Modeling of charge collection efficiency degradation in semiconductor devices induced by MeV ion beam irradiation

Ettore Vittone
Physics Department
University of Torino - Italy

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

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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

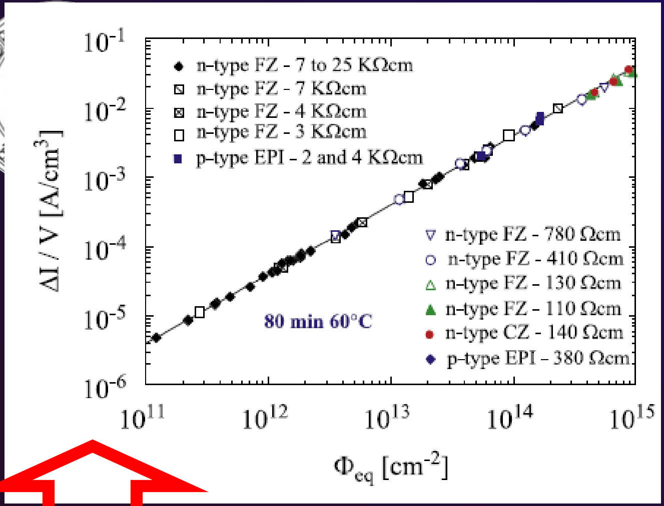
Radiation damage is the general alteration of the operational properties of semiconductor devices induced by ionizing radiation

Three main types of effects:

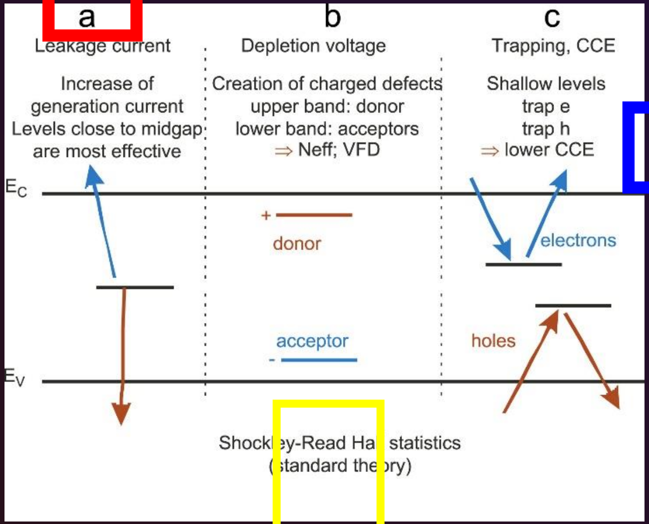
- Transient ionization. This effect produces electron-hole pairs; *particle detection with semiconductors is based on this effect.*

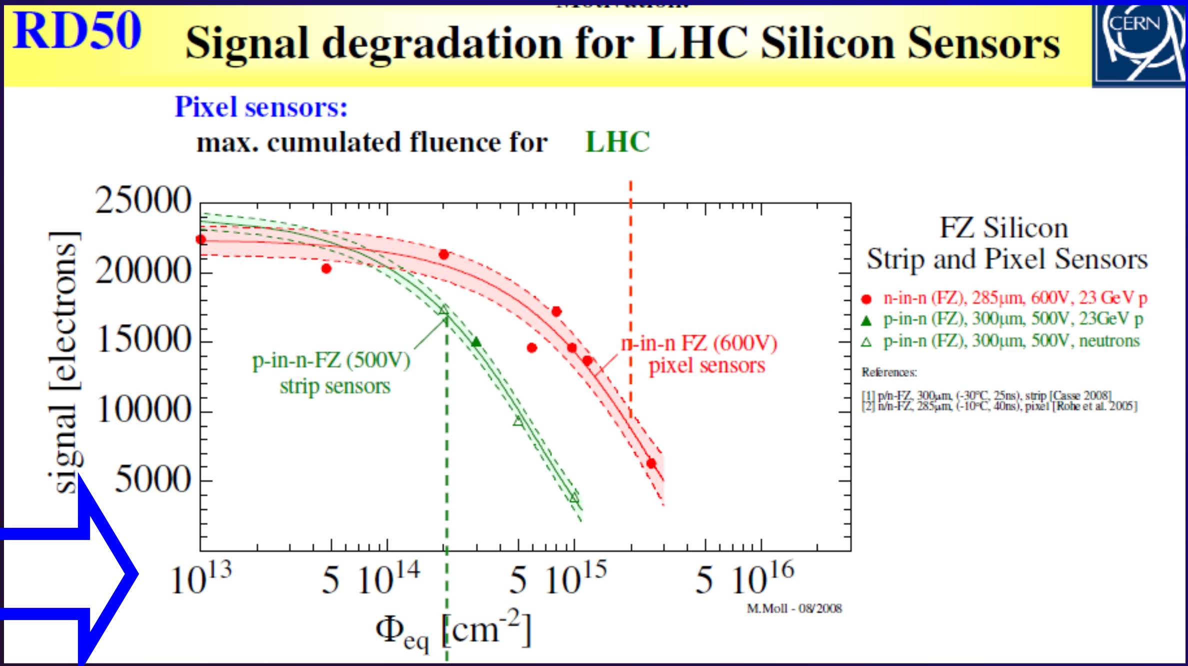
-Long term ionization. In insulators (oxides), the material does not return to its initial state, if the electrons and holes produced are fixed, and charged regions are induced.

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



M. Bruzzi, M. Moll, RD50, 2010

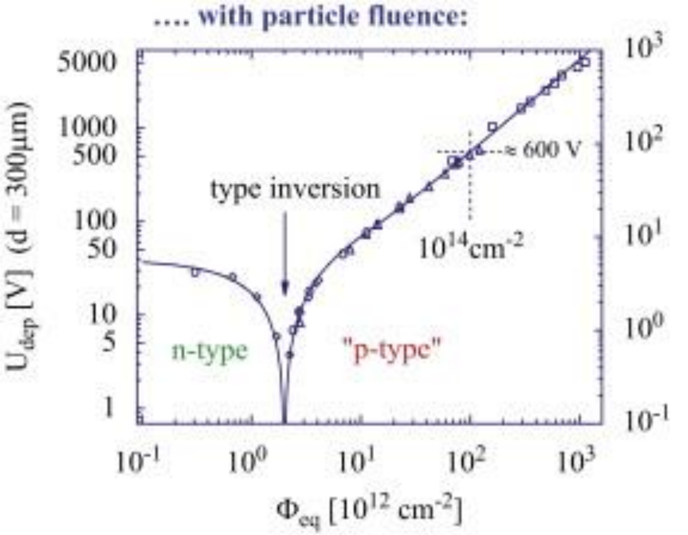




RD50 **Signal degradation for LHC Silicon Sensors**

Pixel sensors:

max. cumulated fluence for LHC



Frank Hartmann, Silicon tracking detectors in high-energy physics
Nuclear Instruments and Methods in Physics Research A 666 (2012) 25–46

Modeling radiation degradation in solar cells extends satellite lifetime

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

A physics-based model of the effect of radiation on the performance of solar cells in space may enhance the on-orbit lifetime of Earth-orbiting spacecraft. SPIE 2011

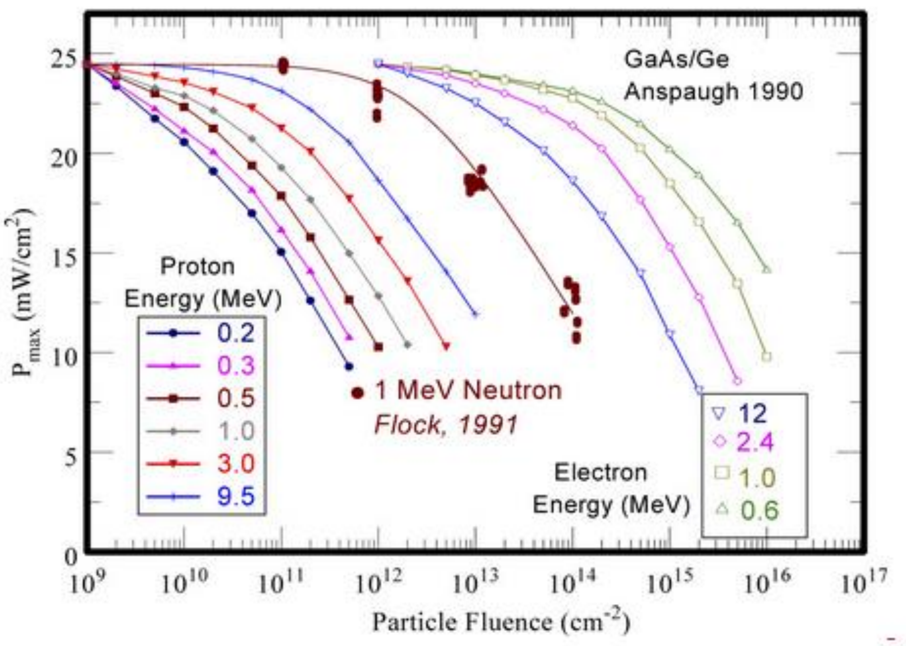


Figure 2. *Measured degradation of a single junction gallium arsenide (GaAs) solar cell under proton, electron,[2] and neutron irradiation.[3] These data can be used to empirically determine the energy dependence of the solar-cell degradation thereby enabling on-orbit performance prediction. P_{max}: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

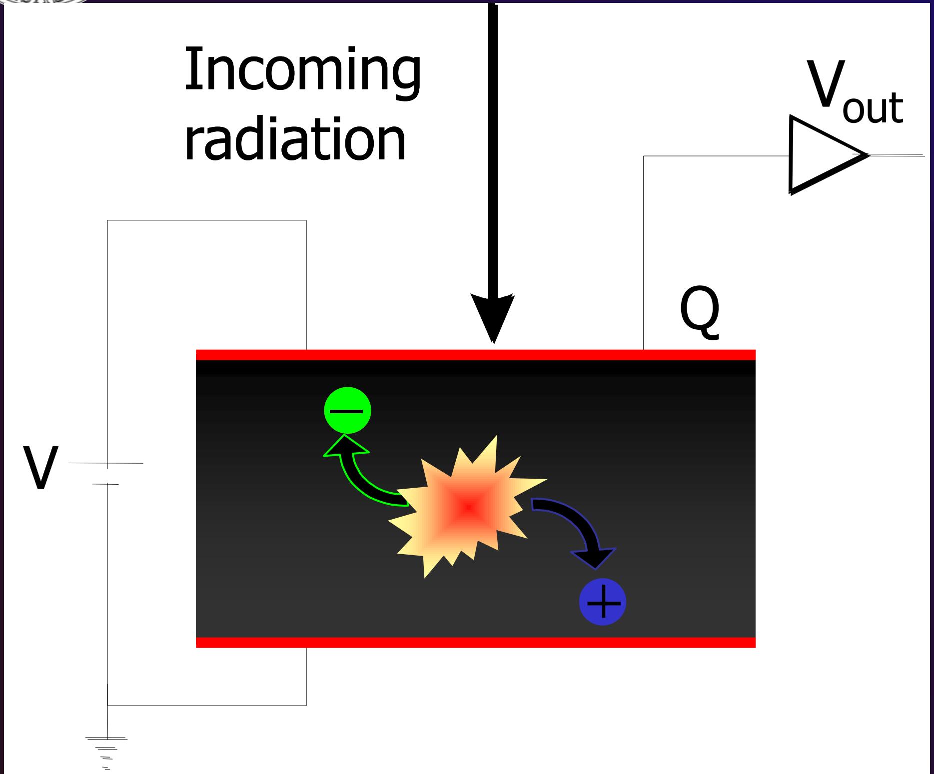
Displacement dose

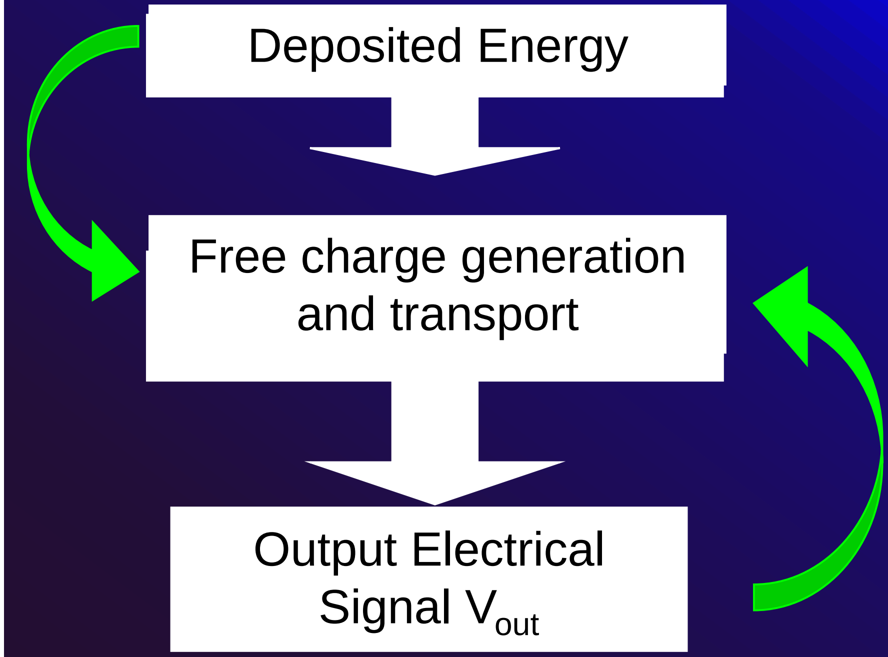
First order: proportionality, independent of the particle, between the damage factor and the particle NIEL

