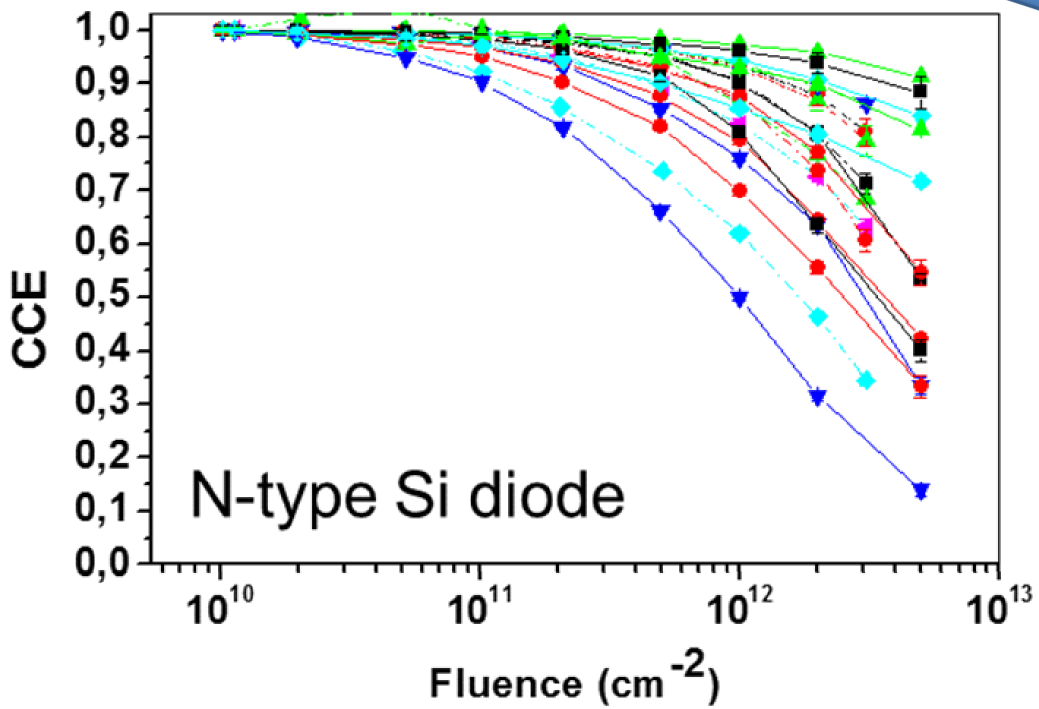
Probing Ion Beam (PIB)

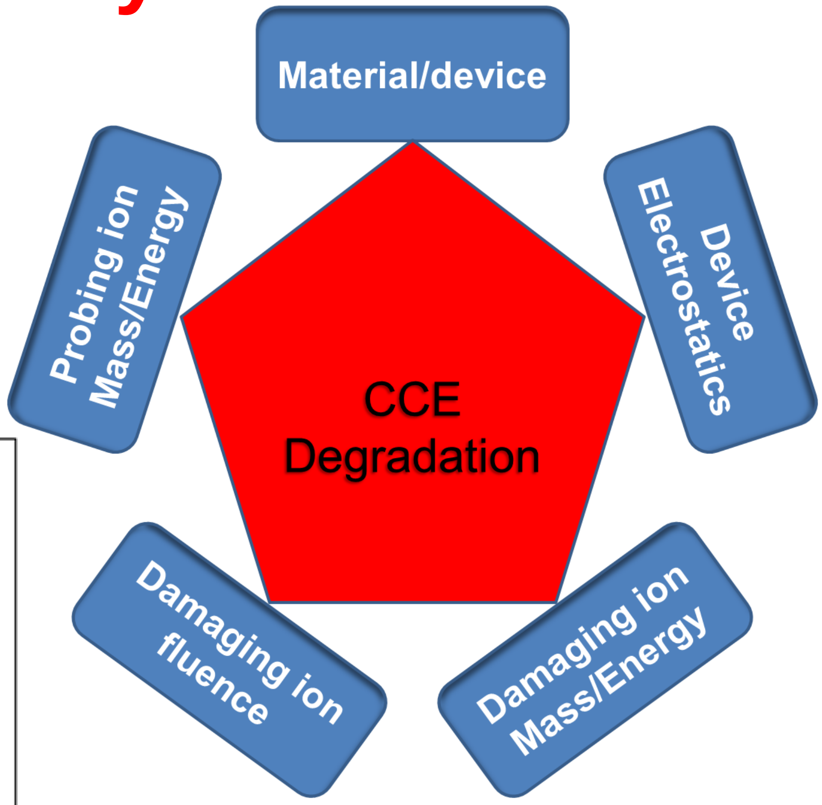
H	1 MeV
He	2 MeV
H	4.5 MeV
He	8 MeV
He	12 MeV

Damaging Ion Beam (DIB) = He 8 MeV

Summary

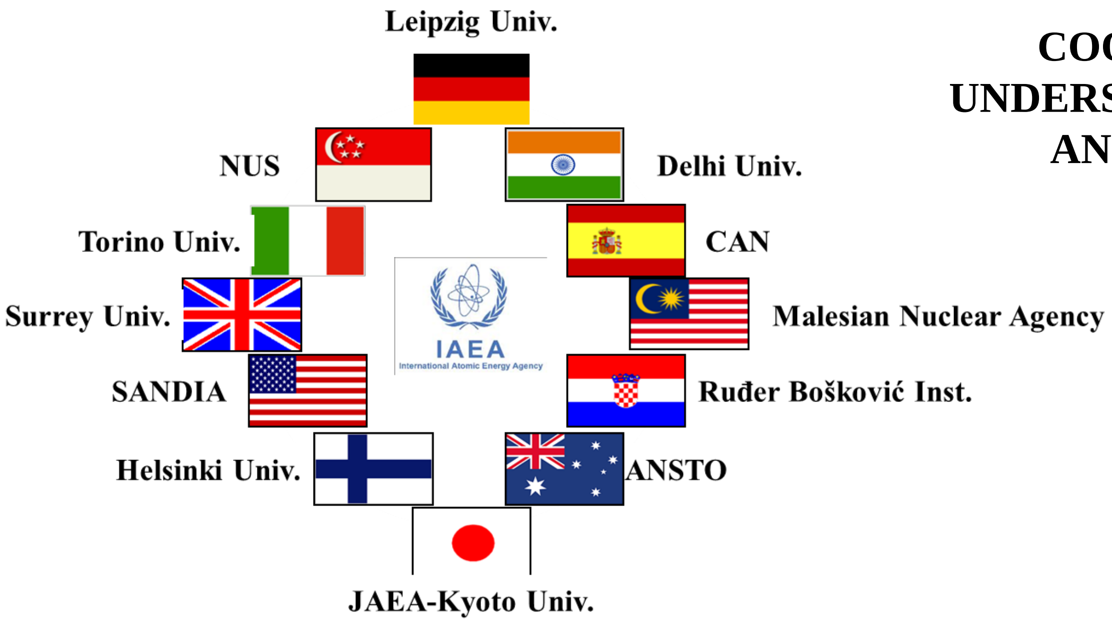
CCE degradation
DIBs(12 MeV and 8 MeV He)
PIBs (1, 2, 4.5 H; 8, 12 MeV He)
Different bias voltages (10,20,50 V)





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

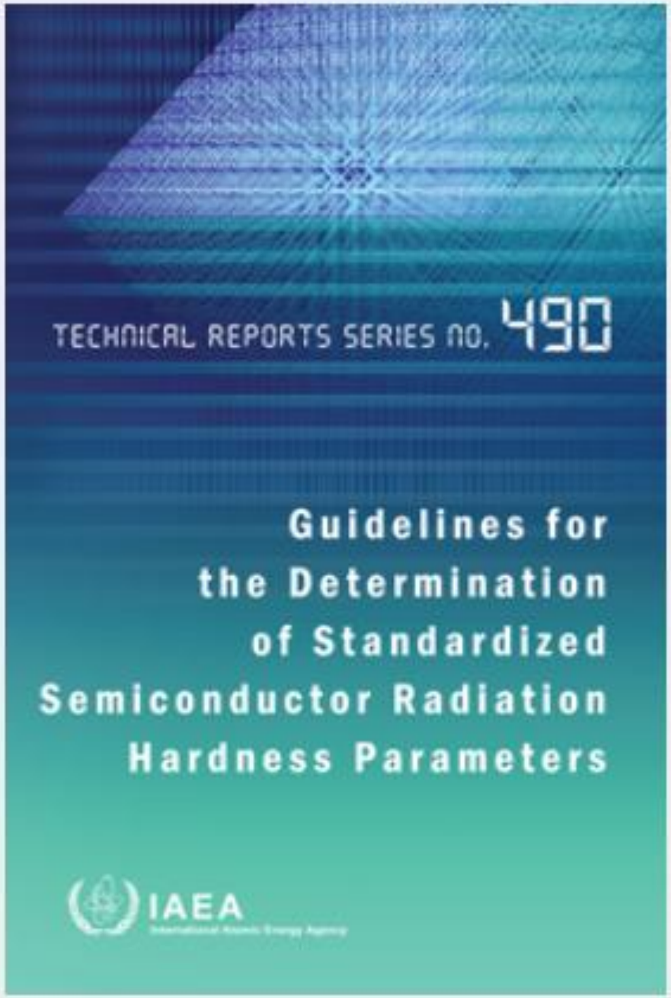
“Utilization of ion accelerators for studying and modeling of radiation induced defects in semiconductors and insulators”



COOPERATION AND MUTUAL UNDERSTANDING LEAD TO GROWTH AND GLOBAL ENRICHMENT

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.



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89 pages ¦ 42 figures

Date published: 2023

https://www.iaea.org/publications/12356/guidelines-for-the-determination-of-standardized-semiconductor-radiation-hardness-parameters

Goals

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

- **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 Gunn's theorem**

- **Adjoint equation method: the CCE is the solution of the Adjoint Equation**

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Pulse shapes calculation

Gunn's theorem

Solid-State Electronics Pergamon Press 1964. Vol. 7, pp. 739–742. Printed in Great Britain

A GENERAL EXPRESSION FOR ELECTROSTATIC INDUCTION AND ITS APPLICATION TO SEMICONDUCTOR DEVICES

J. B. GUNN

IBM Watson Research Center, Yorktown Heights, New York

(*Received* 2 *March* 1964; *in revised form* 26 *March* 1964)

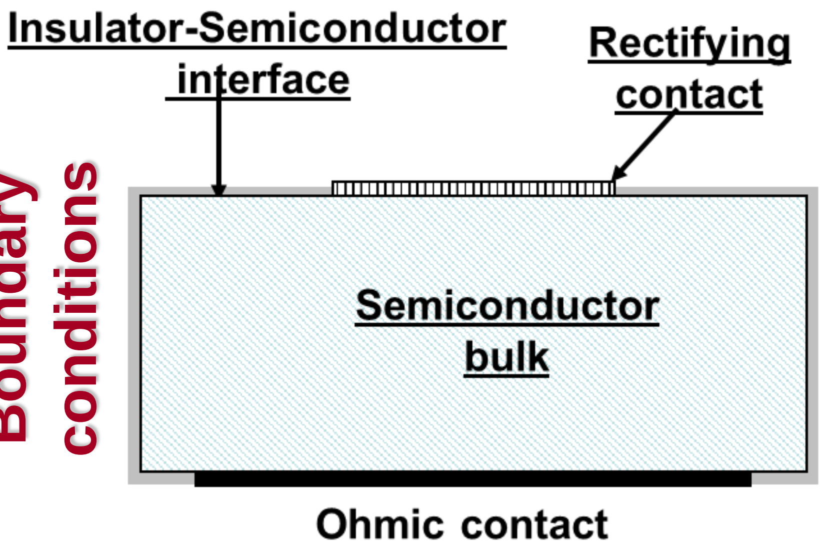
Abstract—A new formula is deduced, under rather general conditions, for the charges induced upon a system of conductors by the motion of a small charge nearby. The conditions are found under which this result can be simplified to yield various previously derived formulas applicable to the problem of collector transit time in semiconductor devices.

$$I = -q \cdot \mathbf{v} \cdot \frac{\partial \mathbf{E}}{\partial V}$$

Weighting field

Formalism based on the Gunn's theorem

Boundary conditions



Initial conditions

For mapping charge pulses

$$G_{n,p} = \delta(r - r_0) \cdot \delta(t)$$

$$r_0 = \text{Generation point at } t = 0$$

Solve the continuity equations using the potential ϕ_0 defined by boundary conditions, space charge

$$\frac{\partial n}{\partial t} = +\vec{\nabla} \cdot \left(-\mu_n \cdot \vec{\nabla}\phi_0 \cdot n + D_n \cdot \vec{\nabla} n\right) + G_n - \frac{n}{\tau_n}$$

$$\frac{\partial p}{\partial t} = -\vec{\nabla} \cdot \left(+\mu_p \cdot \vec{\nabla}\phi_0 \cdot p - D_p \cdot \vec{\nabla} p\right) + G_p - \frac{p}{\tau_p}$$

Evaluate the Gunn's weighting field

$$\frac{\partial E}{\partial V_i}$$

by solving the Poisson's equation

$$\vec{\nabla} \cdot \left(\varepsilon \cdot \vec{E}\right) = \rho$$

The potentials of all the other conductors are held constant

Evaluate the induced charge

$$Q_i(t) = -q \int_0^t dt' \int_\Omega dr \left\{ \left[n(r,t';r_0) \cdot v_n(r) + p(r,t';r_0) \cdot v_p(r) \right] \cdot \left. \frac{\partial E(r)}{\partial V_i} \right|_V \right\}$$

Adjoint equation Method

Short-cut

Charge Induced from electrons

$$Q_{in}(t) = -q\int_0^t dt'\int_\Omega d\mathbf{r}\left\{\left[n(\mathbf{r},t';r_0)\cdot \mathbf{v}_n(\mathbf{r})\right]\cdot \left.\frac{\partial \mathbf{E}(\mathbf{r})}{\partial V_i}\right|_V\right\}$$

is the Green's function for the electron continuity equation

The continuity equation involves linear operators

The charge induced from electrons can be evaluated by solving a single, time dependent adjoint equation.

$$\frac{\partial n^+}{\partial t} = +\vec{\nabla}\cdot\left(+\mu_n\cdot\vec{\nabla}\phi_0\cdot n^+ + D_n\cdot\vec{\nabla}n^+\right) + G^*{}_n - \frac{n^+}{\tau_n}$$

$$\mathbf{n}^+ = \mathbf{Q}_{in}$$

$$\mathbf{G}_n^+ = \mu_n\cdot\nabla\phi\cdot\frac{\partial \mathbf{E}}{\partial \mathbf{V}_i}$$

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

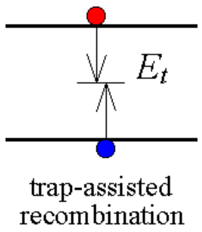
$$Q_S = q \cdot \int_0^d dx \cdot \Gamma(x) \left\{ \begin{array}{l} \displaystyle\int_x^d dy \cdot \frac{\partial F(y)}{\partial V_S} \cdot \exp\left[-\int_x^y dz \left(\frac{1}{v_p \cdot \tau_p} \right) \right] + \\ \displaystyle\int_0^x dy \cdot \frac{\partial F(y)}{\partial V_S} \cdot \exp\left[-\int_y^x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

Holes

Electrons

Drift lengths

Model for CCE degradation
Shockley-Read-Hall model



Basic assumption:

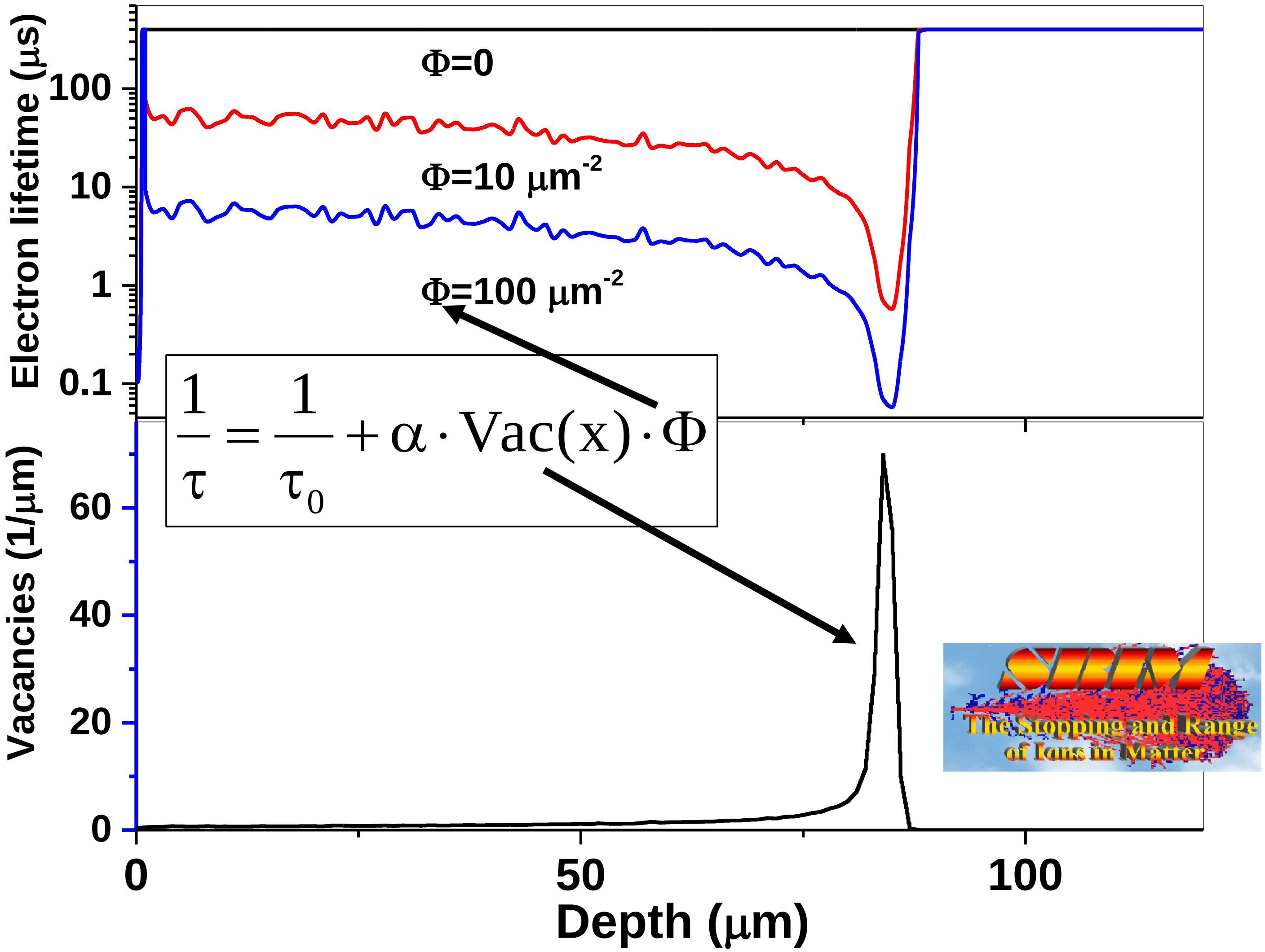
1) **In the linear regime, the ion induced damage affects mainly the carrier lifetime τ**
2) **The ion induced trap density is proportional to the VACANCY DENSITY**

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

Fluence

Capture coefficient

Vacancy Density Profile

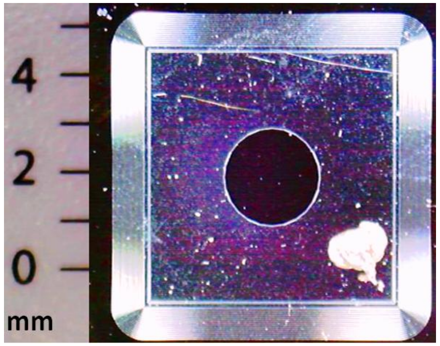


$$\frac{1}{\tau} = \frac{1}{\tau_0} + \alpha \cdot \mathrm{Vac}(x) \cdot \Phi$$

The experimental protocol

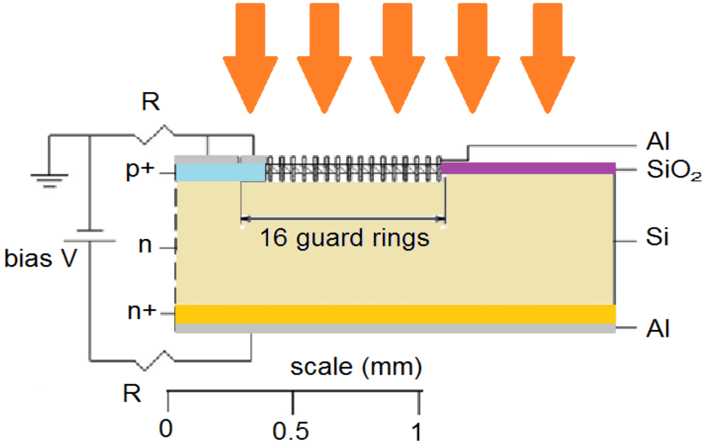
Samples under study

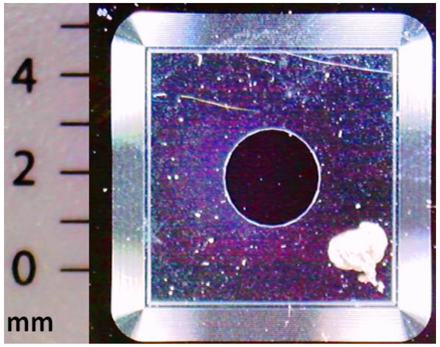
n- and p- type Fz p-i-n Si diodes
Fabricated by the Institute of Physics, University of Helsinki



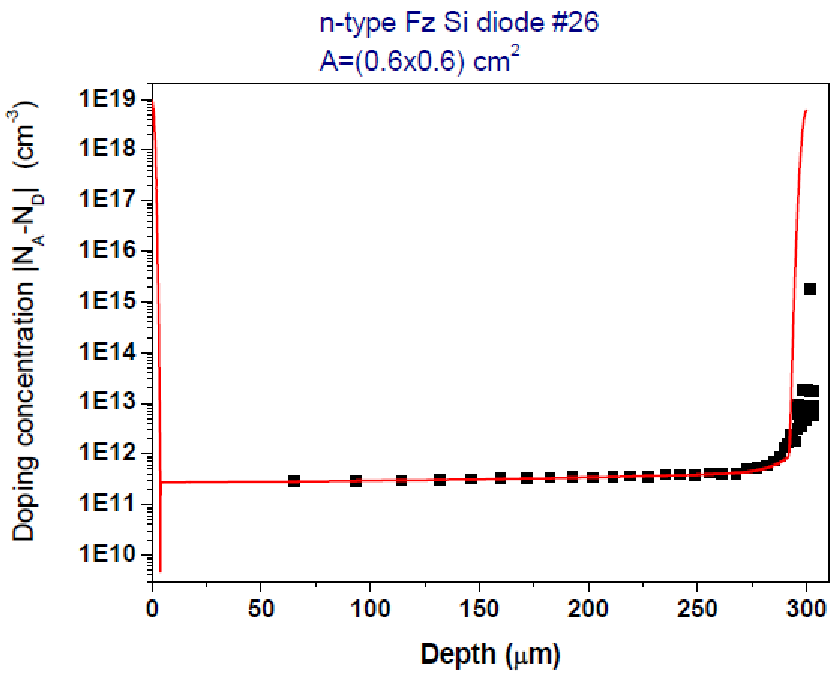
16 floating guard rings
The frontal electrode and the guard rings are coated with Al (0.5 μm]).
The Al electrode has a hole in the center, 1 mm diameter.
Different dimensions: 5 or 2.5 mm

MeV ions





C-V characteristics
Depletion width-voltage



Experimental protocol

- ✓ **Electrical characterization**
- ✓ **Electrostatic modeling**
- ✓ **IBIC map on pristine sample**
- ✓ **Irradiation of 9 regions at different fluences**
- ✓ **IBIC map of irradiated regions**

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Experimental protocol

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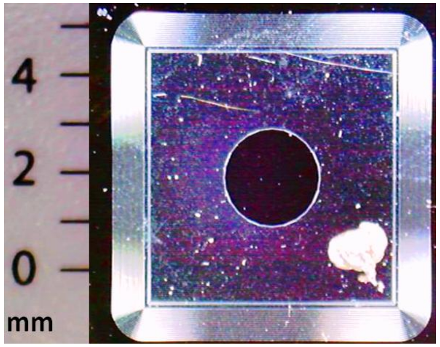
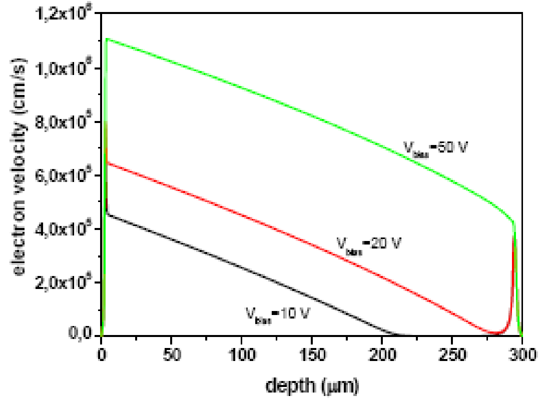
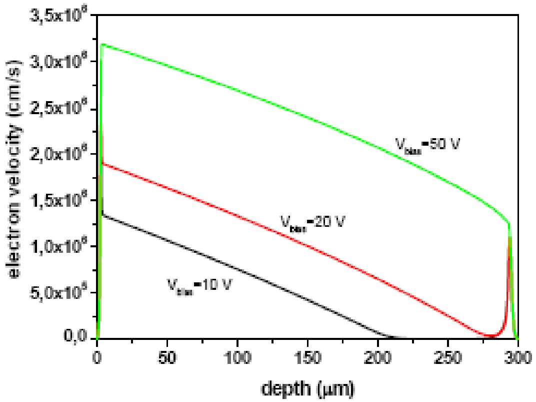


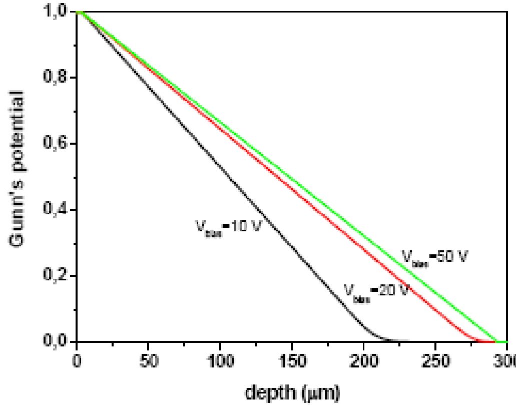
hole drift velocity profiles



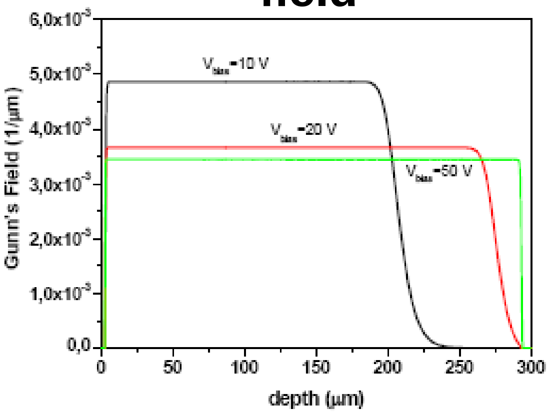


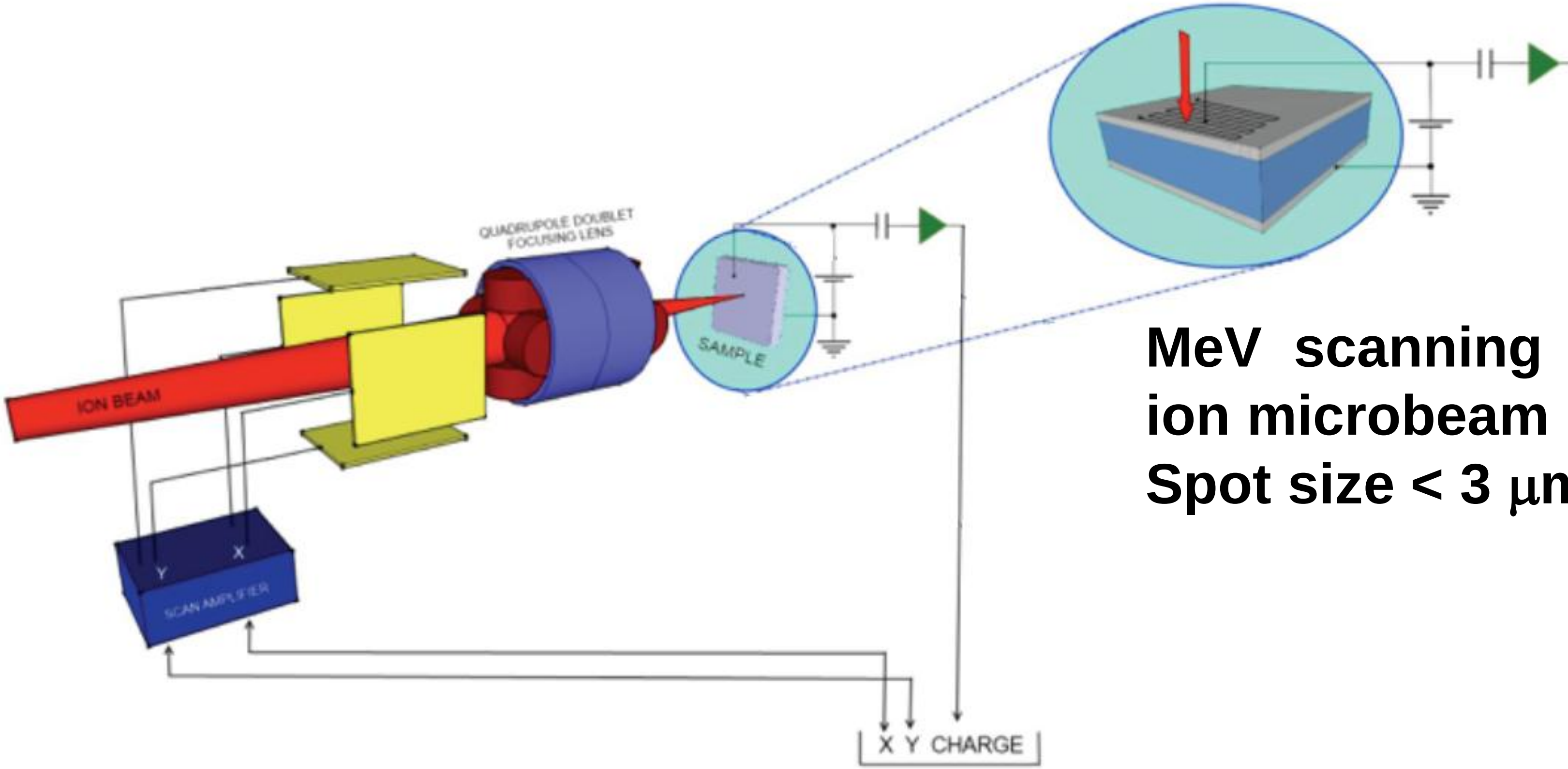
Electron drift velocity profiles

Gunn's weighting potential



Gunn's weighting field





MeV scanning ion microbeam
Spot size < 3 μm

PROBING THE PRISTINE SAMPLE

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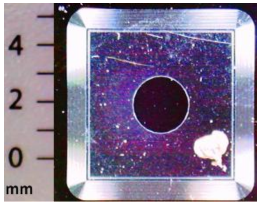
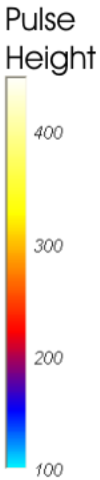
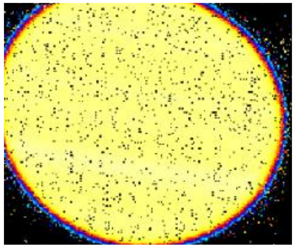
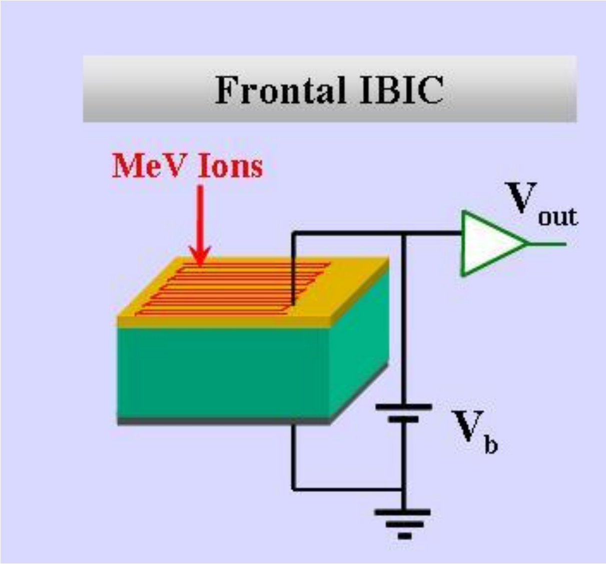
IBIC map on a pristine diode probed with a scanning 1.4 MeV He microbeam;







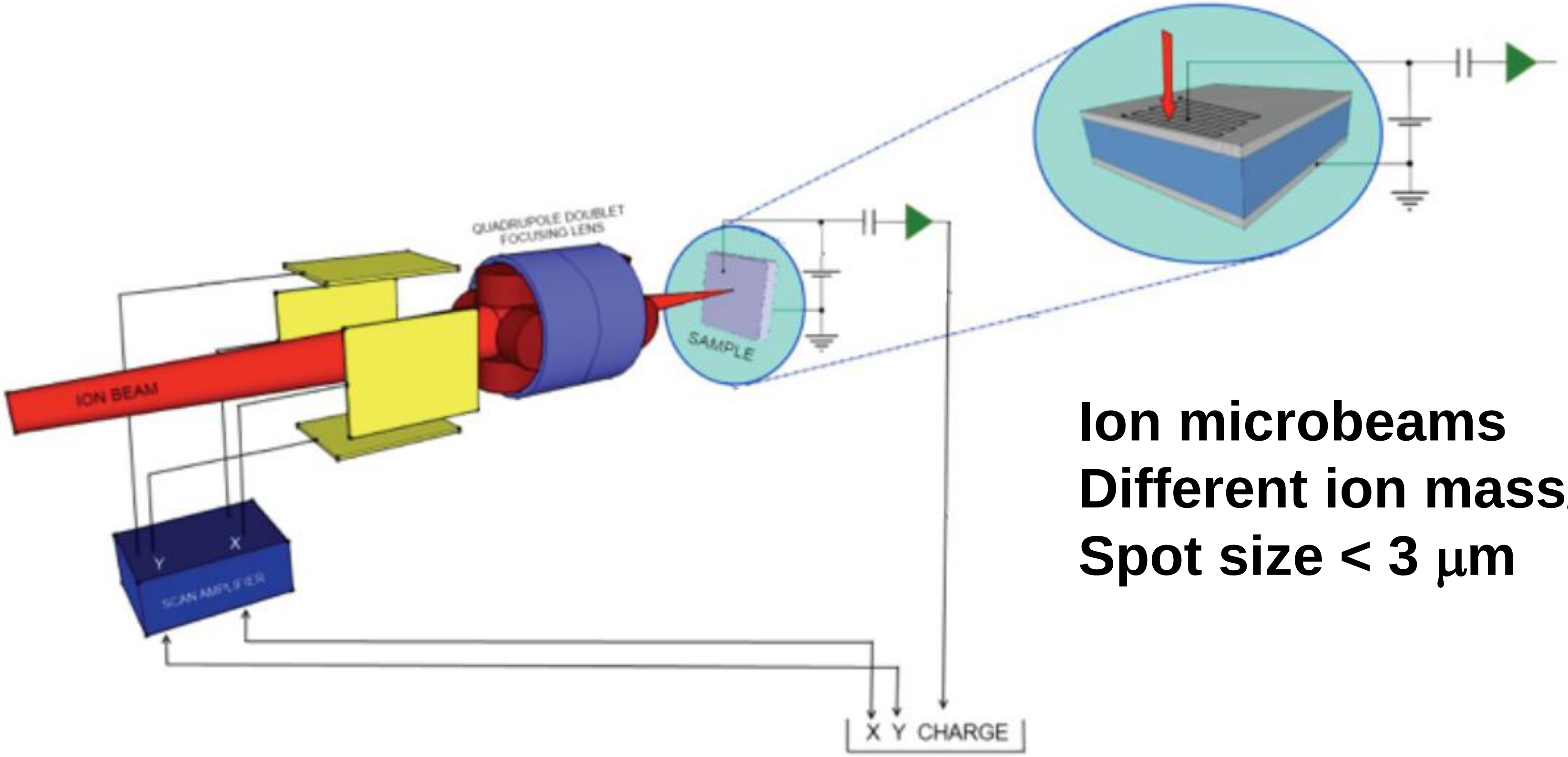
Uniform CCE map



Experimental protocol

- ✓ **Electrical characterization**
- ✓ **Electrostatic modeling**
- ✓ **IBIC map on pristine sample**
- ✓ **Irradiation of 9 regions at different fluences**
- ✓ **IBIC map of irradiated regions**

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 μm²

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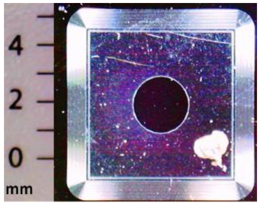
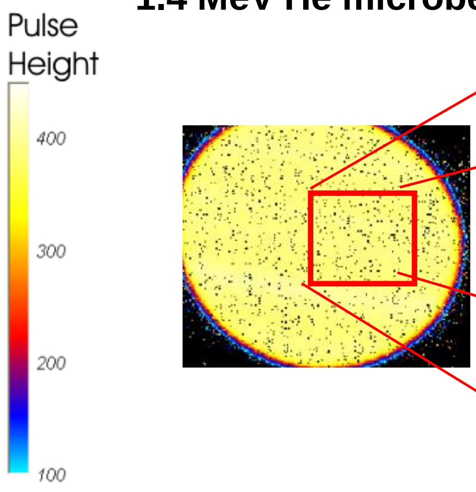
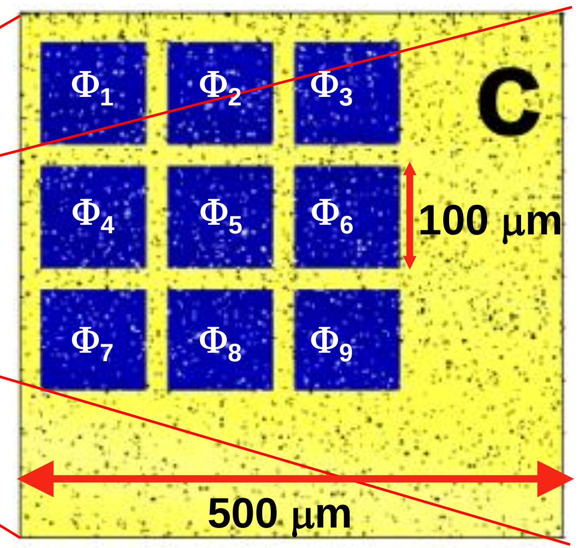


IBIC map on a pristine diode probed with a scanning 1.4 MeV He microbeam;



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



Experimental protocol

- ✓ Electrical characterization
- ✓ Electrostatic modeling
- ✓ IBIC map on pristine sample
- ✓ Irradiation of 9 regions at different fluences
- ✓ IBIC map of irradiated regions

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

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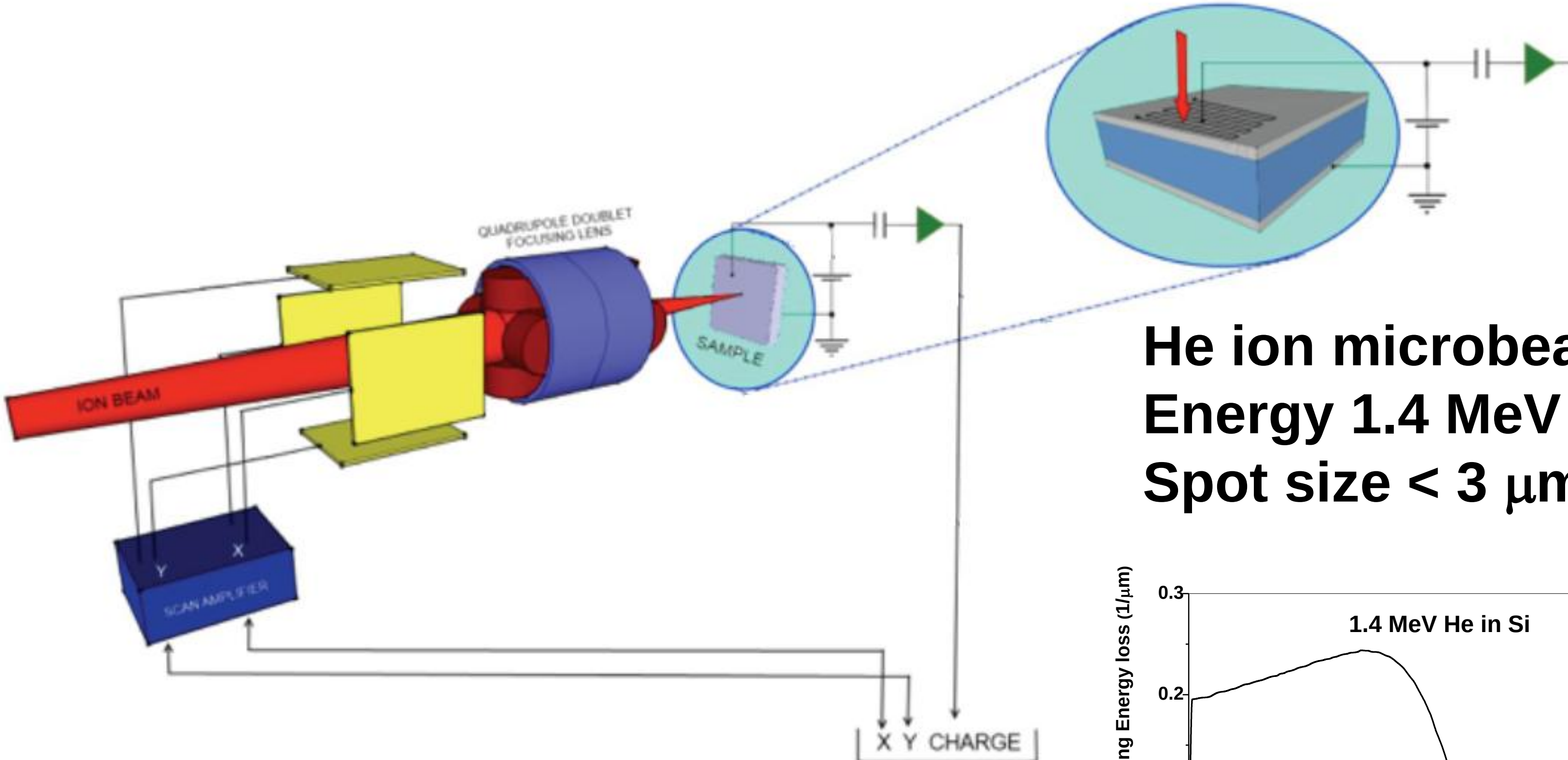
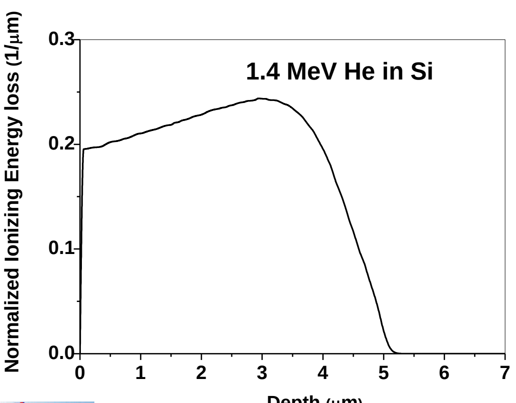


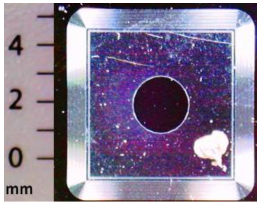
He ion microbeam
Energy 1.4 MeV
Spot size < 3 μm