NIEL approach:

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

IBIC: Ion Beam Induced Charge





Deposited Energy

Free charge generation and transport

Output Electrical Signal V_{out}

$$V_{out} = F(\text{Deposited Energy}, \text{Free Carrier Transport})$$

Measured

Well known

Material Characterization

Characterization of radiation induced damage:

Induced Charge after irradiation

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

Induced Charge before irradiation

Particle Fluence

Equivalent damage factor

Displacement dose

MeV Ion beams

to induce the damage ⟶ DIB=DAMAGING IONS

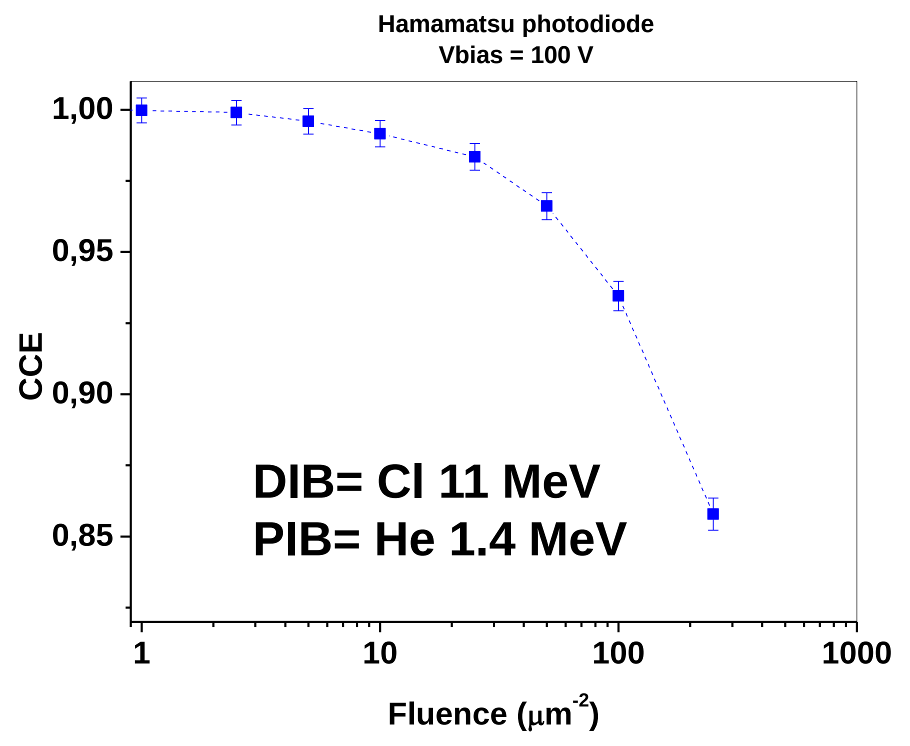
And

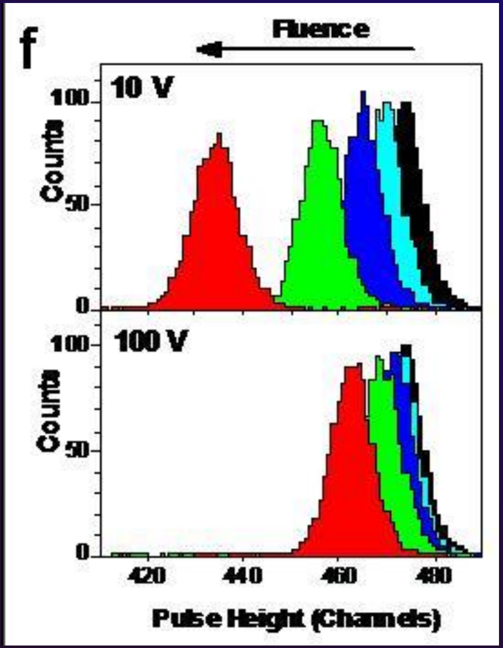
to probe the damage ⟶ PIB=PROBING IONS

CCE degradation induced by ion irradiation

Is a function of the damaging ion fluence

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

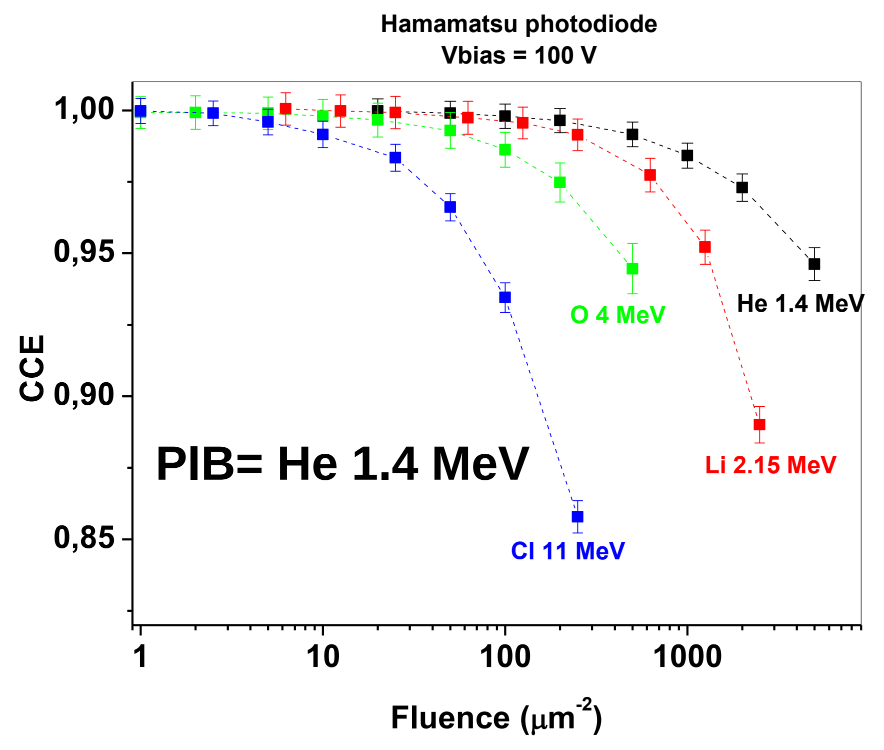




CCE degradation induced by ion irradiation

Is a function of the ion energy and mass

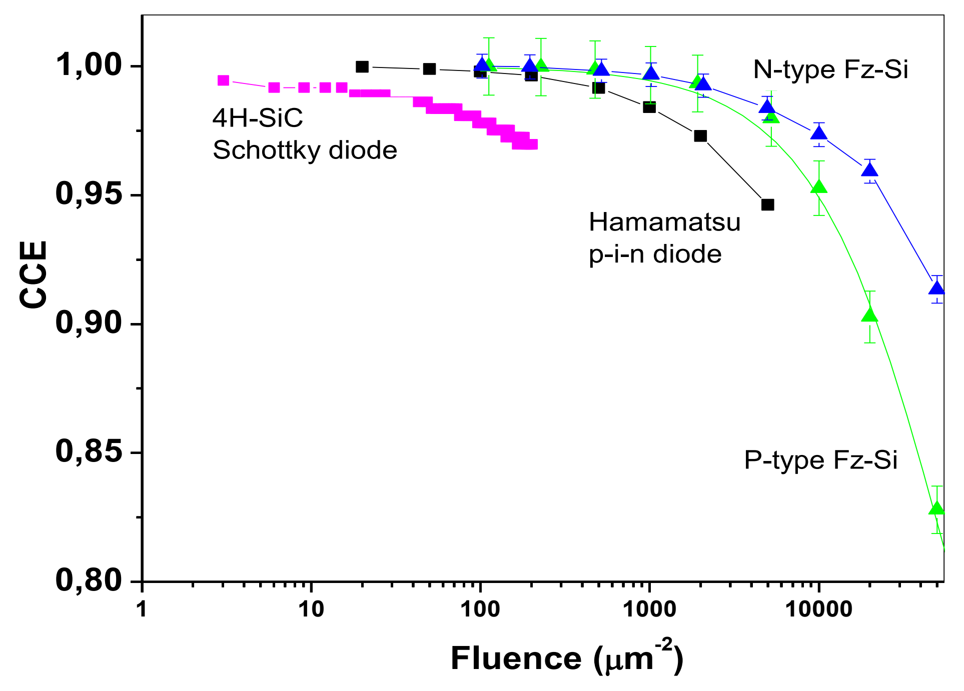
$$\eta = \frac{Y}{Y_0} = 1 - K \cdot \Phi = 1 - K_{ed} \cdot D_d$$



CCE degradation induced by ion irradiation

Is a function of the material and/or device

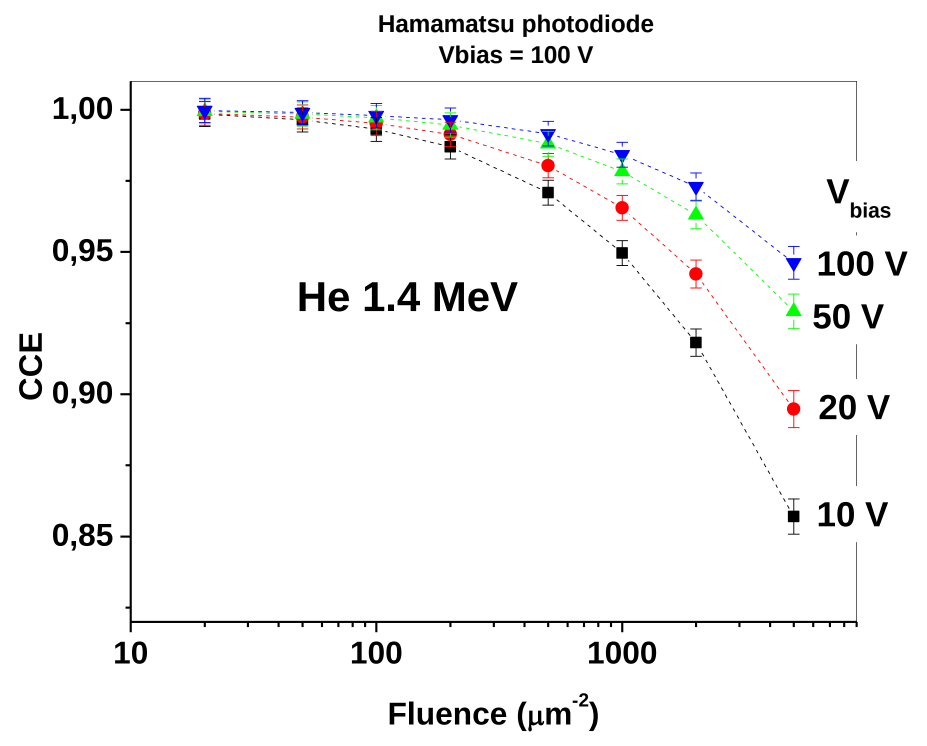
$$\eta = \frac{Y}{Y_0} = 1 - K \cdot \Phi = 1 - K_{ed} \cdot D_d$$



CCE degradation induced by ion irradiation

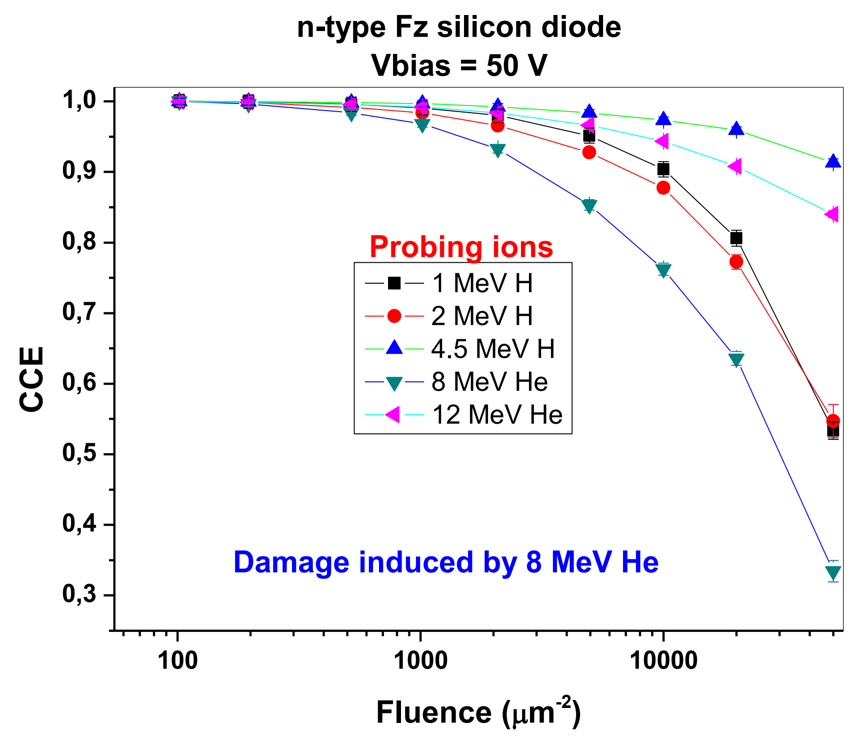
Is a function of the polarization state of the device