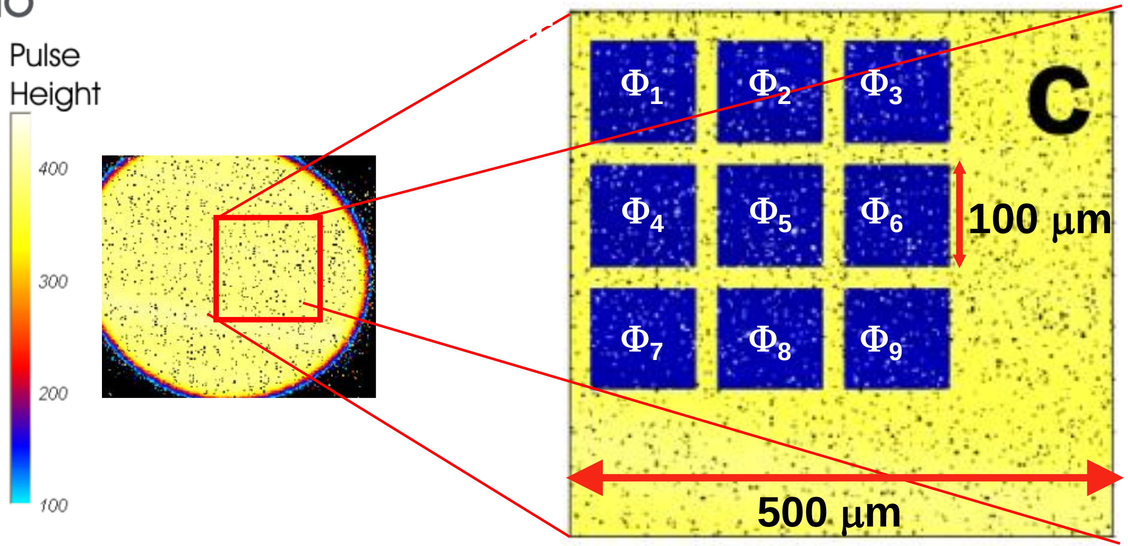


Data from SRIM

PROBING DAMAGED AREAS

SRIM The Stopping and Range of Ions in Matter





Experimental protocol

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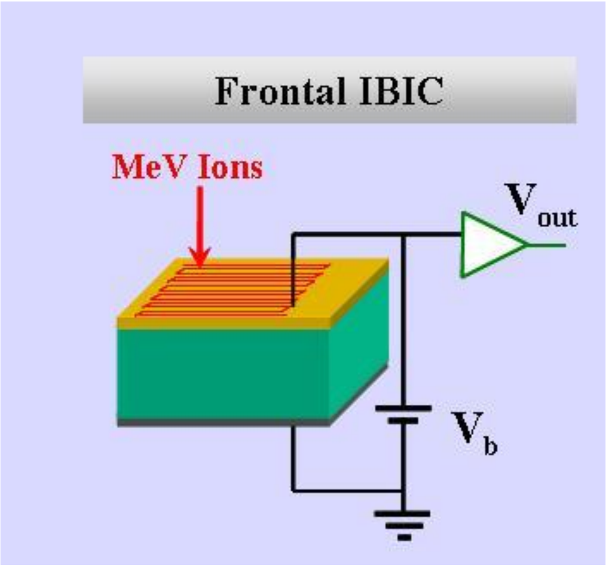
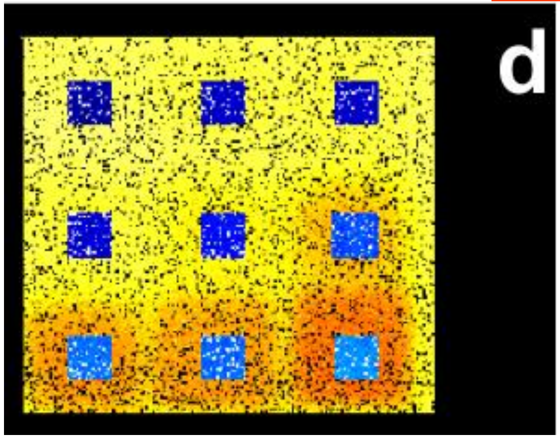
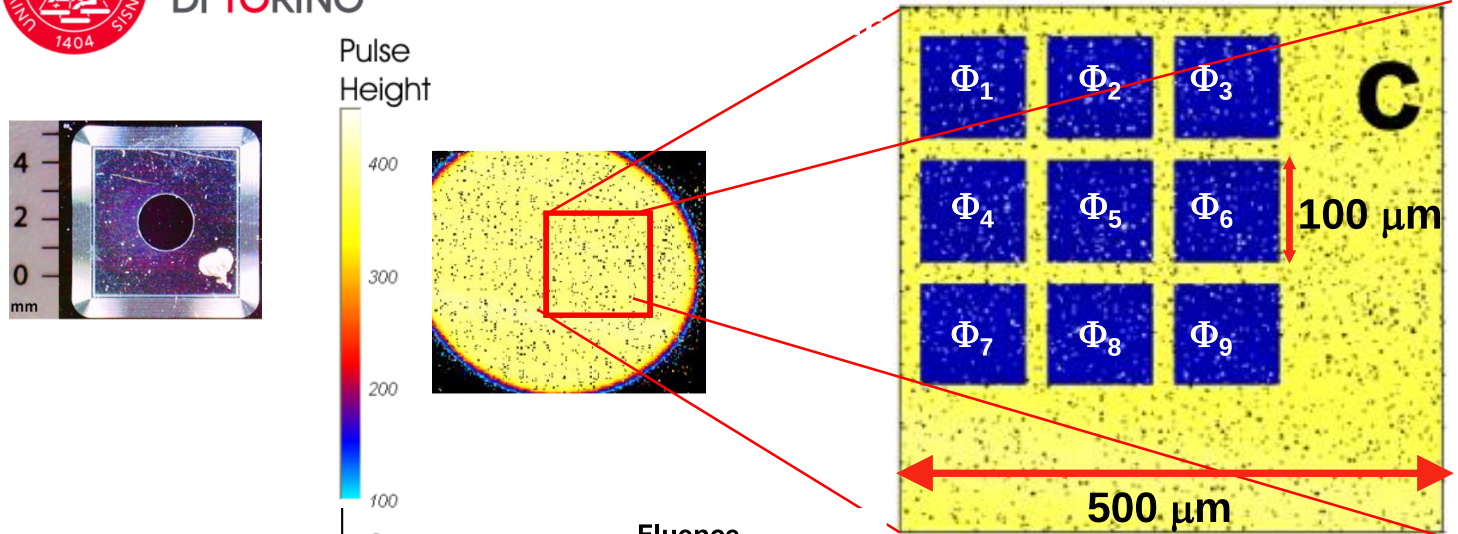


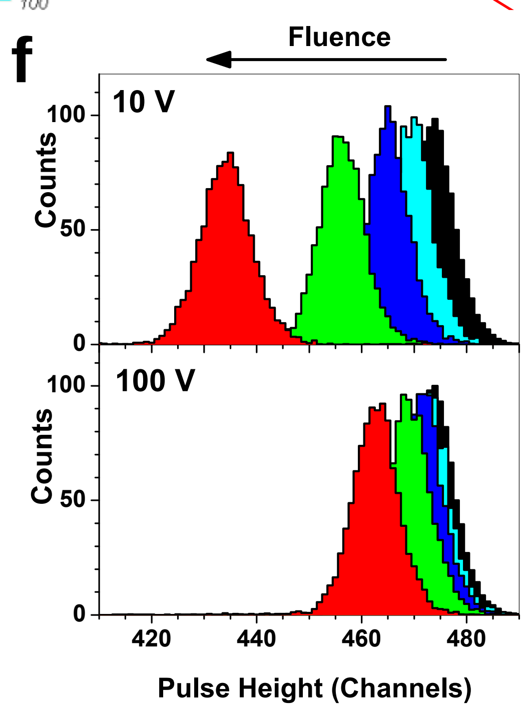


a measured 2D distribution of the IBIC signal amplitude after irradiation

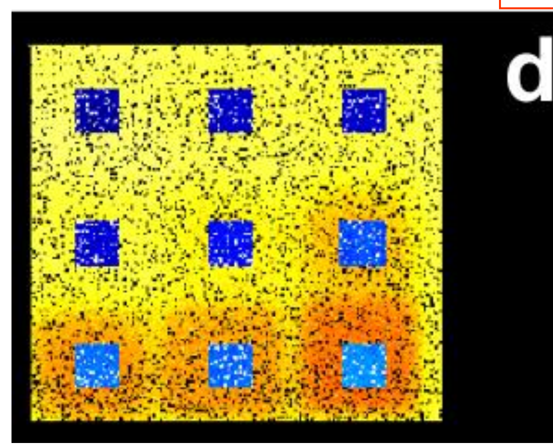
Experimental protocol

- ✓ Electrical characterization
- ✓ Electrostatic modeling
- ✓ IBIC map on pristine sample
- ✓ Irradiation of 9 regions at different fluences
- ✓ IBIC map of irradiated regions



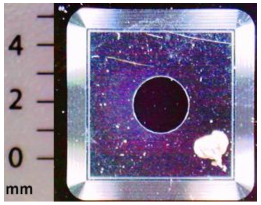


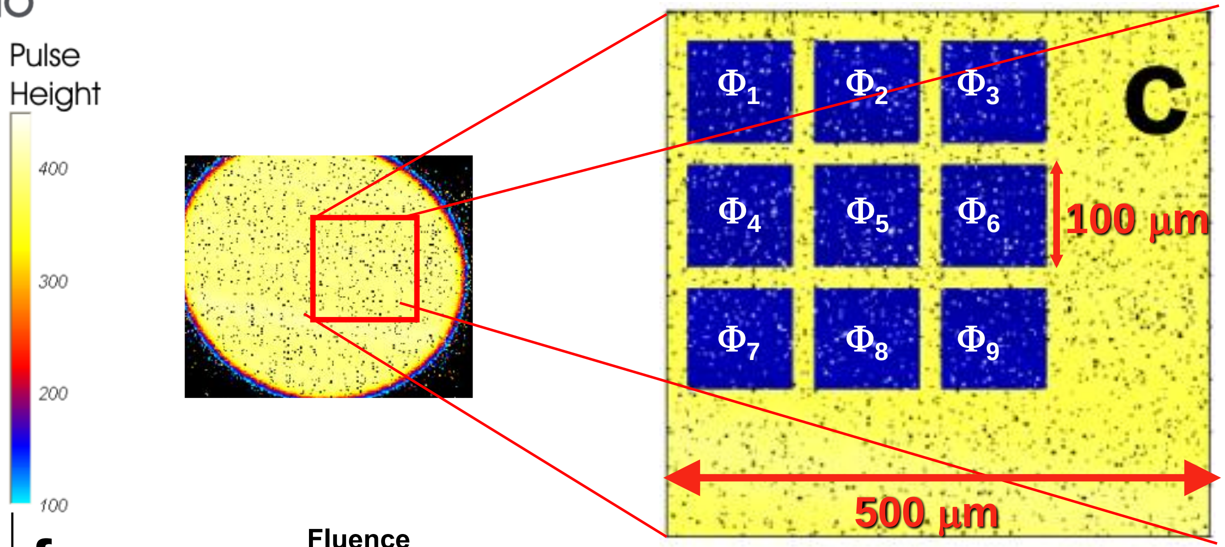
IBIC spectra (bias voltage = 10 V and 100 V) from the central regions of four of the areas shown in Fig. c

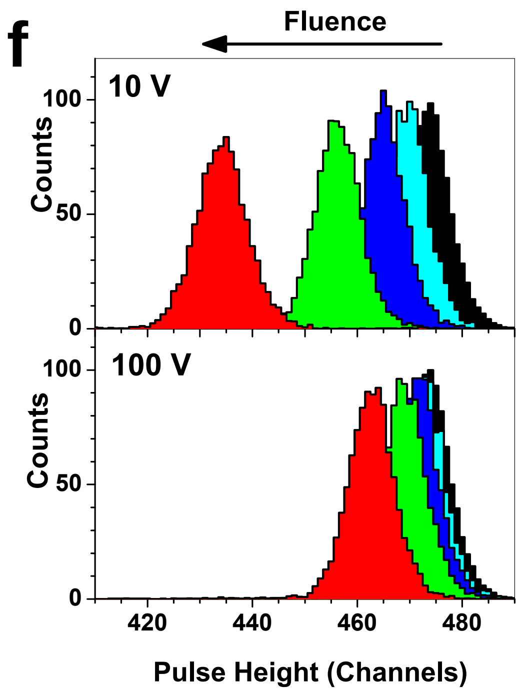


a measured 2D distribution of the IBIC signal amplitude after irradiation

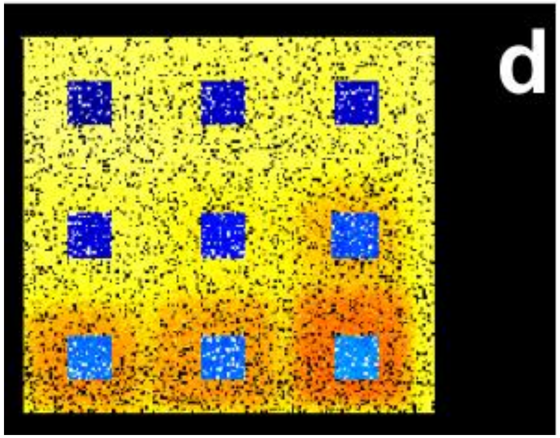
Z. Pastuovic et al., IEEE Trans on Nucl. Sc. 56 (2009) 2457; APL (98) 092101 (2011)





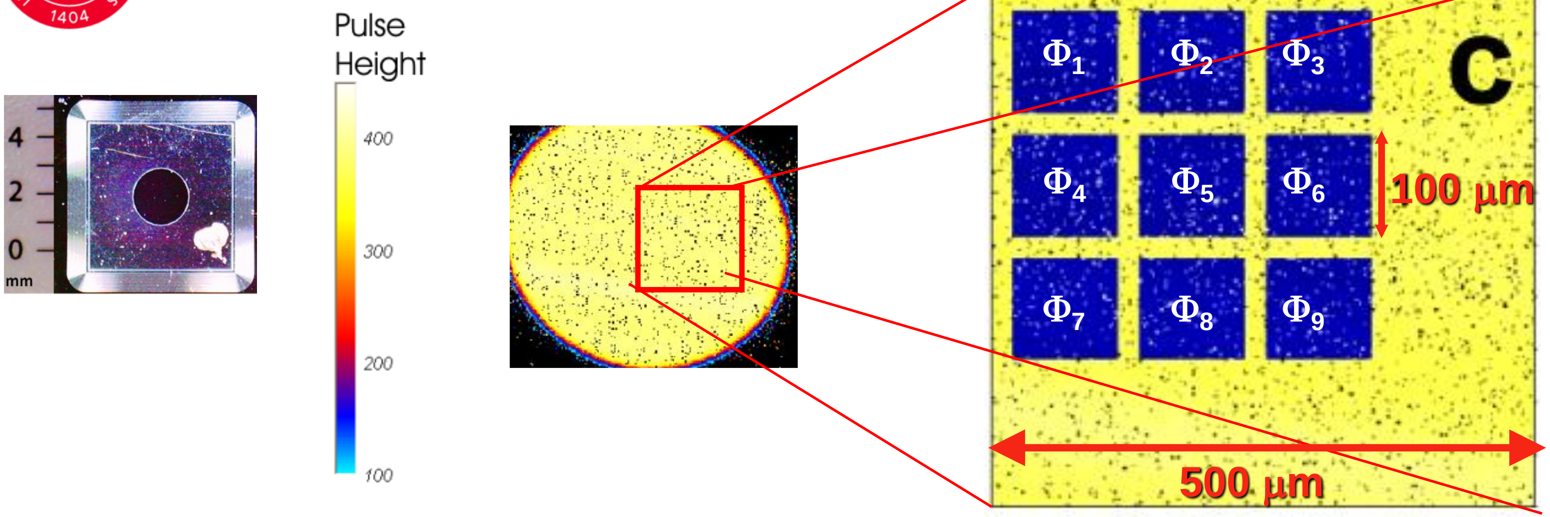


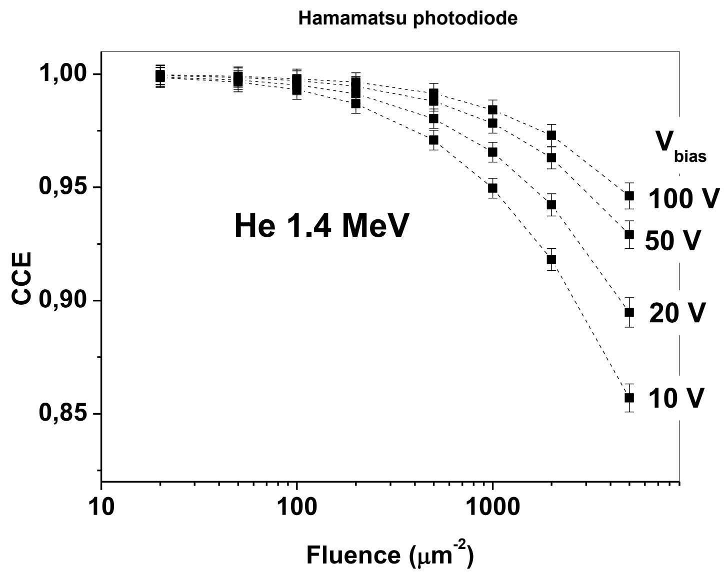
IBIC spectra (bias voltage = 10 V and 100 V) from the central regions of four of the areas shown in Fig. c

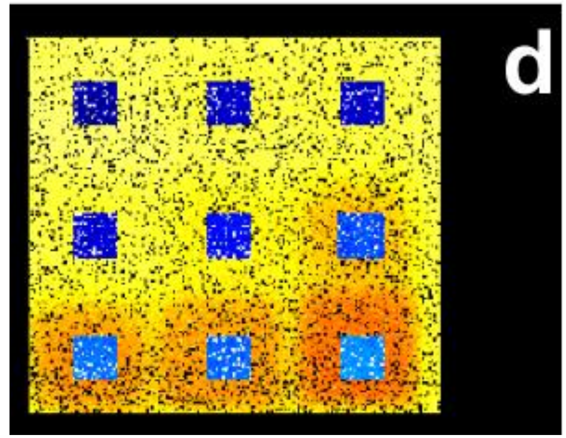


a measured 2D distribution of the IBIC signal amplitude after irradiation

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



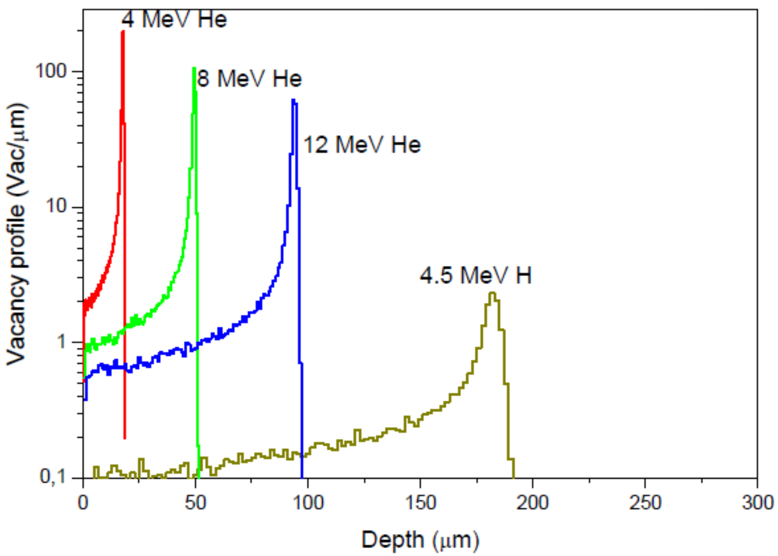




a measured 2D distribution of the IBIC signal amplitude after irradiation

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

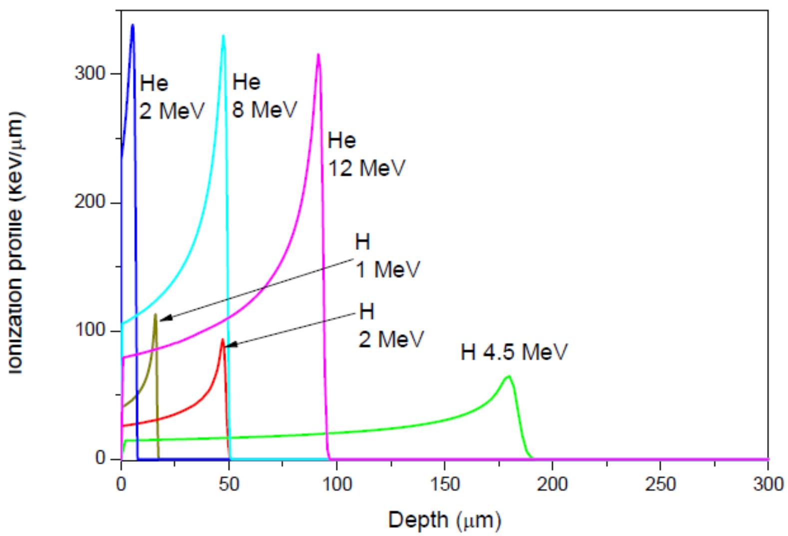
DIB: Vacancy profiles



PIB = 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		

PIB: Ionization profiles



Different bias voltages

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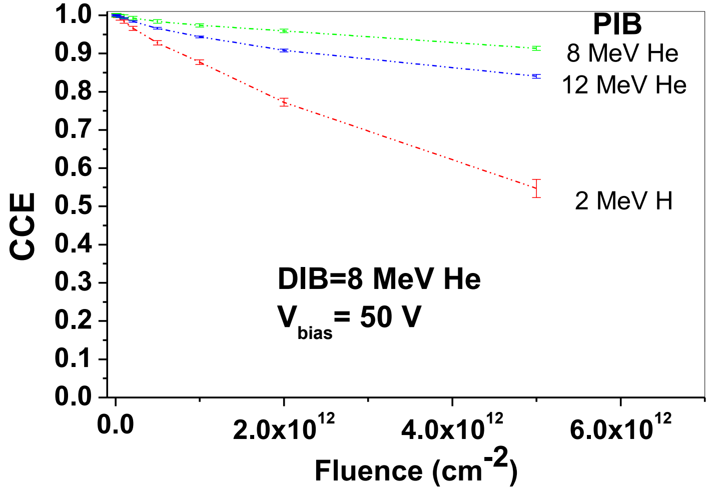
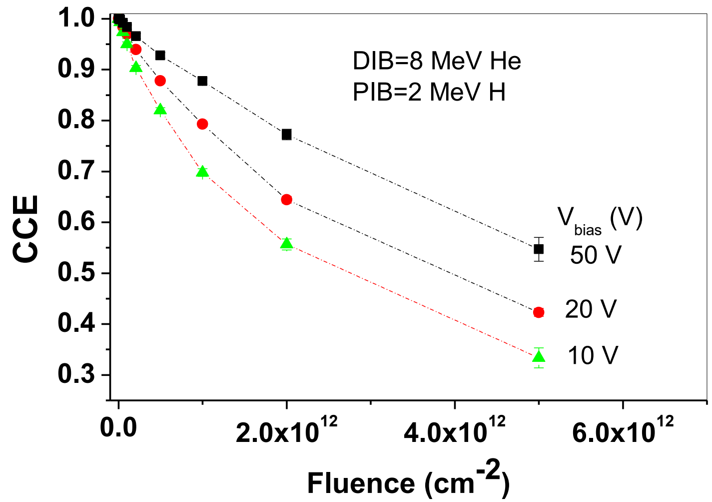
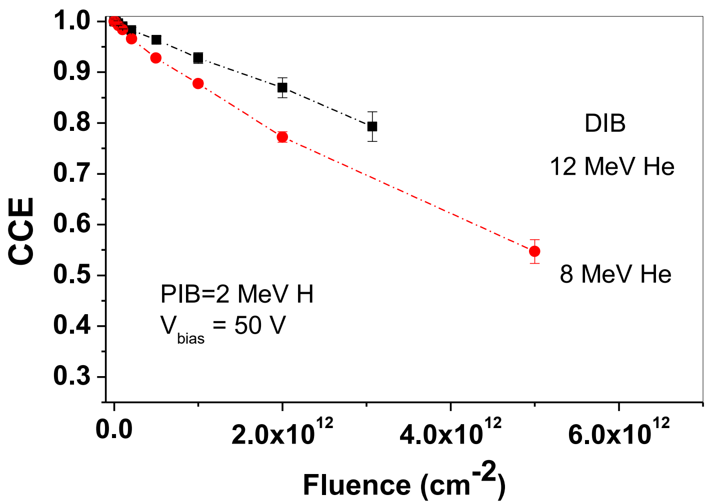


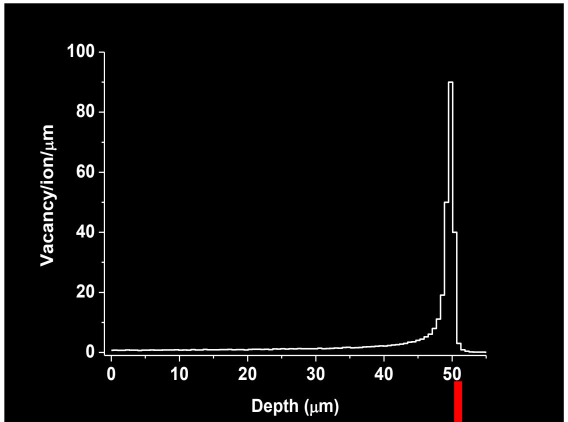
Fixed DIB
Fixed V_{bias}
Variable PIBs

Fixed DIB
Fixed PIB
Variable V_{bias}

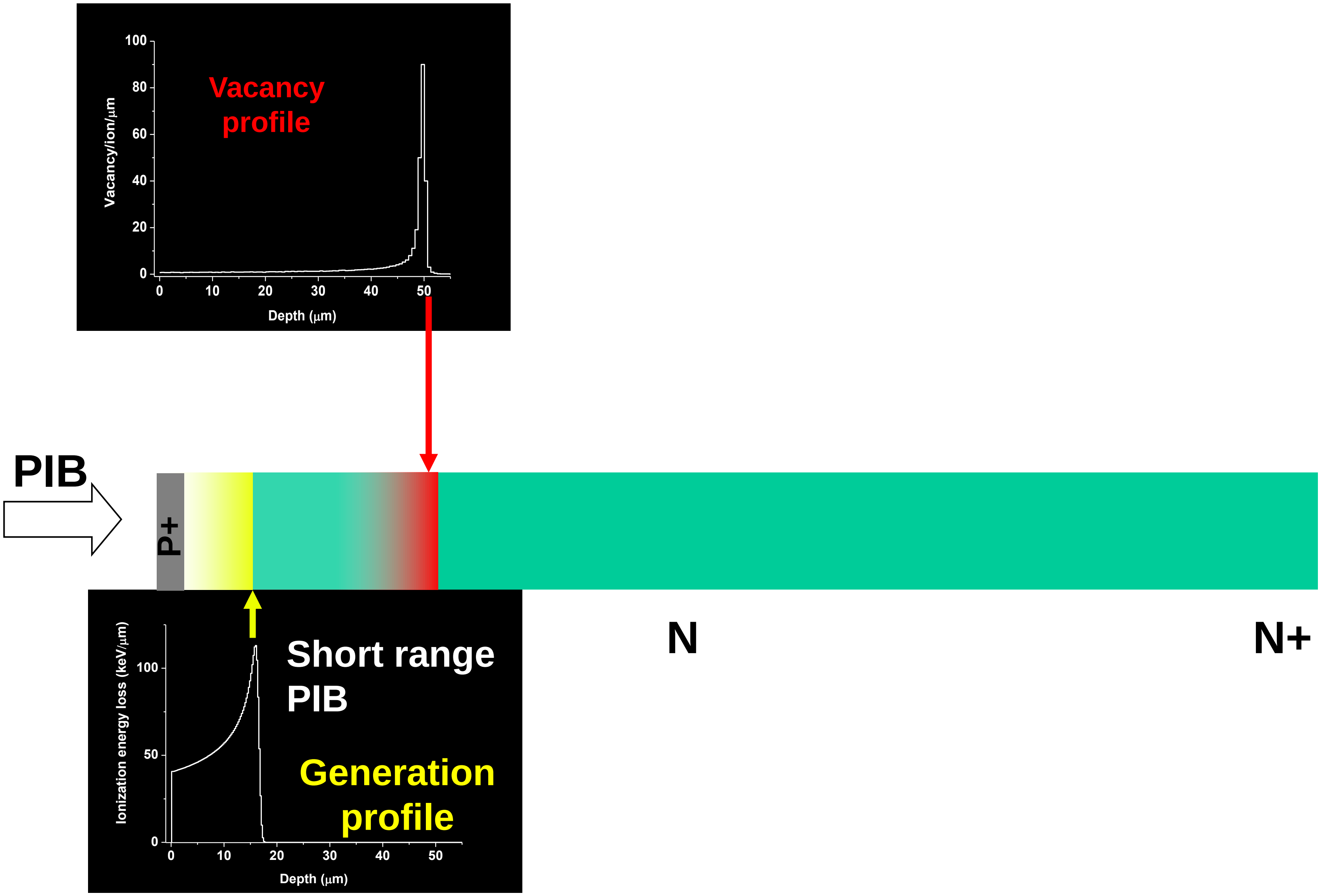
Variable DIB
Fixed PIB
FIXED V_{bias}



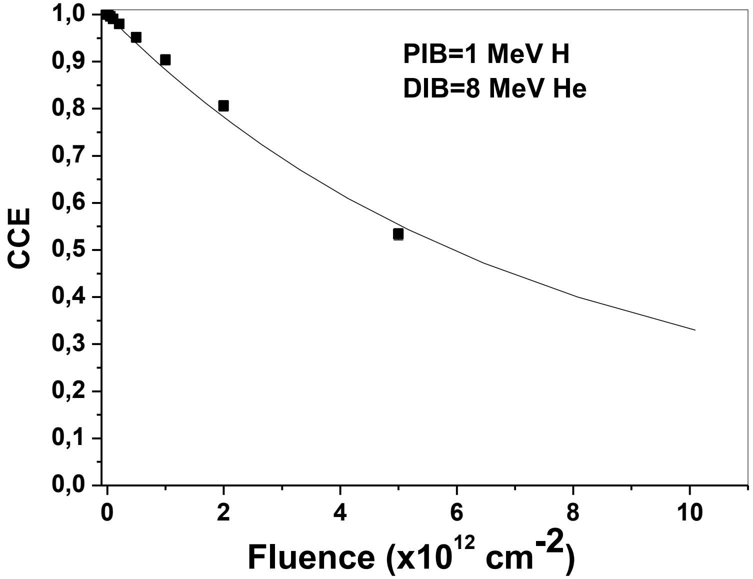


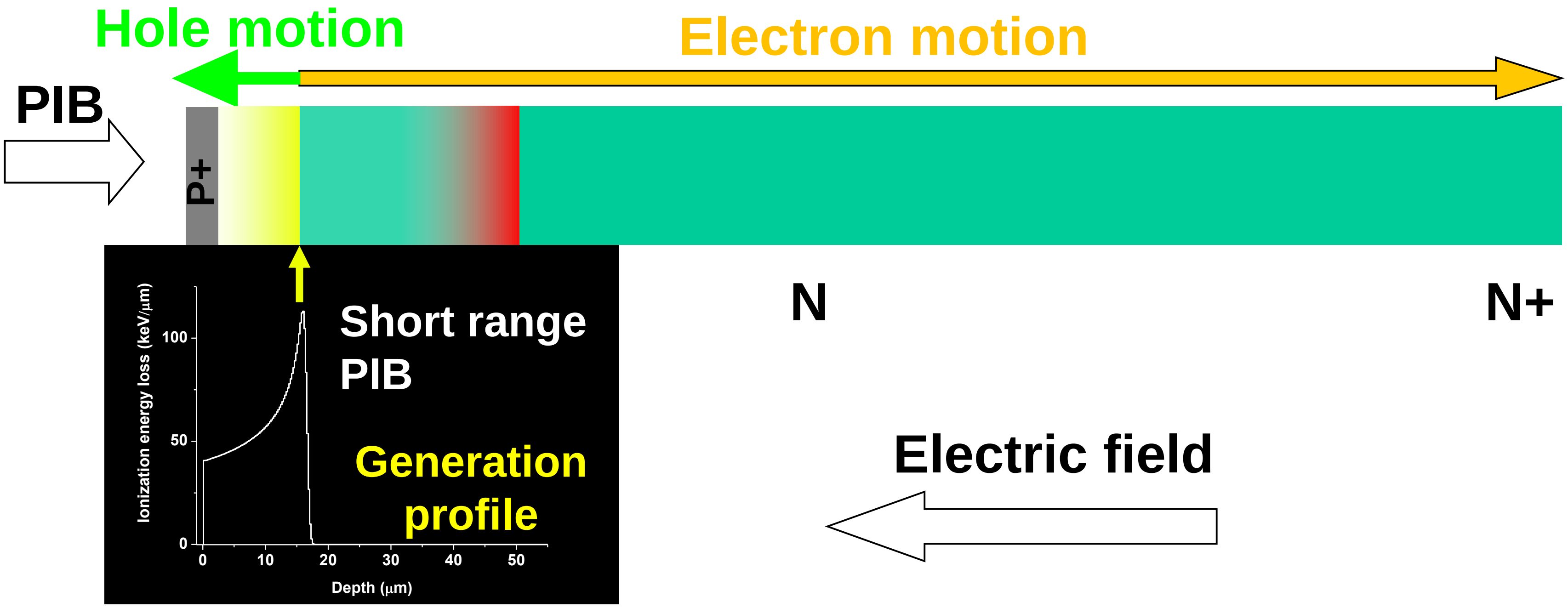

Vacancy/ion/μm
100
80
60
40
20
0
0
10
20
30
40
50
Depth (μm)