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



CCE degradation induced by ion irradiation

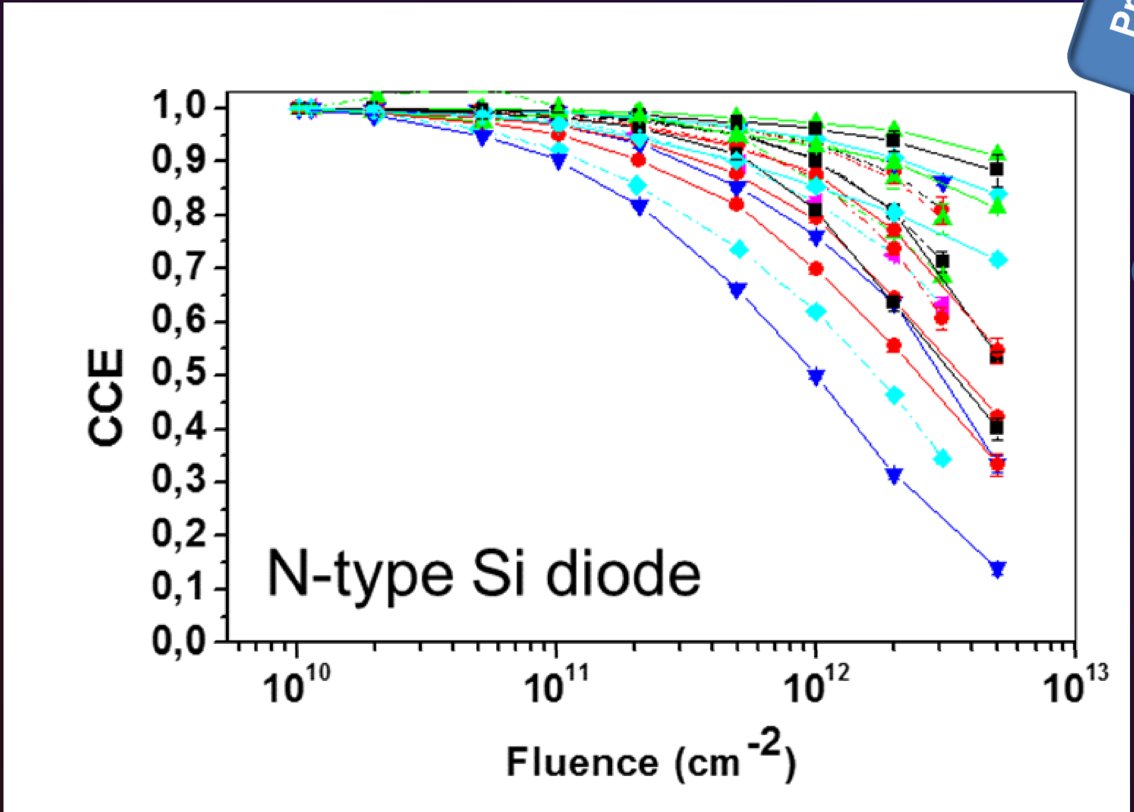
Is a function of the probing ions (PIB)



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

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)



CCE Degradation

Material/device

Device Electrostatics

Damaging ion Mass/Energy

Damaging ion fluence

Probing ion Mass/Energy

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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)

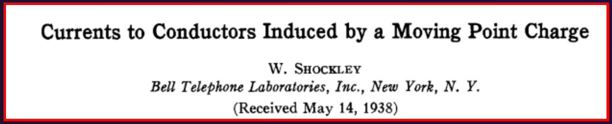
- **Formalism based on the Shockley-Ramo-Gunn theorem**

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

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

Pulse shapes calculation

Shockley-Ramo theorem



Currents to Conductors Induced by a Moving Point Charge

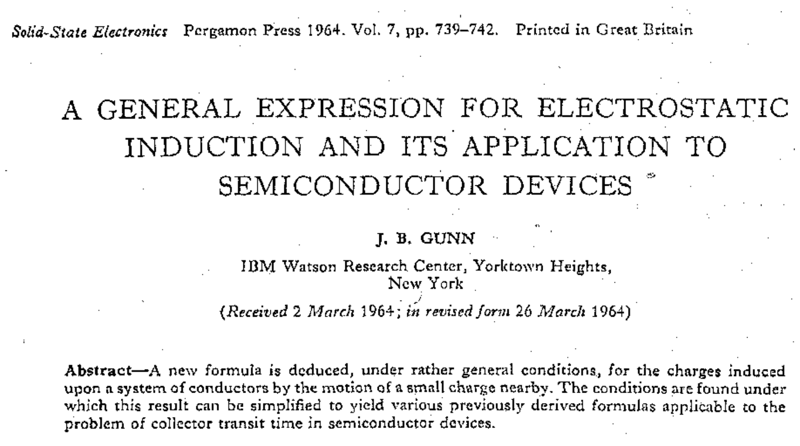
W. SHOCKLEY
Bell Telephone Laboratories, Inc., New York, N. Y.
(Received May 14, 1938)

Currents Induced by Electron Motion*

SIMON RAMO†, ASSOCIATE MEMBER, I.R.E.

$$I = -q \cdot \mathbf{v} \cdot \frac{1}{d}$$

Gunn 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

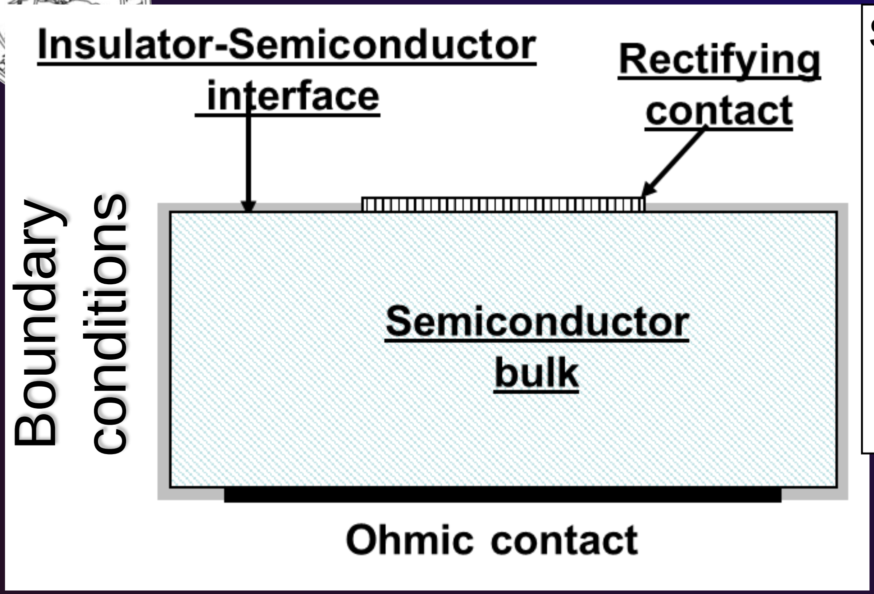
(*Received 2 March 1964; in revised form 26 March 1964*)

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



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

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

$$\frac{\partial \mathbf{p}}{\partial \mathbf{t}} = -\vec{\nabla}\cdot\left(+\mu_p\cdot\vec{\nabla}\phi_0\cdot\mathbf{p}-\mathbf{D}_p\cdot\vec{\nabla}\mathbf{p}\right)+\mathbf{G}_p-\frac{\mathbf{p}}{\tau_p}$$

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

Initial conditions

For mapping charge pulses

$$\mathbf{G}_{n,p} = \delta(\mathbf{r}-\mathbf{r}_0)\cdot\delta(\mathbf{t})$$

$\mathbf{r}_0 =$ **Generation point at** $\mathbf{t}=0$

Evaluate the induced charge

$$\mathbf{Q}_i(\mathbf{t}) = -\mathbf{q}\int_0^t \mathbf{dt'}\int_\Omega \mathbf{dr}\left\{\left[\mathbf{n}(\mathbf{r},\mathbf{t'};\mathbf{r}_0)\cdot\mathbf{v}_n(\mathbf{r})+\mathbf{p}(\mathbf{r},\mathbf{t'};\mathbf{r}_0)\cdot\mathbf{v}_p(\mathbf{r})\right]\cdot\left.\frac{\partial \mathbf{E}(\mathbf{r})}{\partial \mathbf{V}_i}\right|_{\mathbf{V}}\right\}$$

Model for charge pulse formation (IBIC theory)

- **Formalism based on the Shockley-Ramo-Gunn theorem**

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

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

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.

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

$$n^+ = Q_{in}$$

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

Model for charge pulse formation (IBIC theory)

1D

Fully depleted device

No diffusion

Ramo Theorem

Ionization profile

SRIM
The Stopping and Range of Ions in Matter

Gunn's weighting field

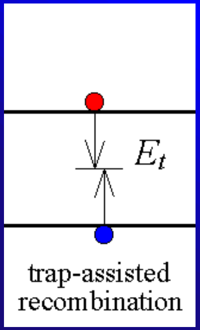
$$Q_S = q \cdot \int_0^d dx \cdot \Gamma(x) \left\{ \begin{array}{l} \displaystyle\int_x^d dy \cdot \frac{\partial F(y)}{\partial V_S} \cdot \exp\left[-\int_x^y dz \left(\frac{1}{v_p \cdot \tau_p} \right) \right] + \\ \displaystyle\int_0^x dy \cdot \frac{\partial F(y)}{\partial V_S} \cdot \exp\left[-\int_y^x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

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

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

Fluence

Capture coefficient

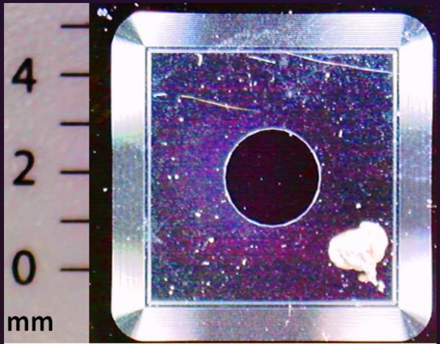
Vacancy Density Profile

The experimental protocol

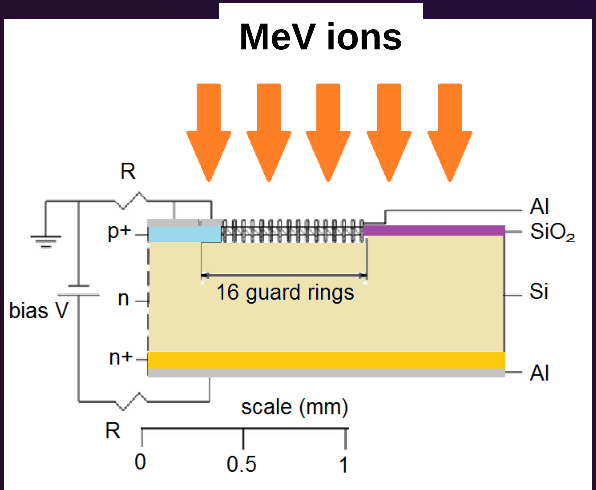
Z. Pastuovic et al., IEEE Trans on Nucl. Sc. 56 (2009) 2457; APL (98) 092101 (2011)

Samples under study

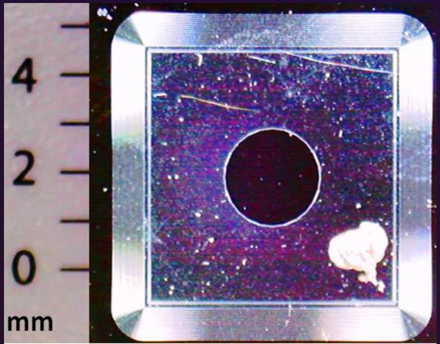
n- and p- type Fz p-i-n Si diodes
Fabricated by the Institute of Physics, University of Helsinki