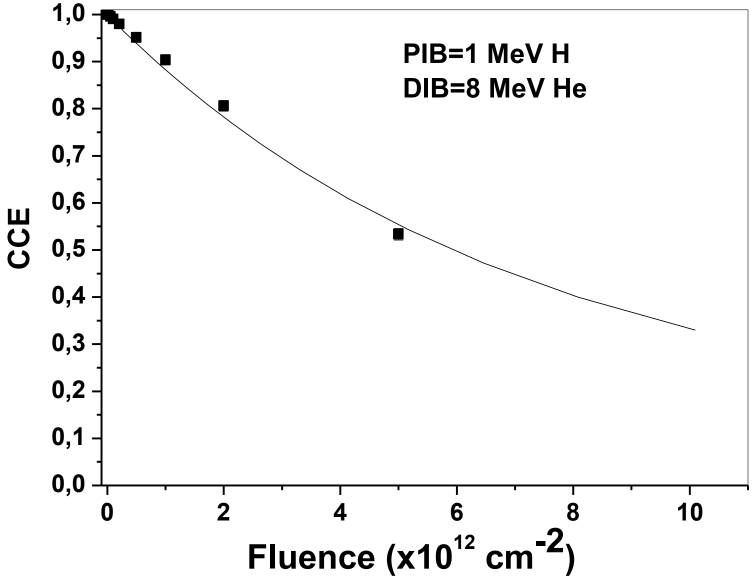

DIB
P+
N
N+

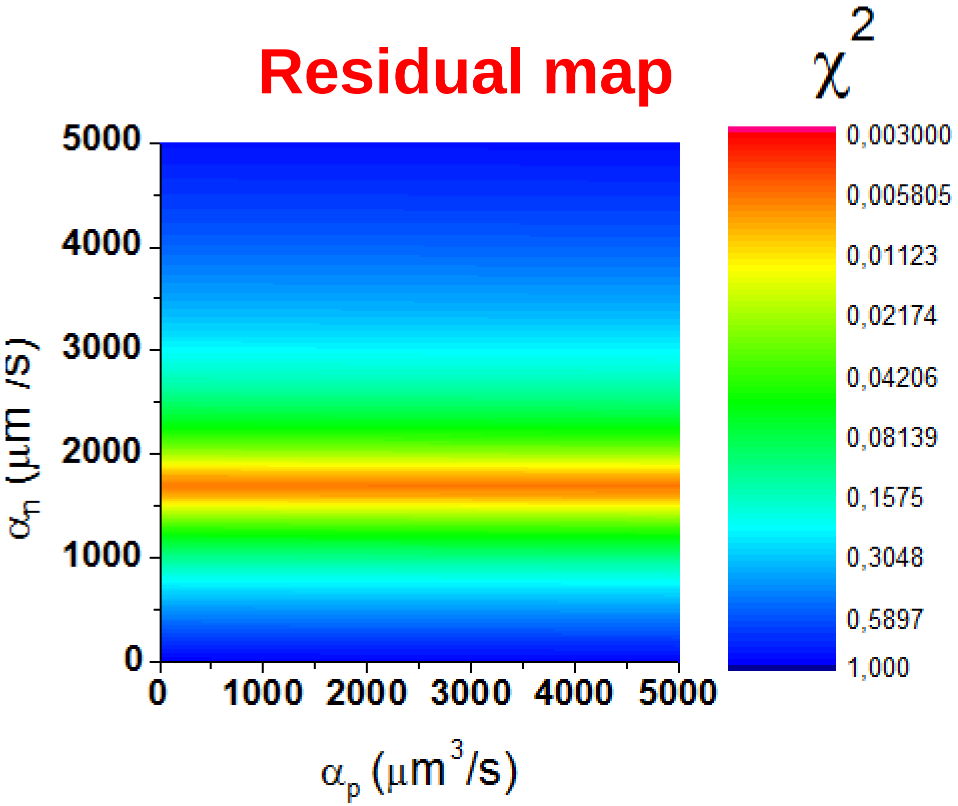


Vacancy/ion/μm
100
80
60
40
20
0
0
10
20
30
40
50
Depth (μm)
Vacancy profile
PIB
P+
N
N+
Ionization energy loss (keV/μm)
100
50
0
0
10
20
30
40
50
Depth (μm)
Short range PIB
Generation profile


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+
Short range PIB
Generation profile
Ionization energy loss (keV/μm)
100
50
0
0
10
20
30
40
50
Depth (μm)
Electric field

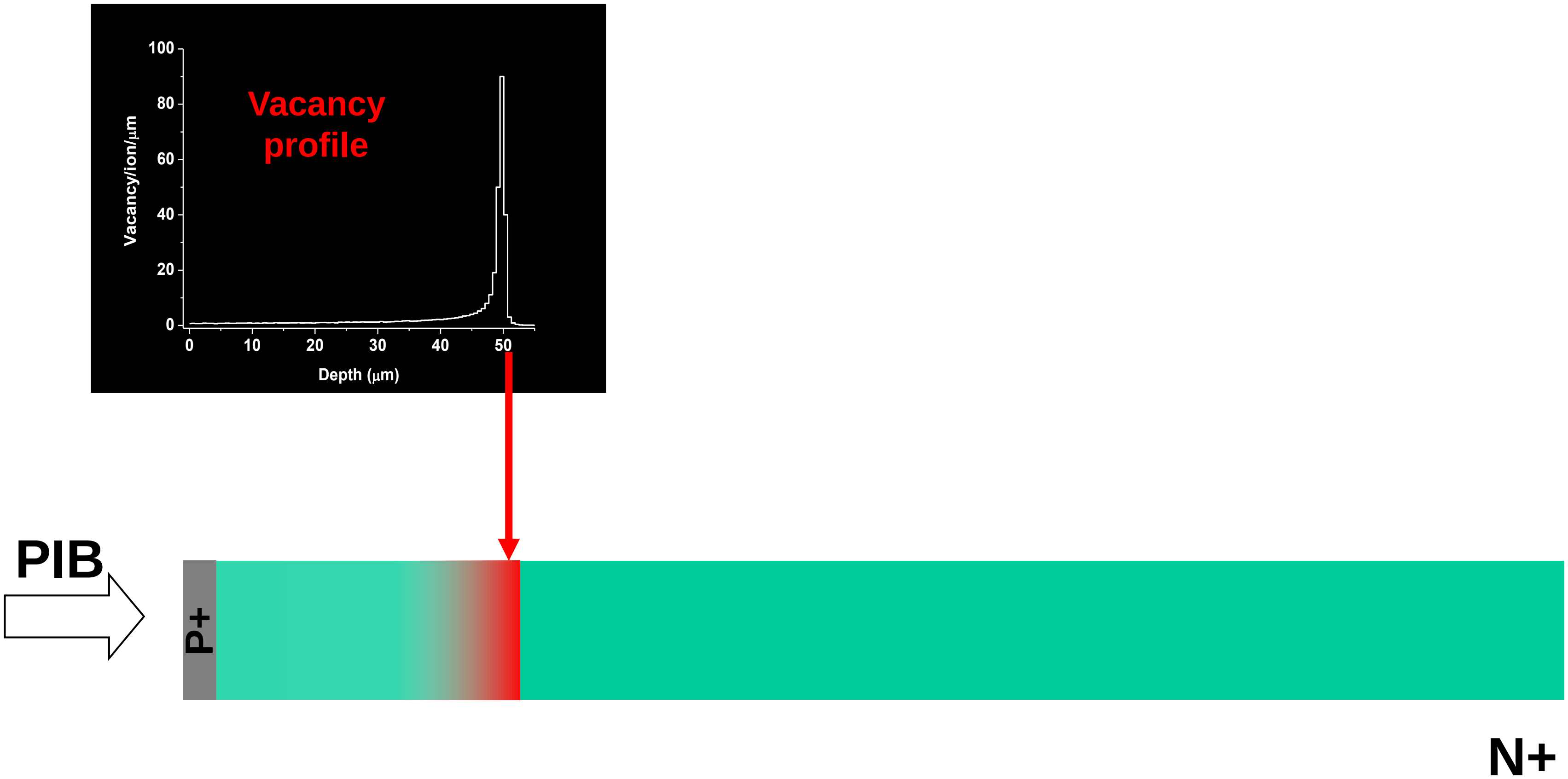


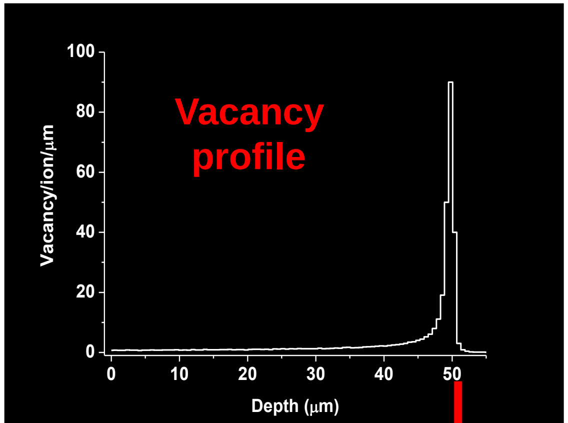


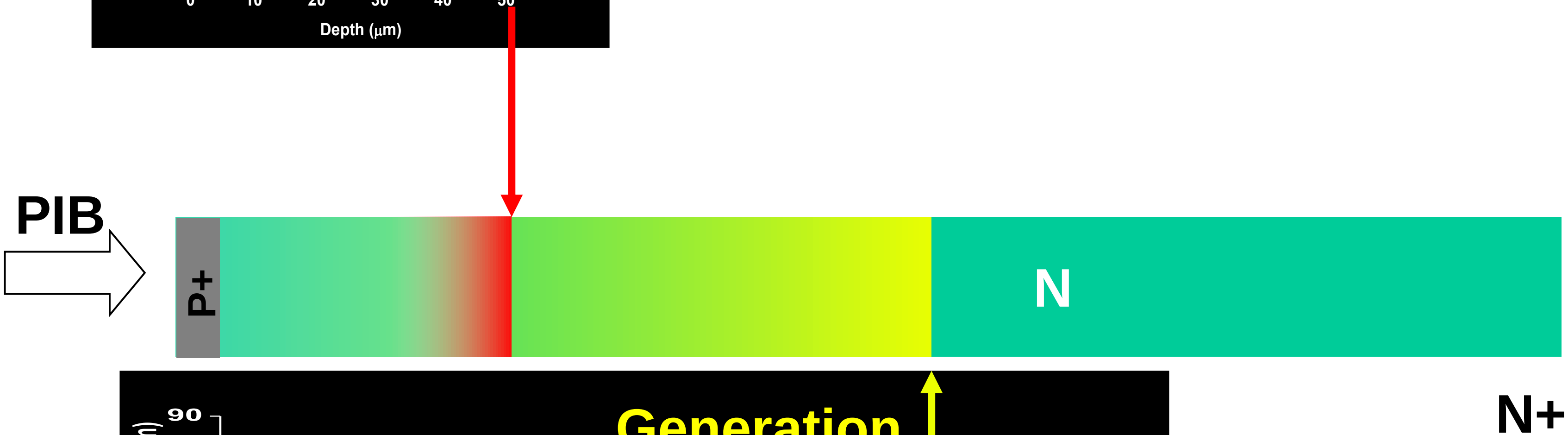
$$\frac{1}{\tau} = \frac{1}{\tau_0} + \alpha \cdot \mathrm{Vac}(x) \cdot \Phi$$

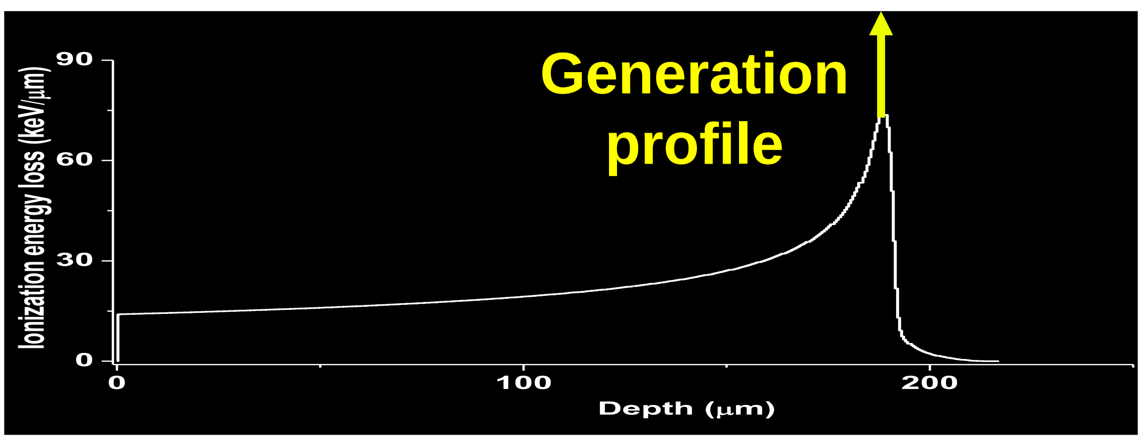
α_n Free parameter

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

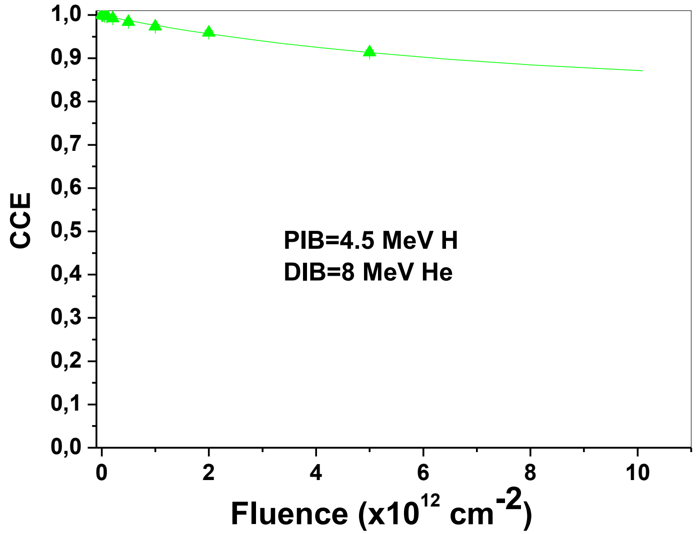

100
80
60
40
20
0
Vacancy/ion/µm
Vacancy profile
0
10
20
30
40
50
Depth (µm)
PIB
P+
N+

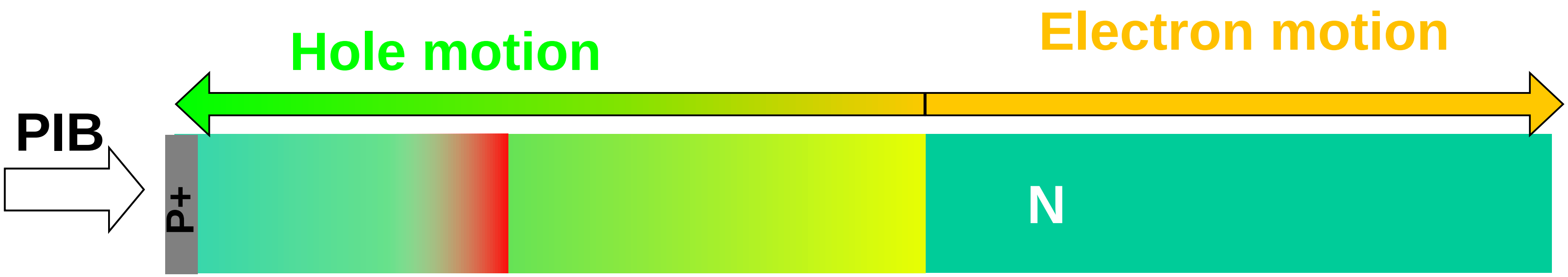


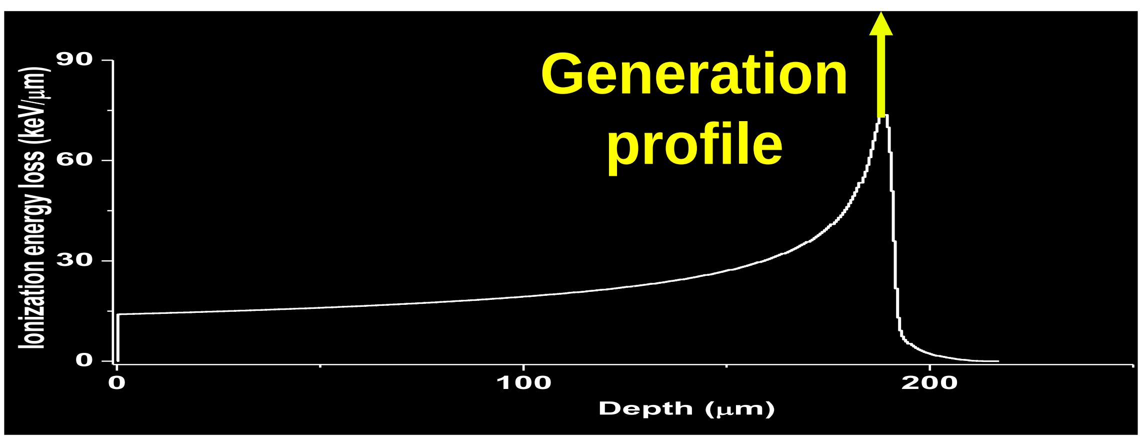




Long range PIB

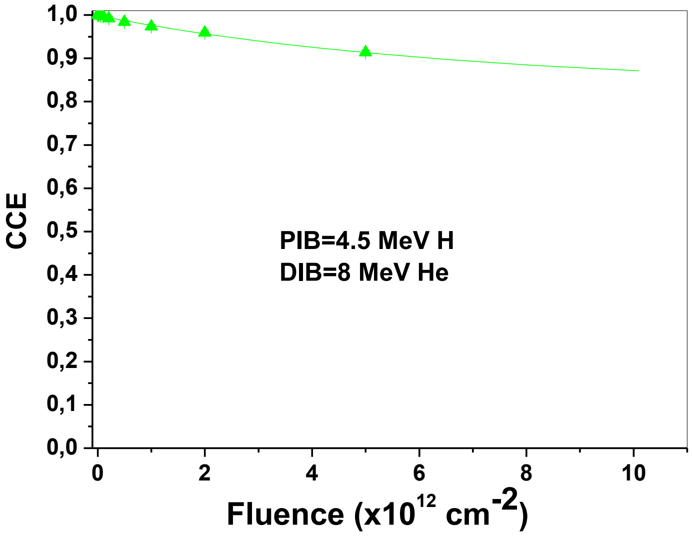


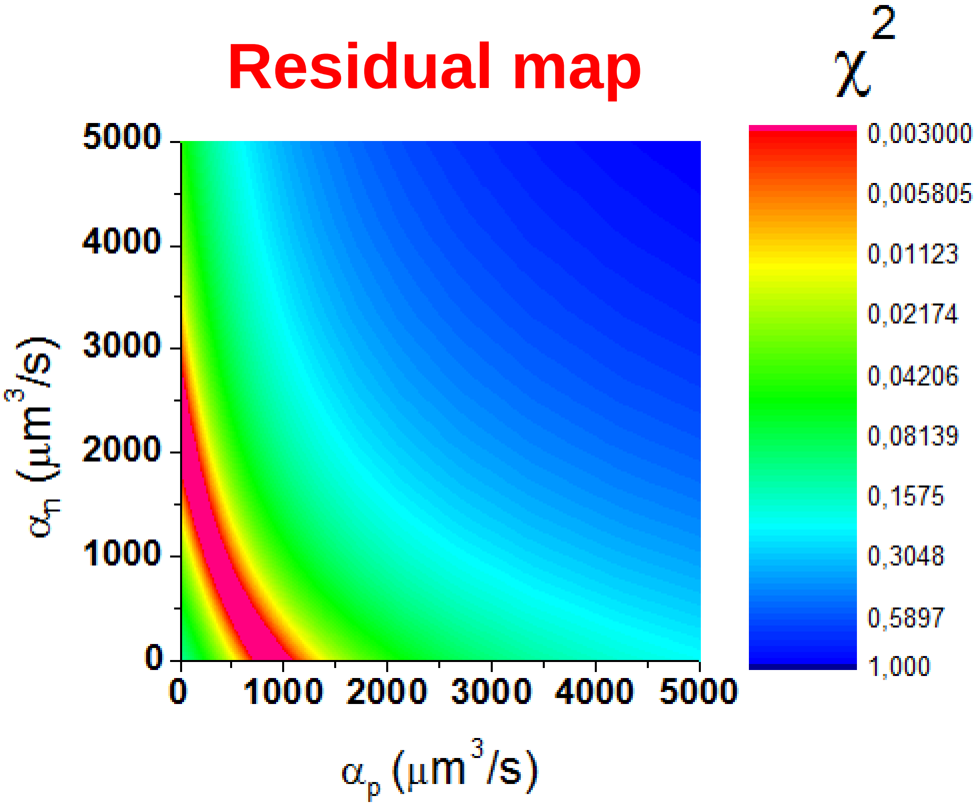




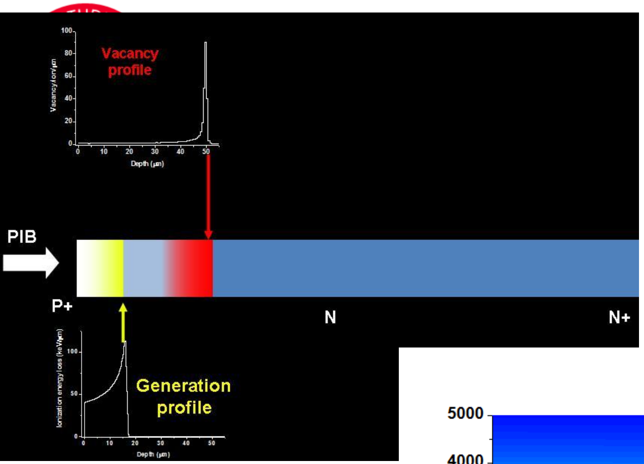
N+

Long range PIB

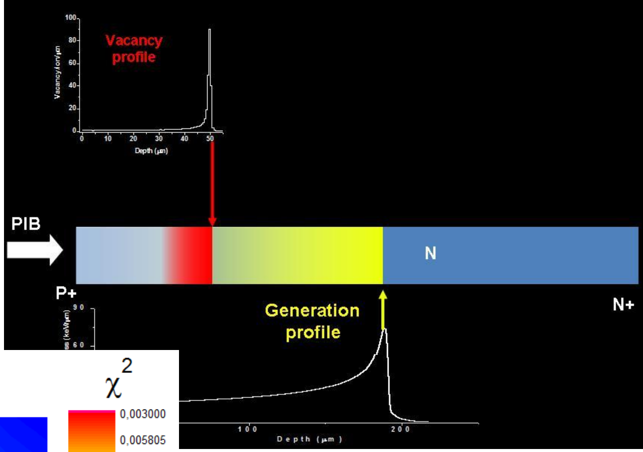


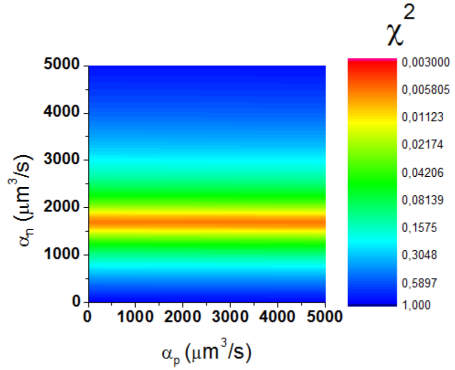


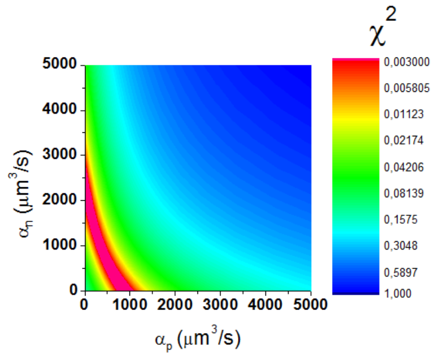
$$Q_S = q \cdot \int_0^d dx \cdot \Gamma(x) \left\{ \begin{array}{l} \displaystyle\int_0^x dy \cdot \frac{\partial F(y)}{\partial V_S} \cdot \exp\left[-\int_y^x dz \frac{1}{v_p} \cdot \left(\frac{1}{\tau_0} + \alpha_p \cdot Vac(x) \cdot \Phi \right) \right] + \\ \displaystyle\int_x^d dy \cdot \frac{\partial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