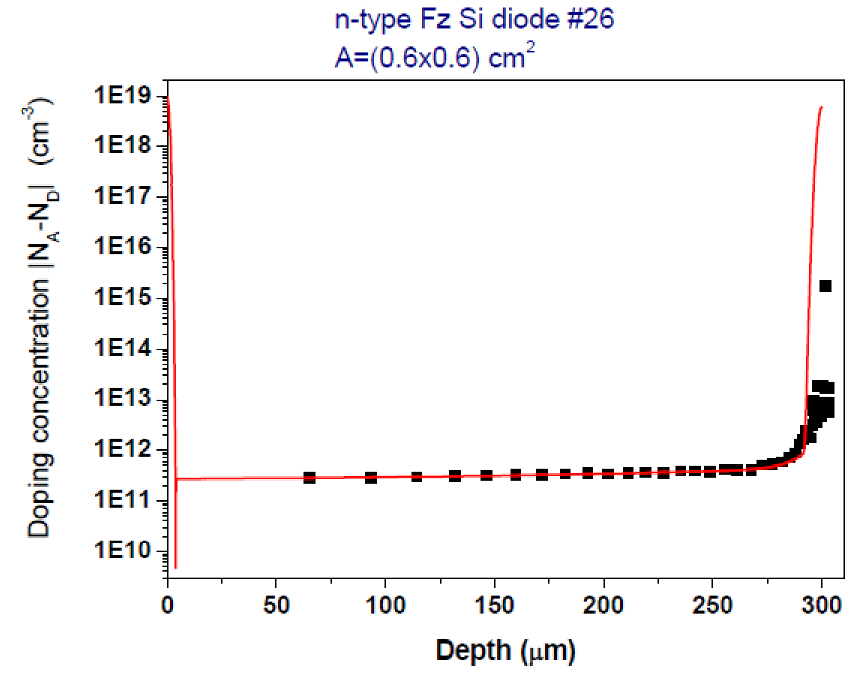
16 floating guard rings
The frontal electrode and the guard rings
are coated with Al (0.5 µm]).
The Al electrode has a hole in the center, 1 mm diameter.
Different dimensions: 5 or 2.5 mm



Experimental protocol



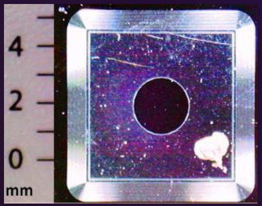
C-V characteristics
Depletion width-voltage

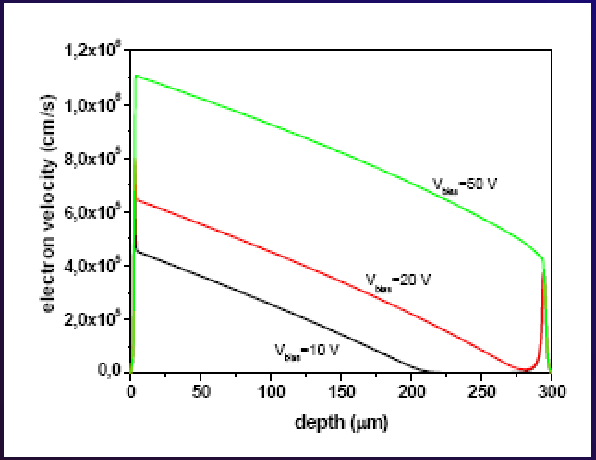


Experimental protocol

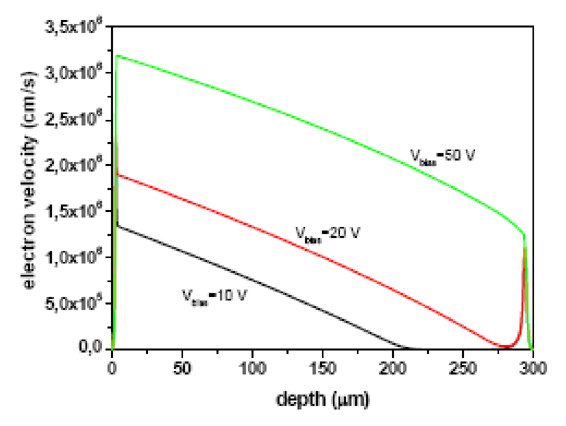
✓**Electrical characterization**

Experimental protocol



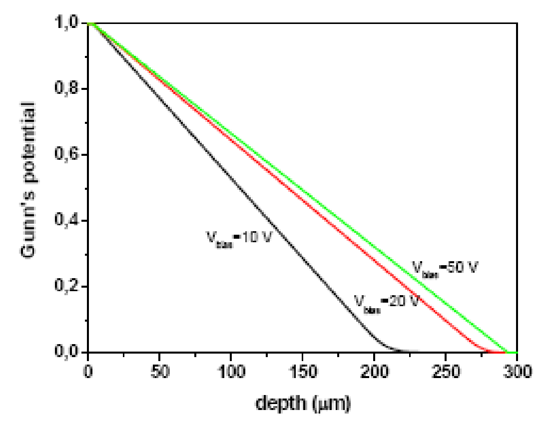


hole drift velocity profiles

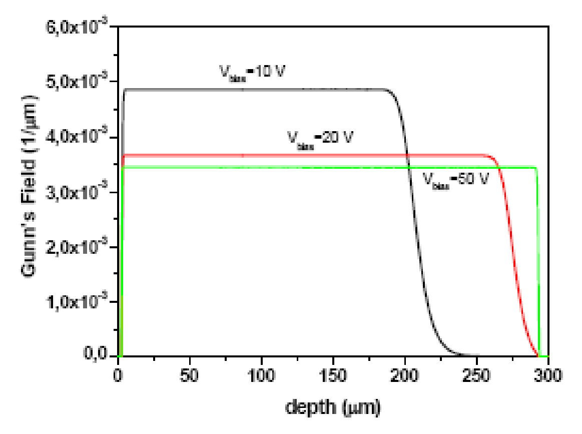


Electron drift velocity profiles

Gunn's weighting potential

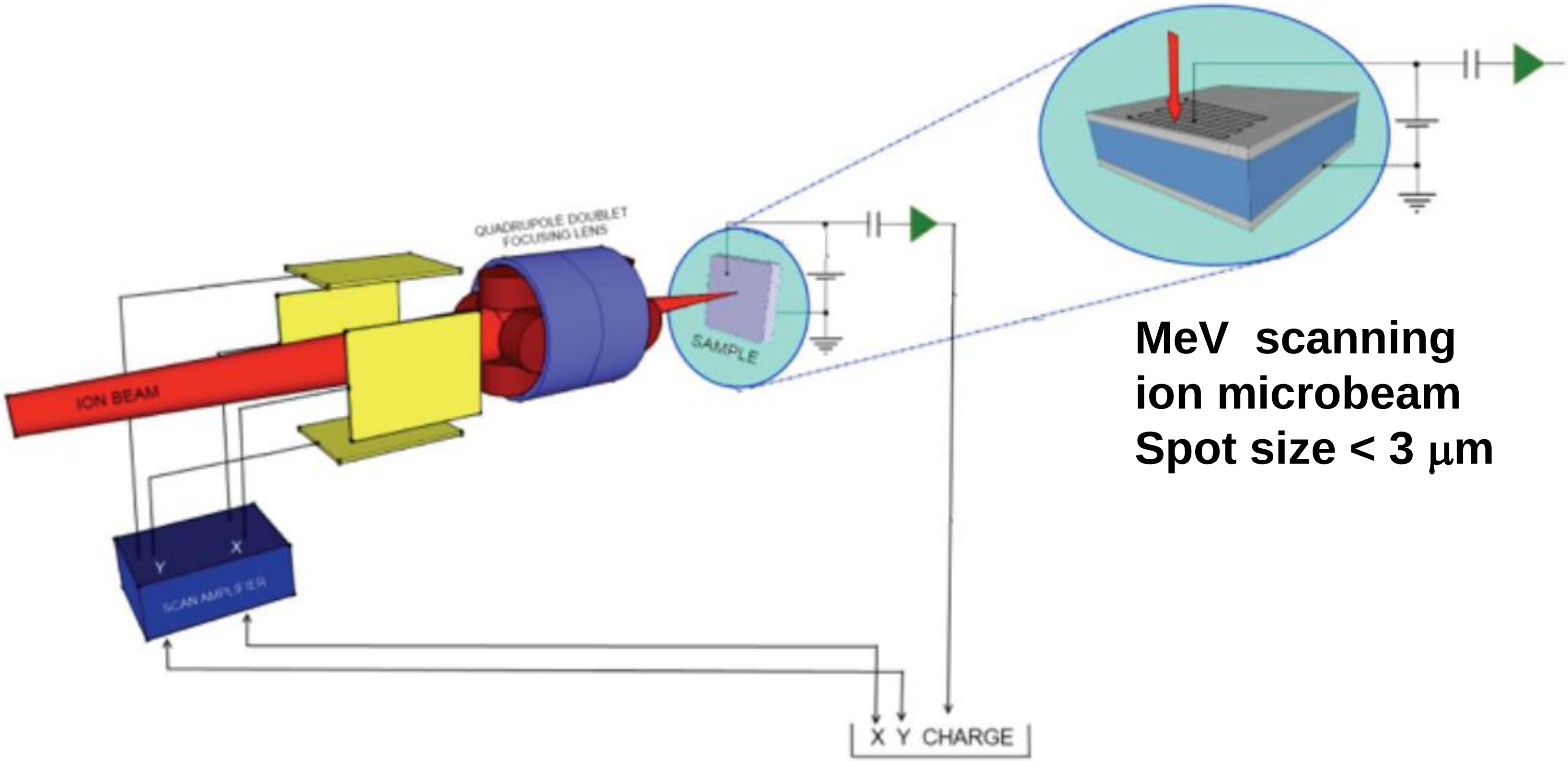


Gunn's weighting field



Experimental protocol

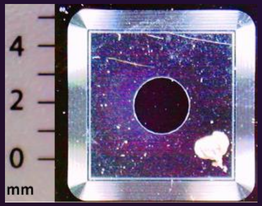
✓Electrical characterization
✓Electrostatic modeling

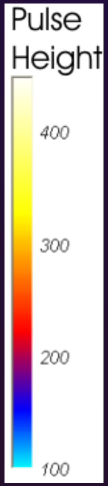


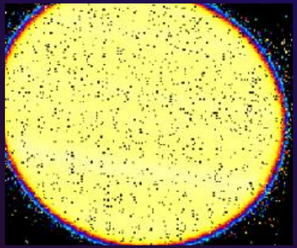
MeV scanning ion microbeam
Spot size < 3 μm

PROBING THE PRISTINE SAMPLE

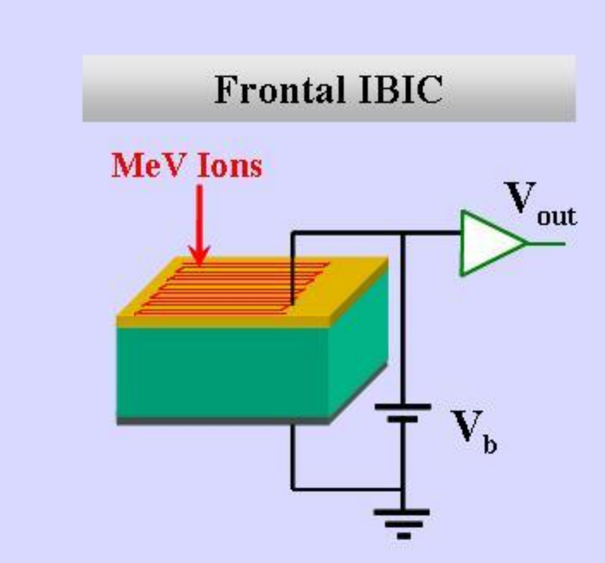
IBIC map on a pristine diode probed with a scanning 1.4 MeV He microbeam;