Short range PIB

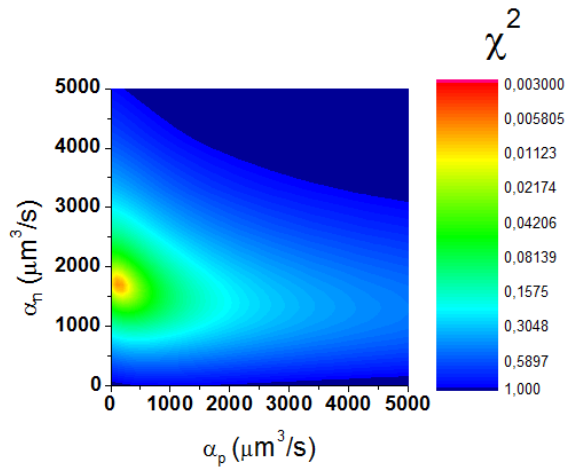






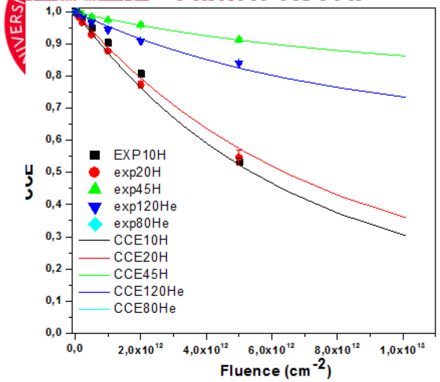
Long range PIB

Bias Voltage = 50 V

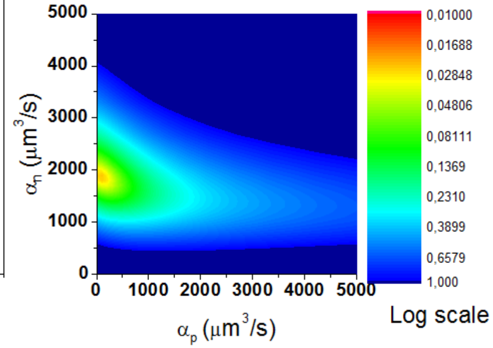


α_n=1700 $\mu m^3/s$

α_p=130 $\mu m^3/s$

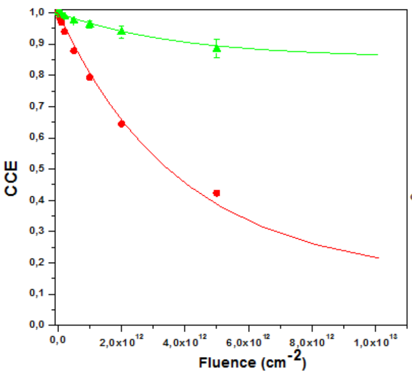


Bias Voltage = 50 V

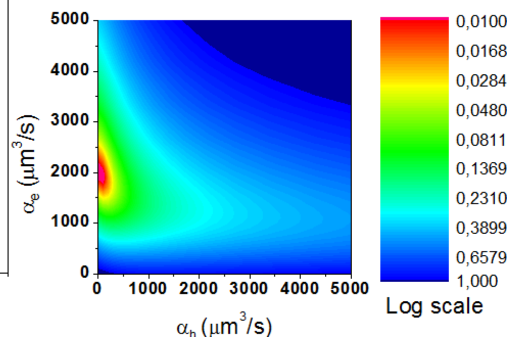


n-type Fz silicon diode

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

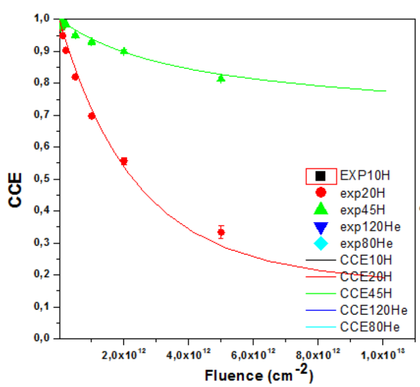


Bias Voltage = 20 V

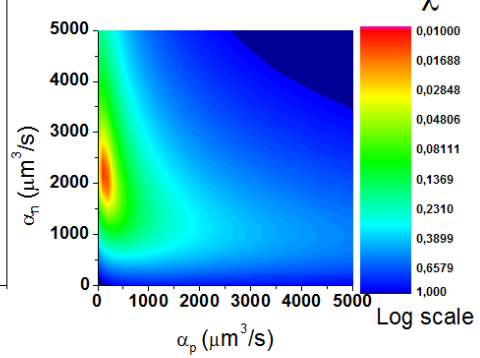


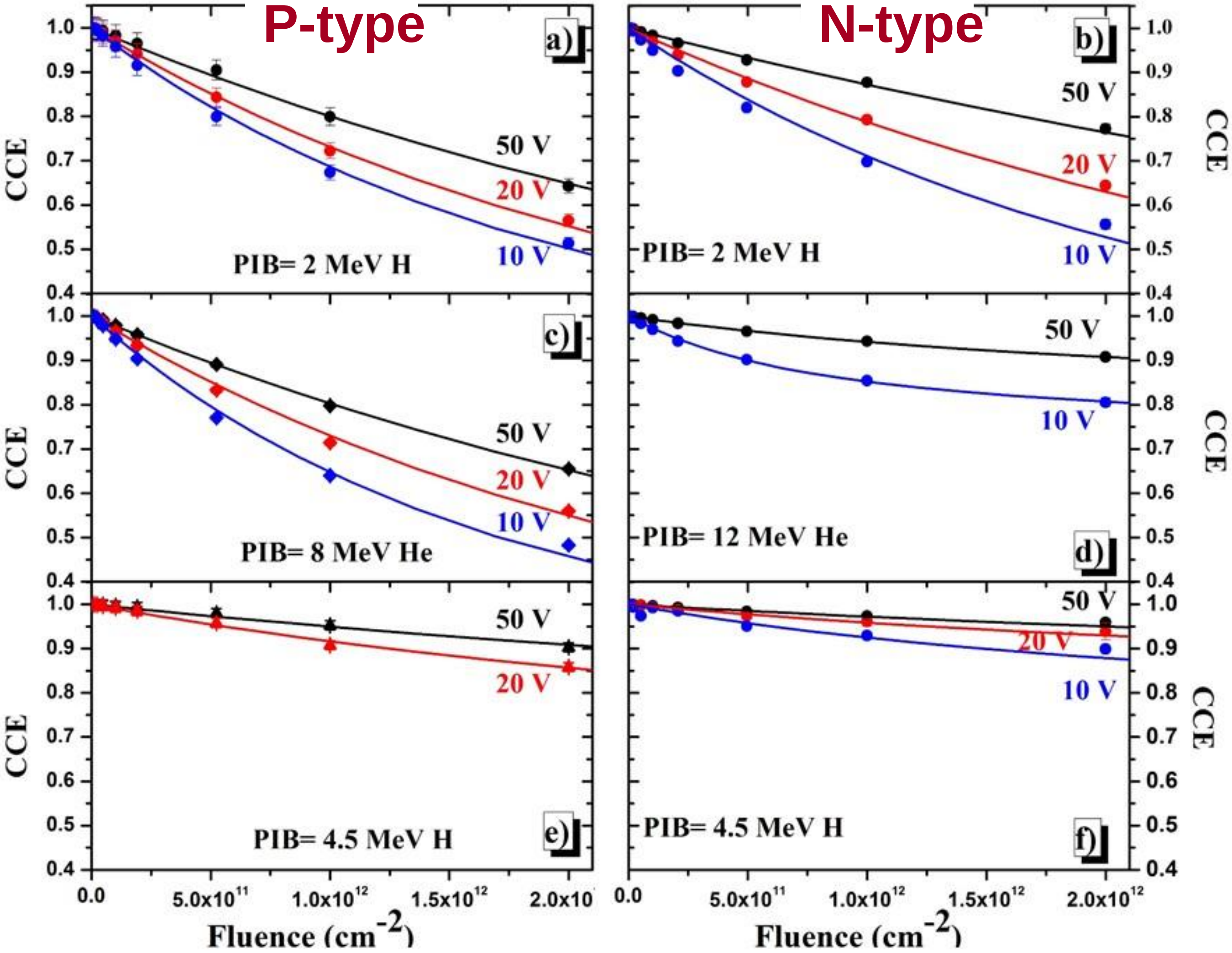
CAPTURE COEFFICIENTS

α_n = (2500±300) $\mu m^3/s$
α_p = (210±160) $\mu m^3/s$



Bias Voltage = 10 V

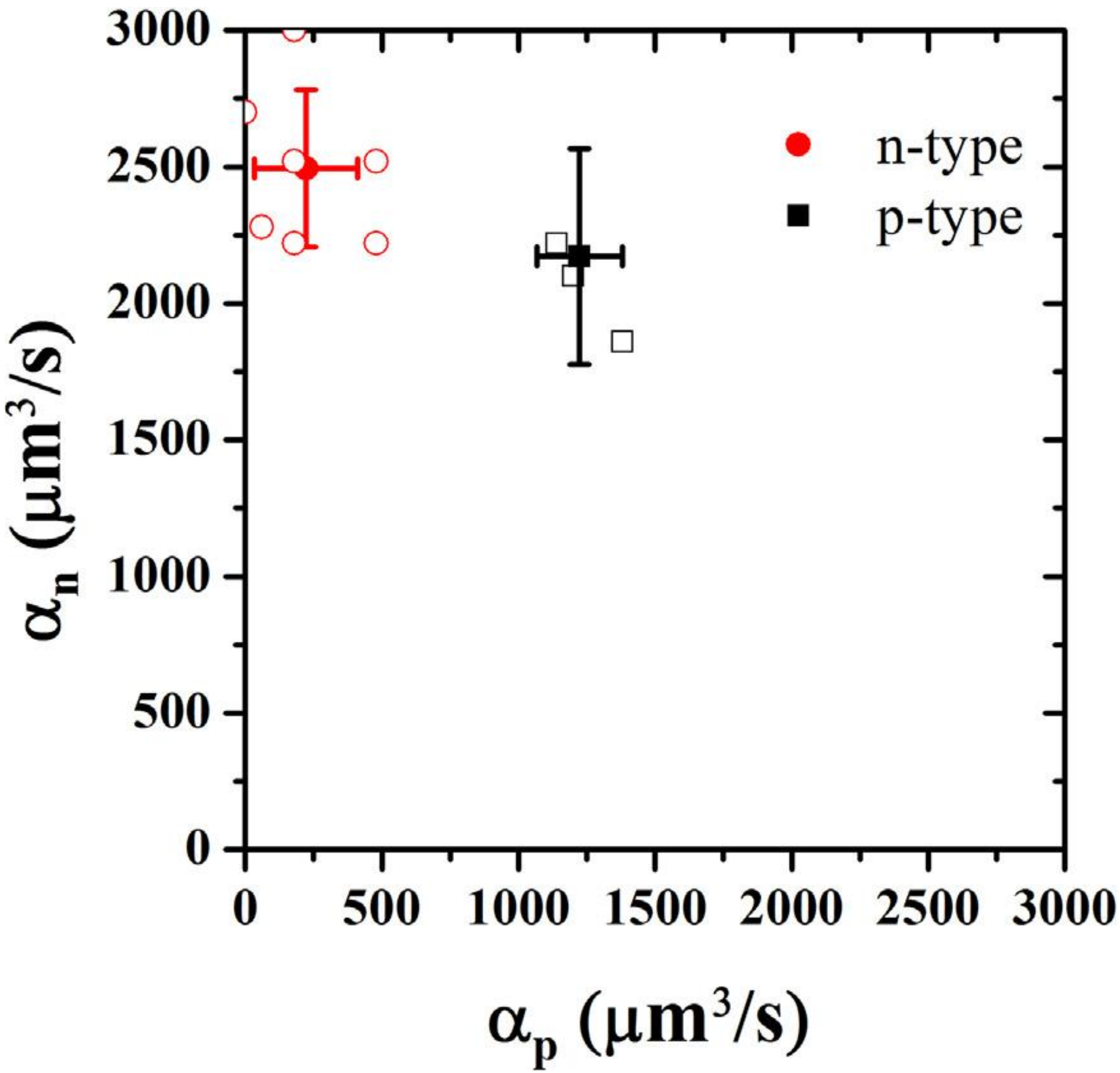




n-type Fz silicon diode

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

Fz silicon diode
Capture coefficient



n-type

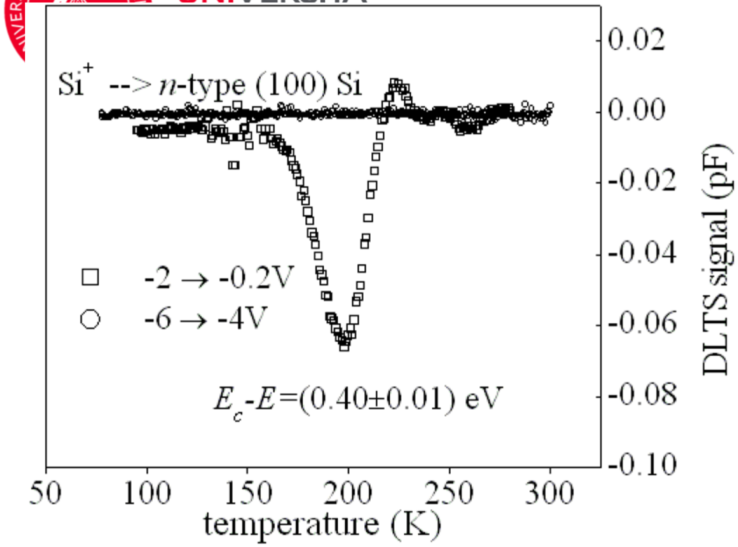
α_n = (2500±300) $\mu m^3/s$

α_p = (210±160) $\mu m^3/s$

p-type

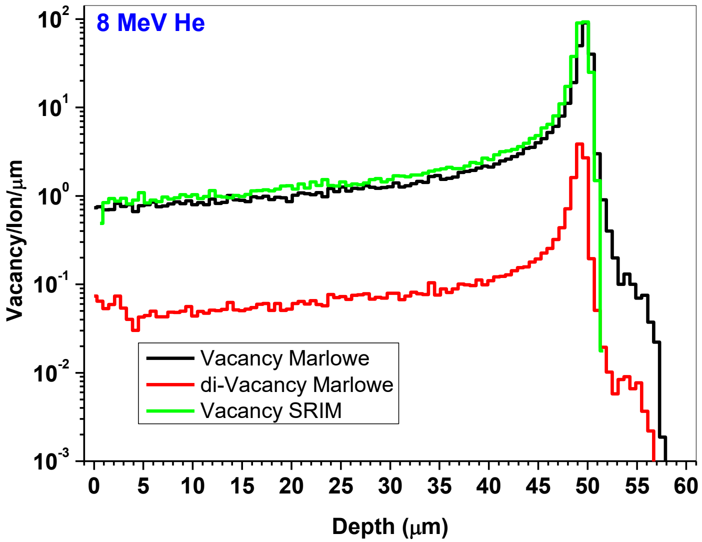
α_n = (1310± 90) $\mu m^3/s$

α_p = (2200±300) $\mu m^3/s$



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

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



From MARLOWE simulation

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

C. R. Crowell,
Appl. Phys. 9, 79-81, 1976
Vth= 1.8 ·10^7 m/s

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

$$\sigma_n \approx (3.6\pm0.4)\cdot 10^{-15}\ \mathrm{cm}^2$$

Solution of the adjoint equations

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

For very low level of radiation

⇓

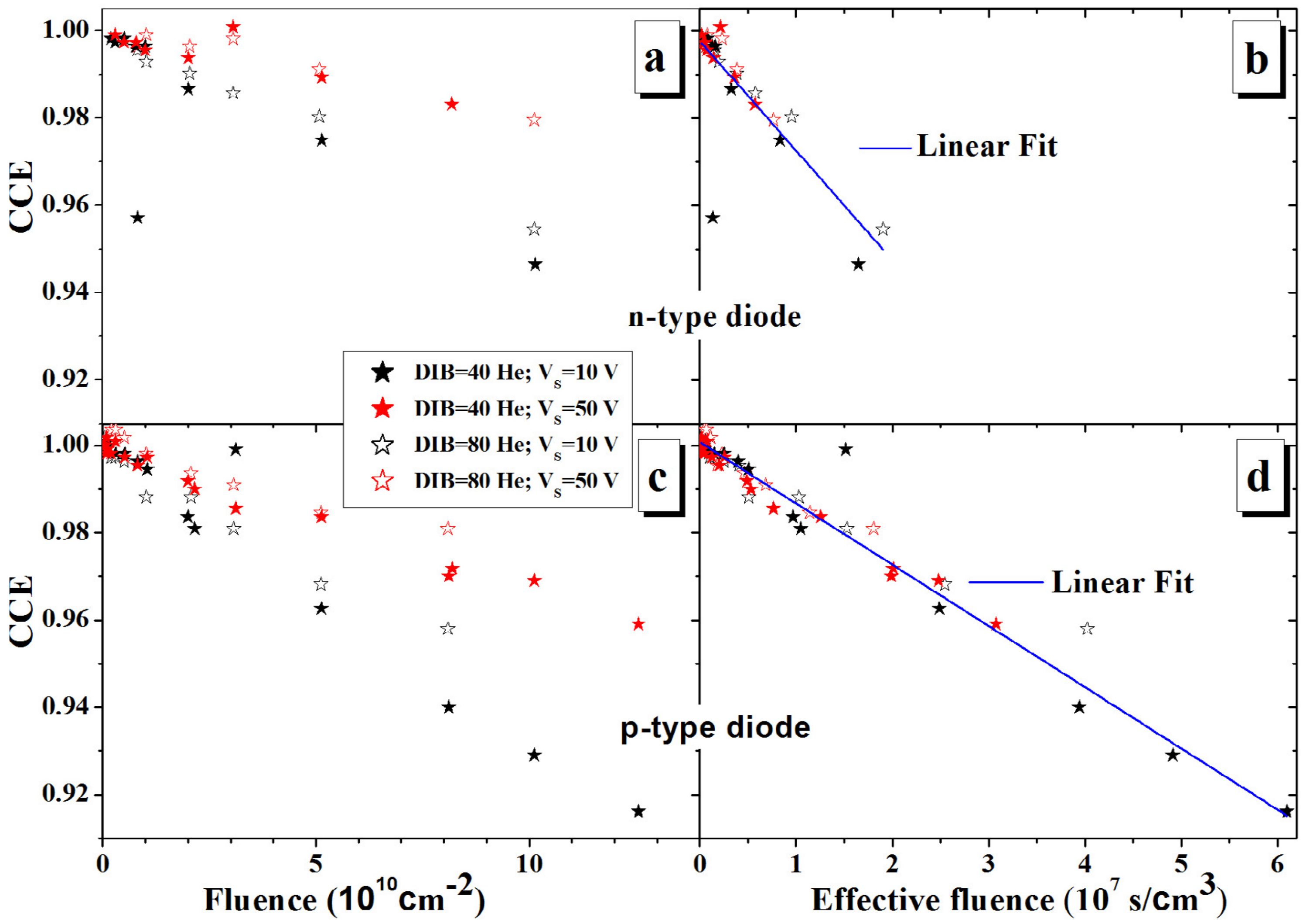
Linearization vs. Φ

⇓

Effective fluence Φ*

$$CCE(\Phi) \cong 1 - \alpha_n \cdot \left\{ \Phi \cdot \int_0^d dz \cdot \frac{V(z)}{v_n(z)} \cdot \int_z^d dy \cdot \frac{\partial F(y)}{\partial V_S} \cdot \int_0^z dx \cdot \gamma(x) \right\} = 1 - \alpha_n \cdot \Phi^*$$

Very low level of damage



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Derivation of the Non Ionizing Energy Loss (NIEL) displacement damage formula

Constant vacancy profile
Low displacement damage

$$CCE = 1 - K_{ed} \cdot D_d$$

$$K_{ed} = \frac{\rho}{M} \cdot \int_0^R dz \cdot \left\{ k_n \cdot \sigma_n^{eff}(z) \cdot \int_z^d dy \cdot \frac{\partial F(y)}{\partial V_S} \cdot \int_0^z dx \cdot \gamma(x) + k_p \cdot \sigma_p^{eff}(z) \cdot \int_0^z dy \cdot \frac{\partial F(y)}{\partial V_S} \cdot \int_z^d dx \cdot \gamma(x) \right\}$$

K_{ed} = equivalent damage factor depends on

- ✓ **Electrostatics of the device**
- ✓ **Carrier transport and recombination**
- ✓ **Ion probe ionization profile**

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

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] E. Vittone et al., Nuclear Inst. and Methods in Physics Research B 449 (2019) 6-10

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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.

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

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

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