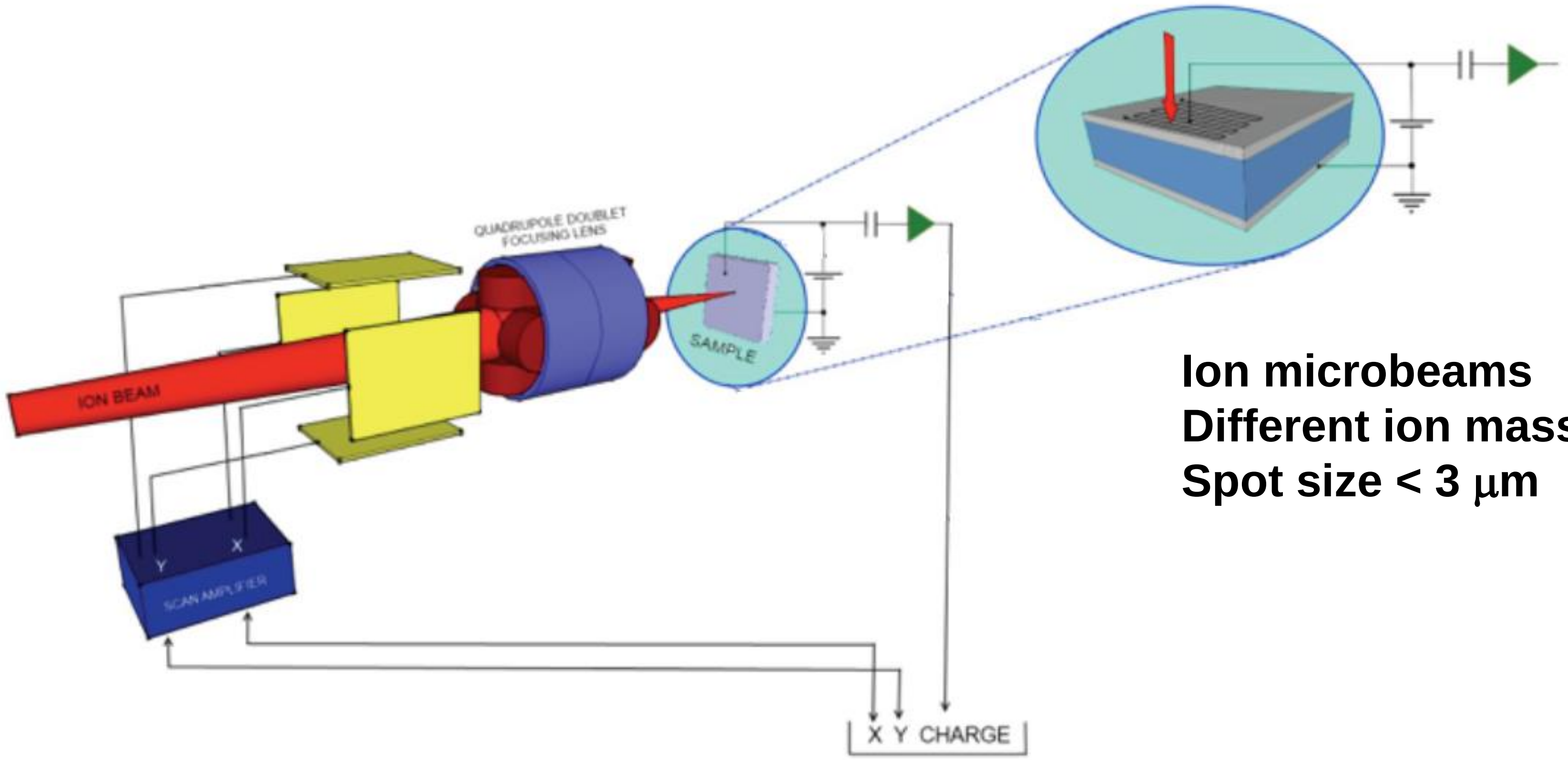
Uniform CCE map



Experimental protocol

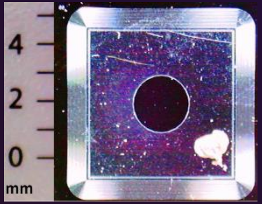
- ✓Electrical characterization
- ✓Electrostatic modeling
- ✓IBIC map on pristine sample

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

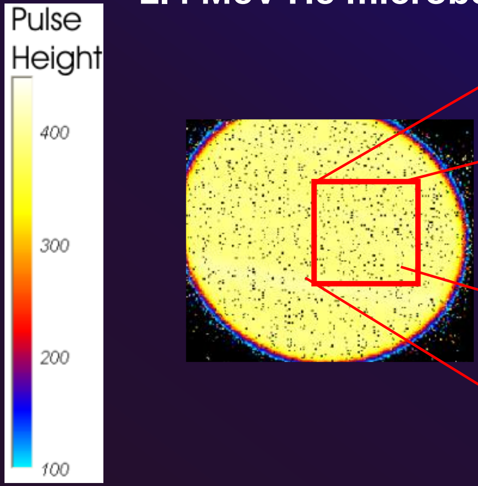


Ion microbeams
Different ion mass/energy
Spot size < 3 μm

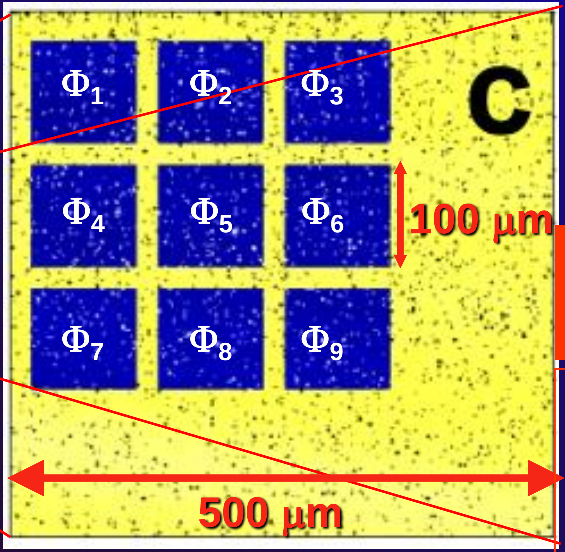
DAMAGING SELECTED AREAS
100X100 μm^2



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

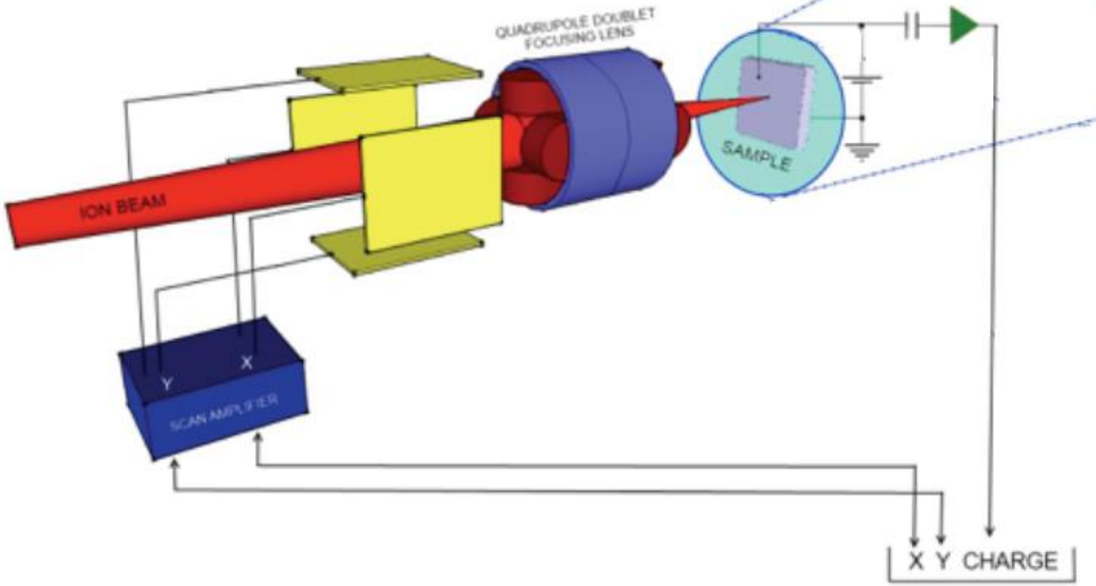


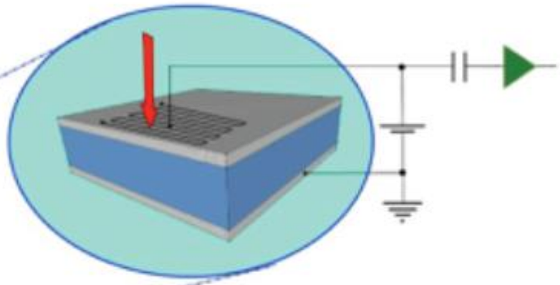
Experimental protocol

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

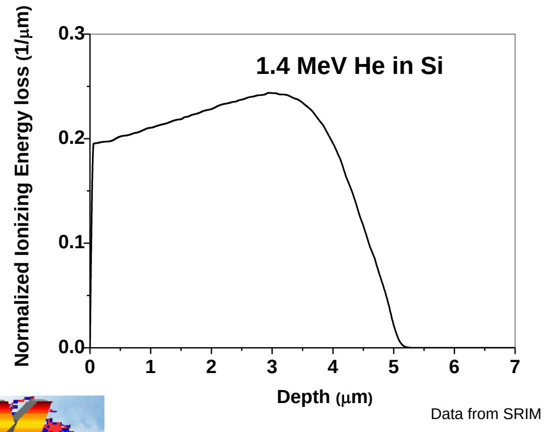
Z. Pastuovic et al., IEEE Trans on Nucl. Sc. 56 (2009) 2457; APL (98) 092101 (2011)

PROBING DAMAGED AREAS





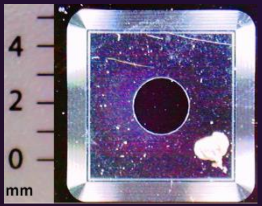
He ion microbeam
Energy 1.4 MeV
Spot size < 3 μm

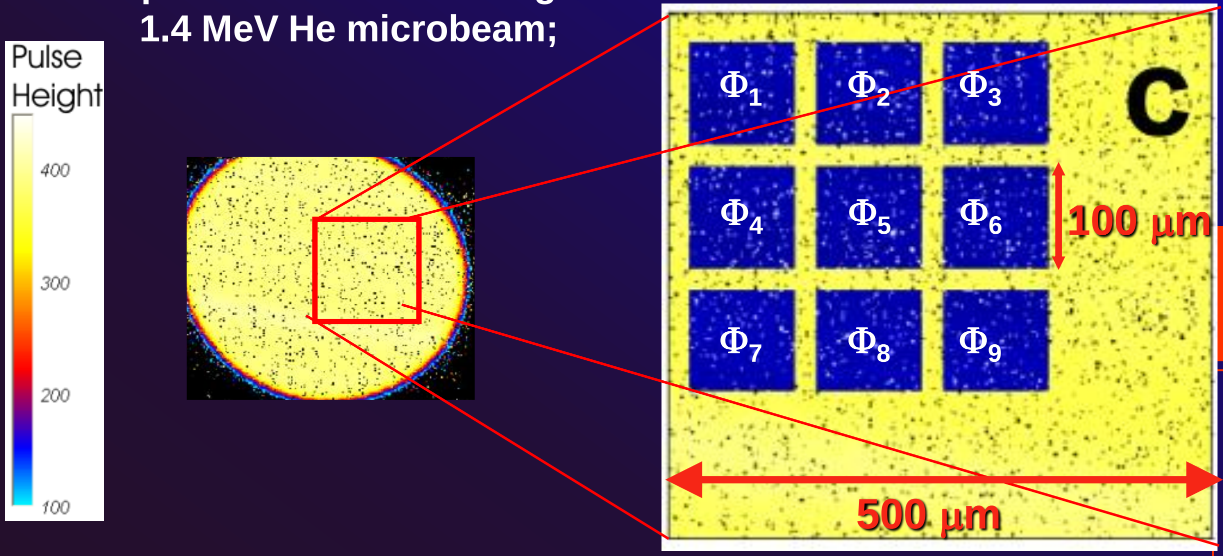


Data from SRIM

SRIM
The Stopping and Range of Ions in Matter

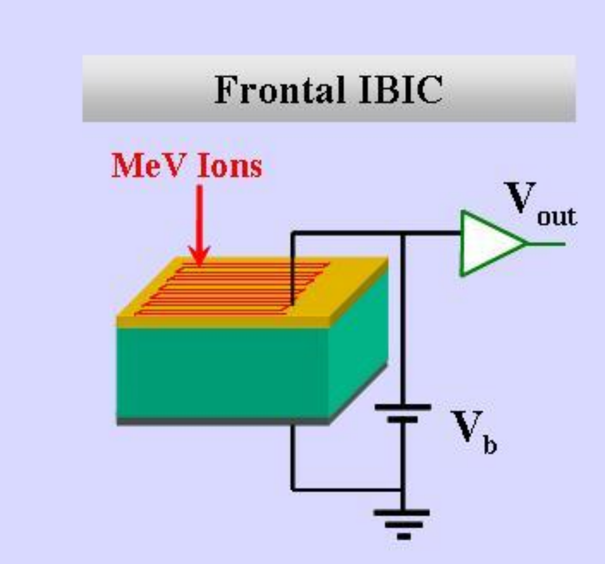
IBIC map on a pristine diode probed with a scanning 1.4 MeV He microbeam;

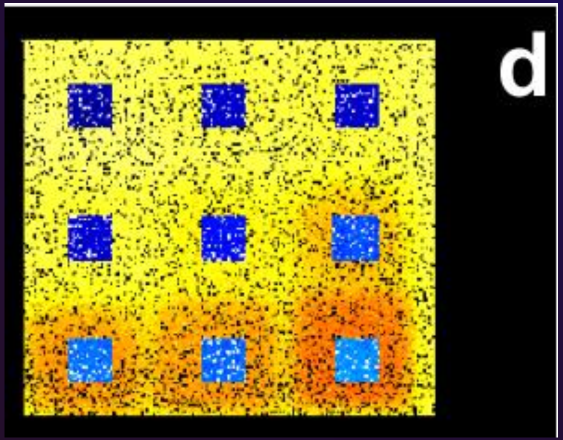




Experimental protocol

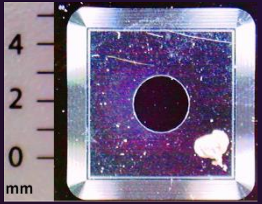
- ✓Electrical characterization
- ✓IBIC map on pristine sample
- ✓Irradiation of 9 regions at different fluences
- ✓IBIC map of irradiated regions



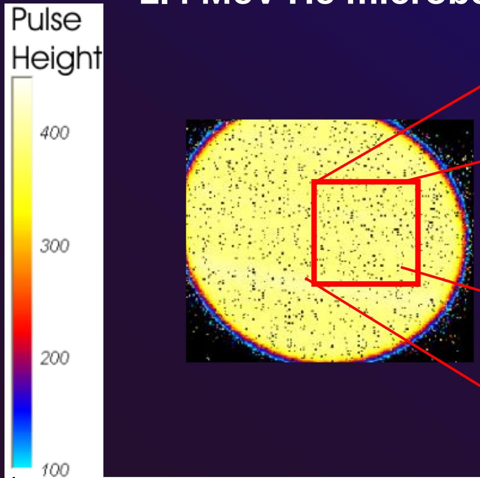


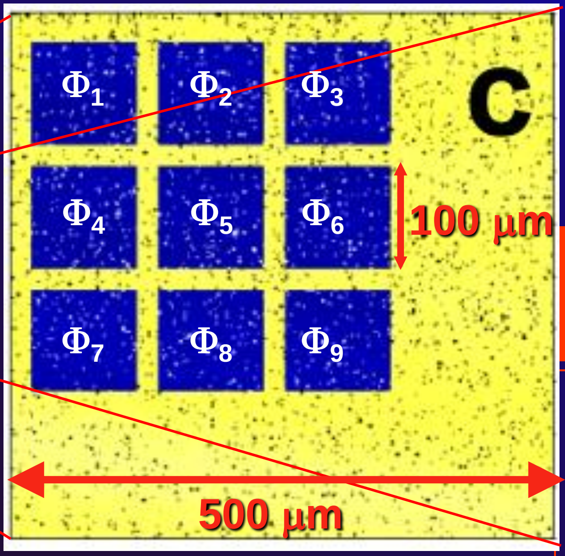
a measured 2D distribution of the IBIC signal amplitude after irradiation

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



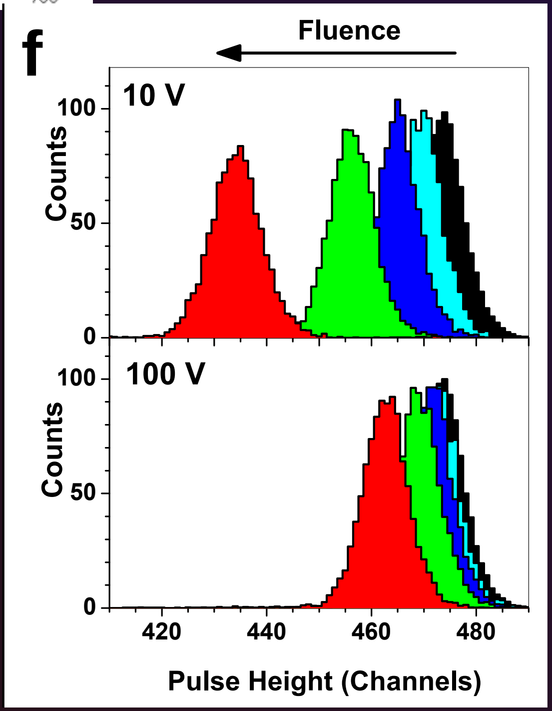
IBIC map on a pristine diode probed with a scanning 1.4 MeV He microbeam;



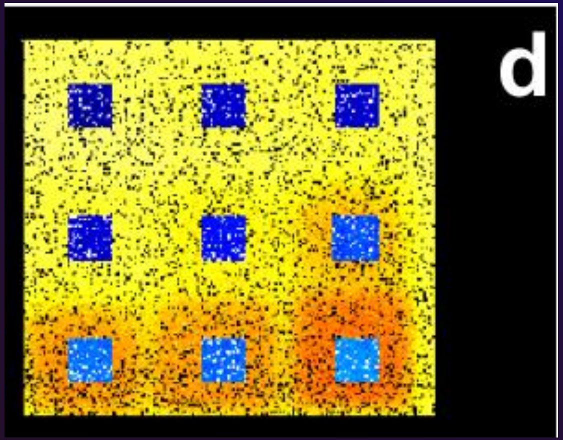


Experimental protocol

- ✓Electrical characterization
- ✓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



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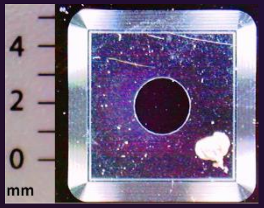

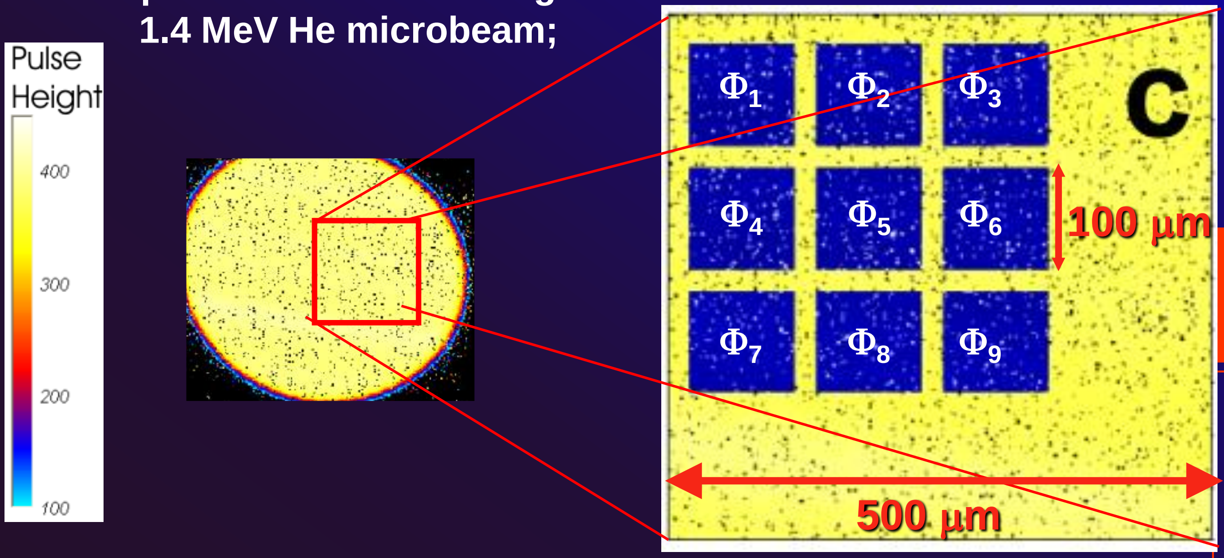

Experimental protocol

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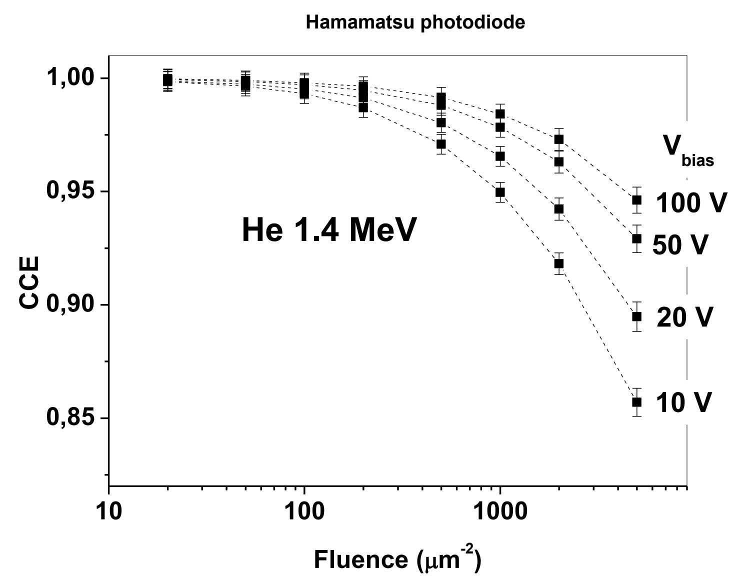
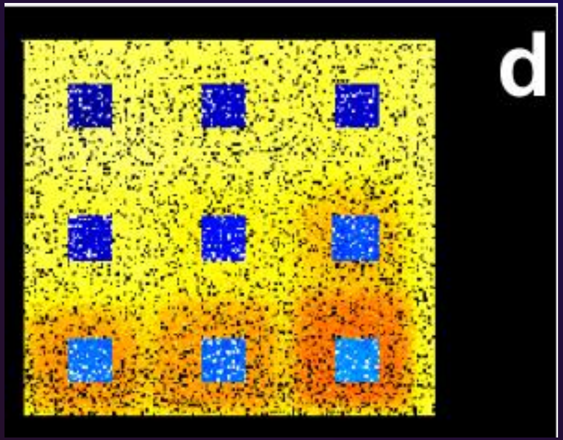
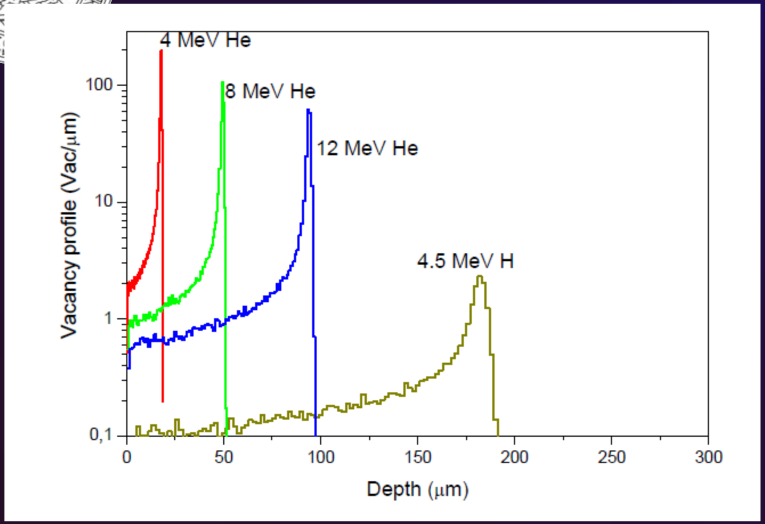




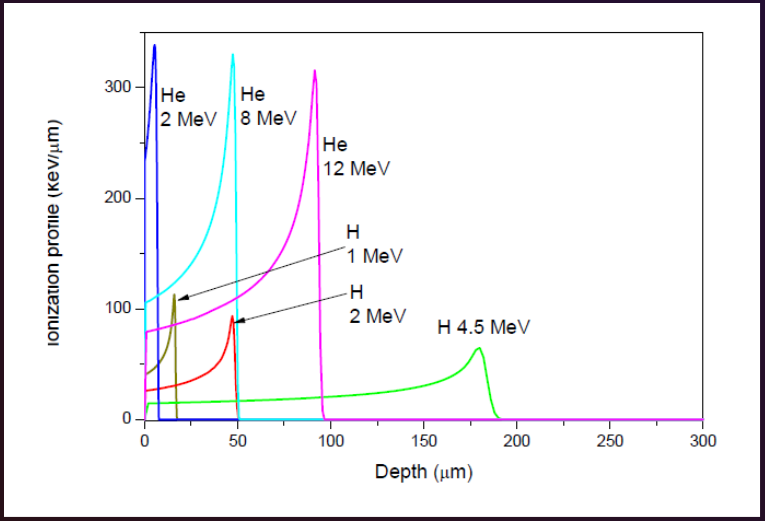
a measured 2D distribution of the IBIC signal amplitude after irradiation

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

DIB: Vacancy profiles



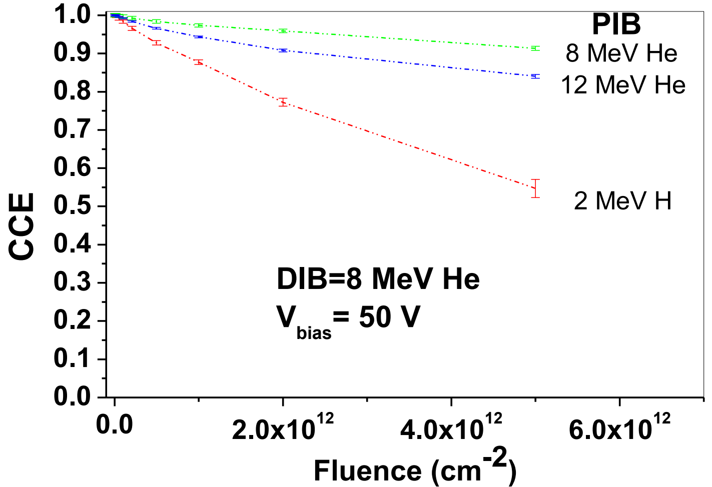
PIB: Ionization profiles



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

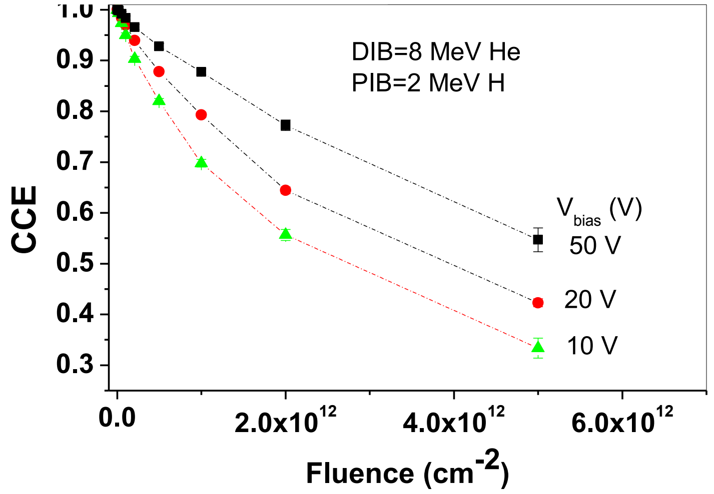
Fixed V_{bias}

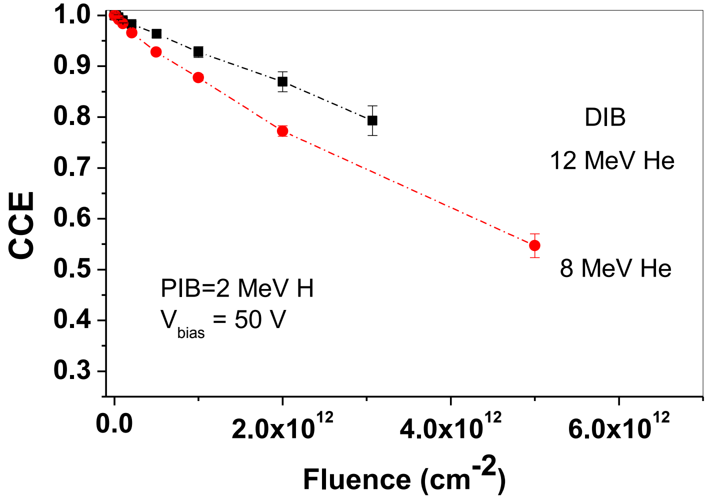
Variable PIBs

Fixed DIB

Fixed PIB

Variable V_{bias}

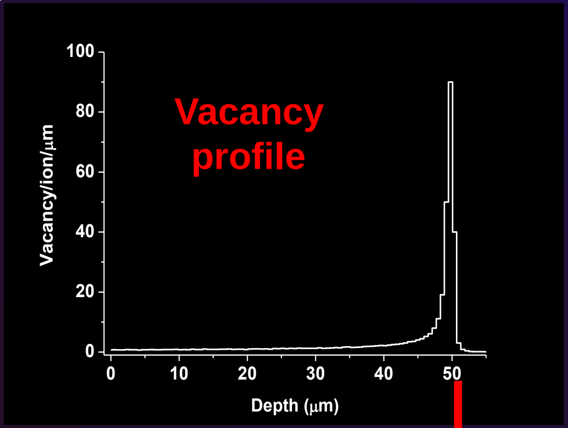


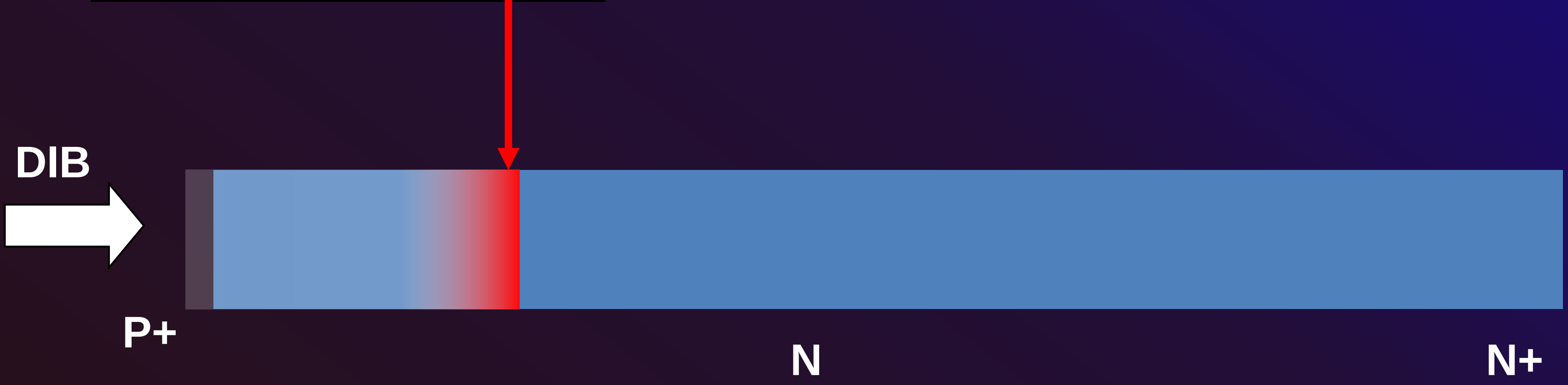


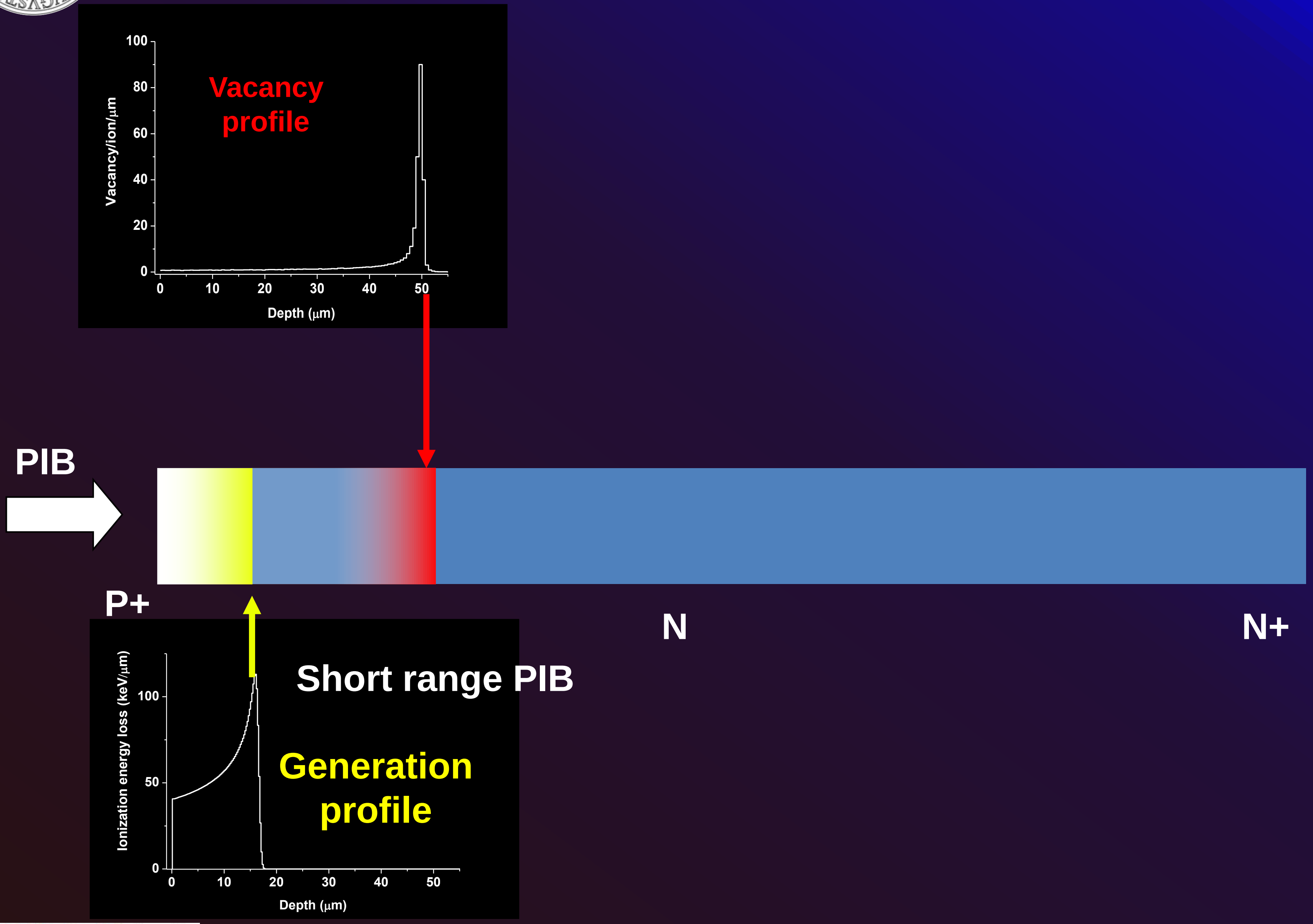
Variable DIB

Fixed PIB

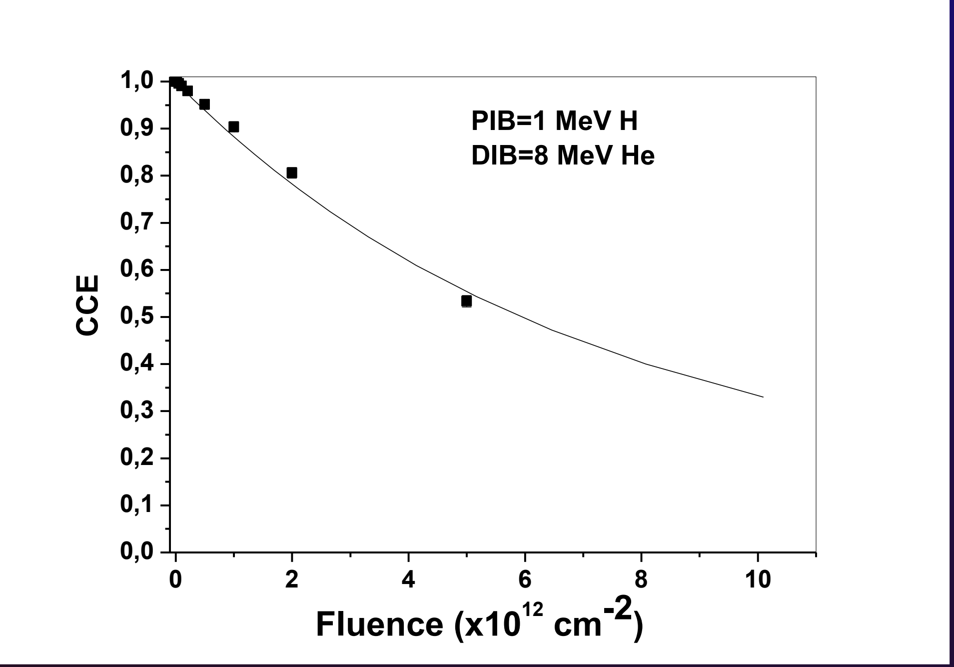
FIXED V_{bias}

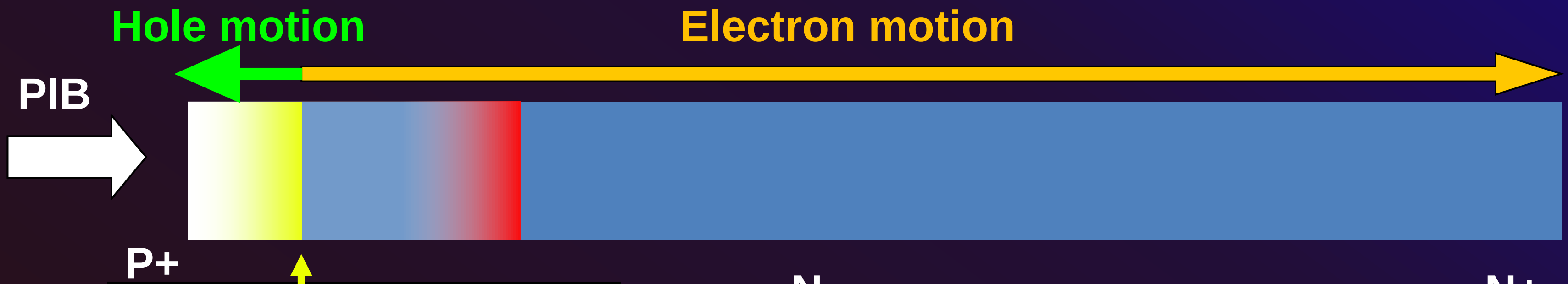

Vacancy profile
Vacancy/ion/μm
100
80
60
40
20
0
0
10
20
30
40
50
Depth (μm)


DIB
P+
N
N+



Short range PIB





Hole motion

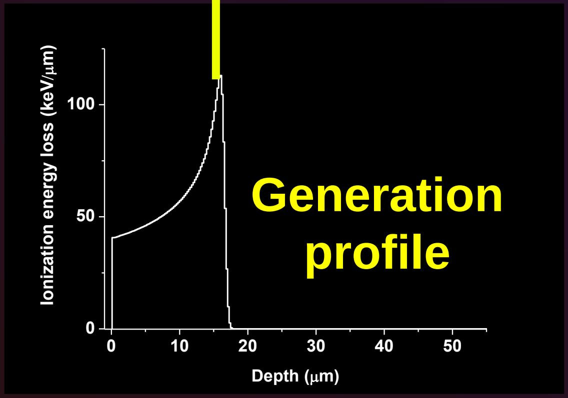
Electron motion

PIB

P+

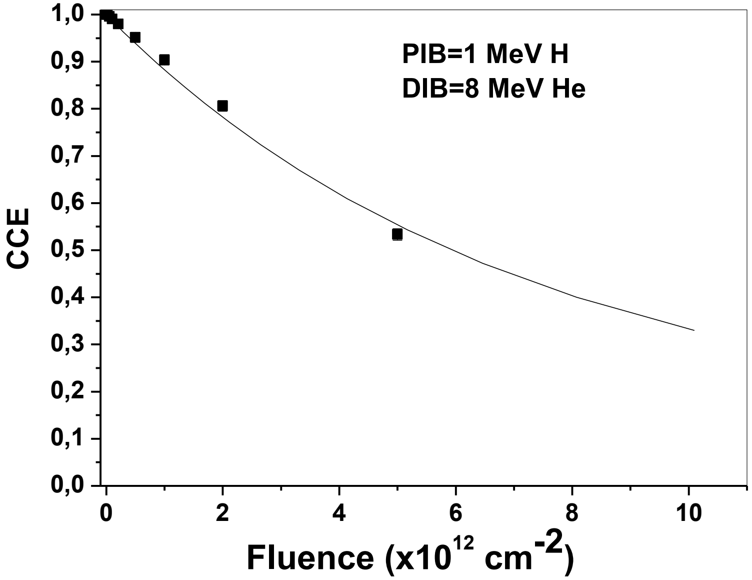
N

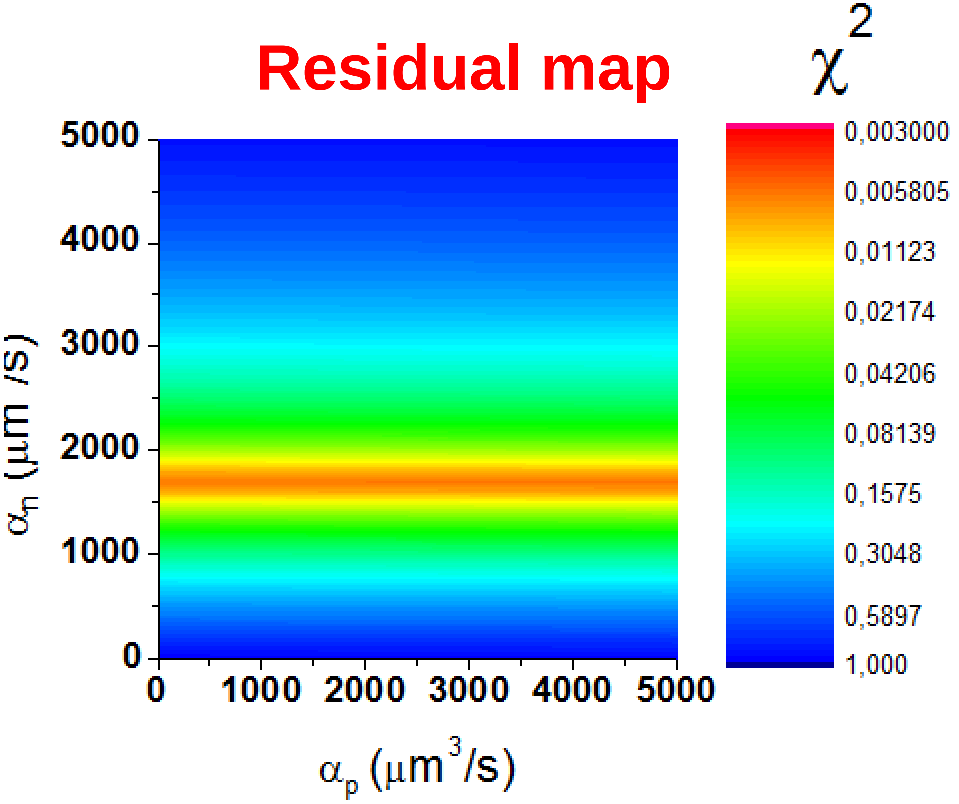
N+



Generation profile

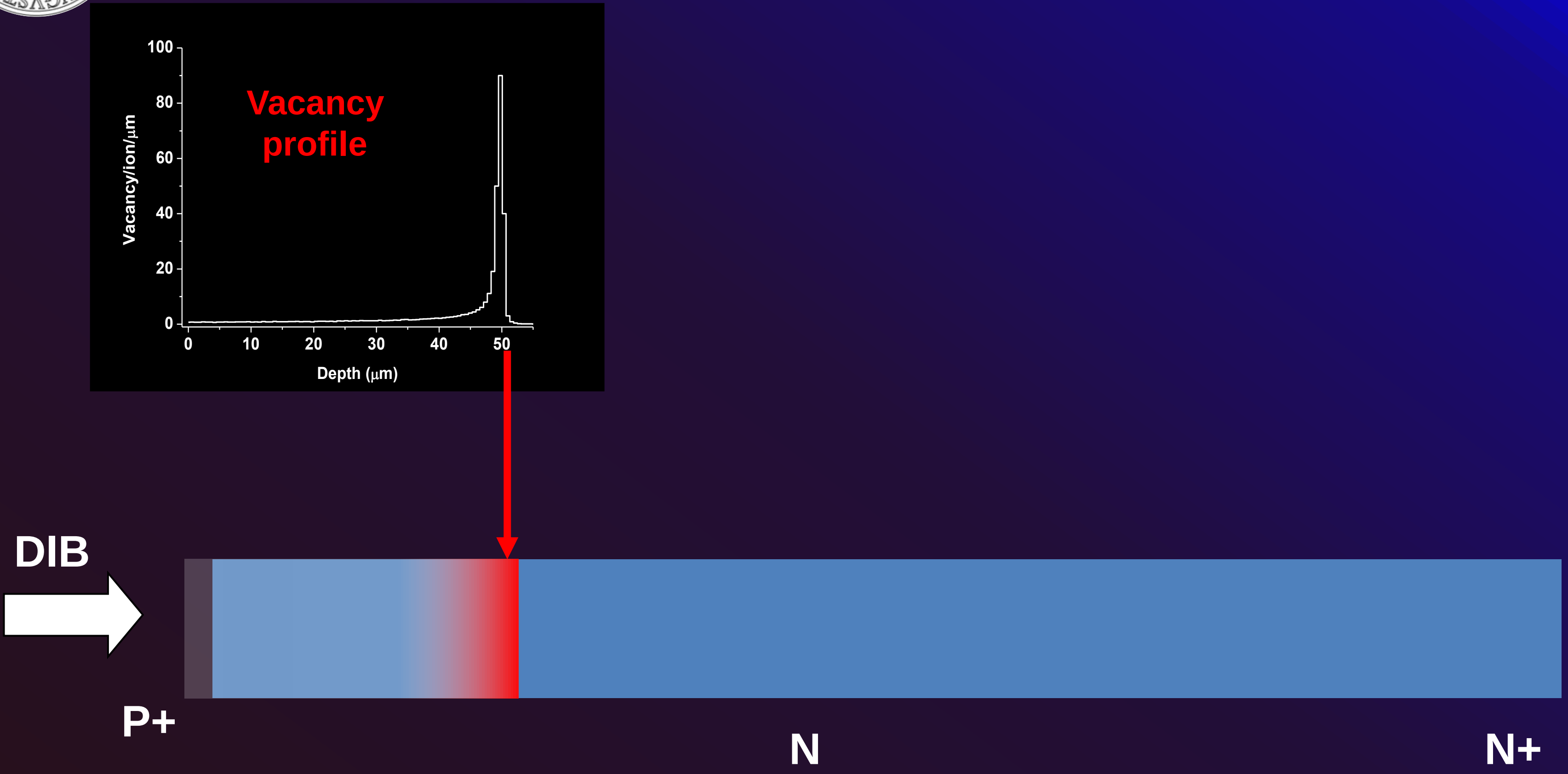
Electric field

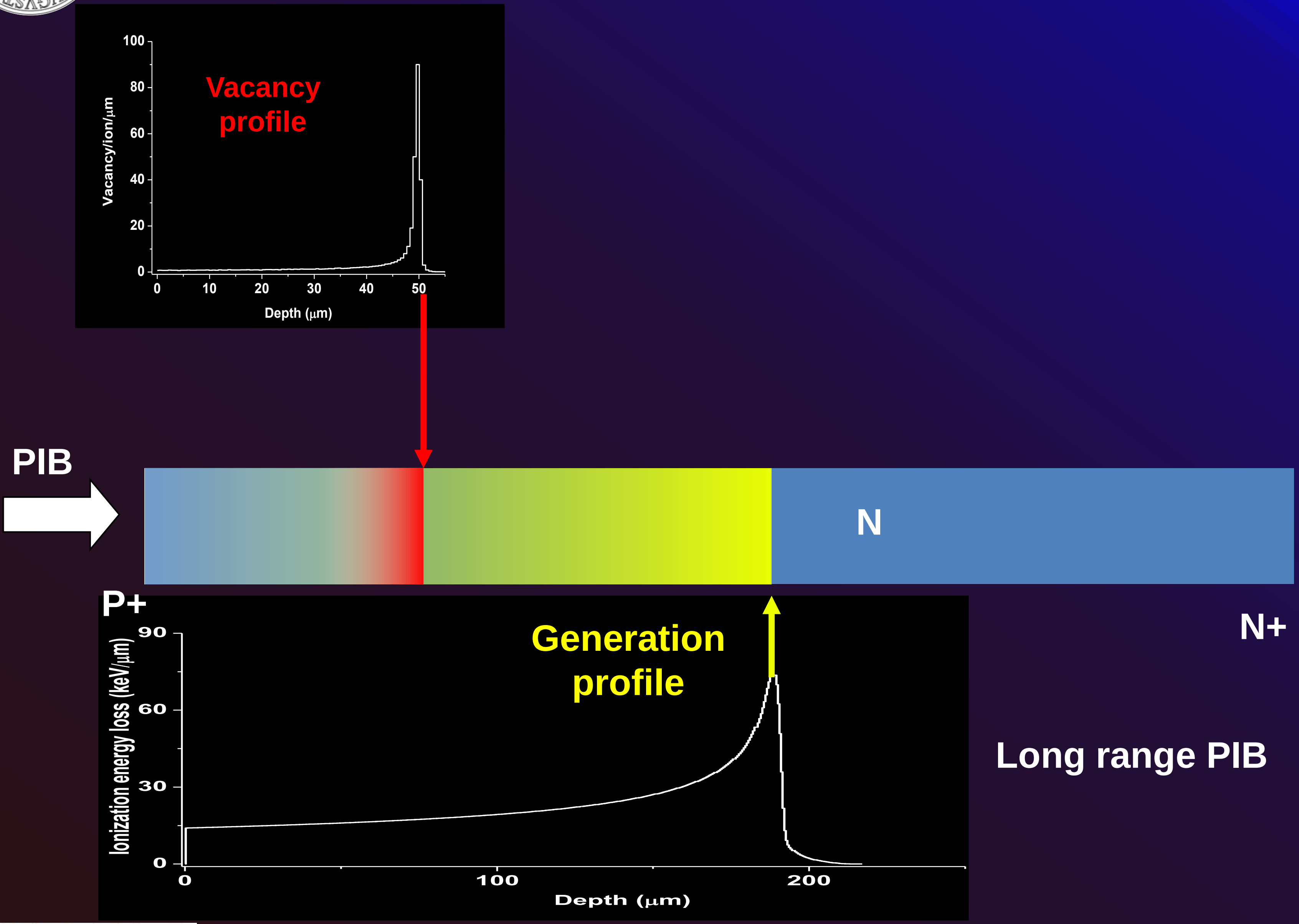




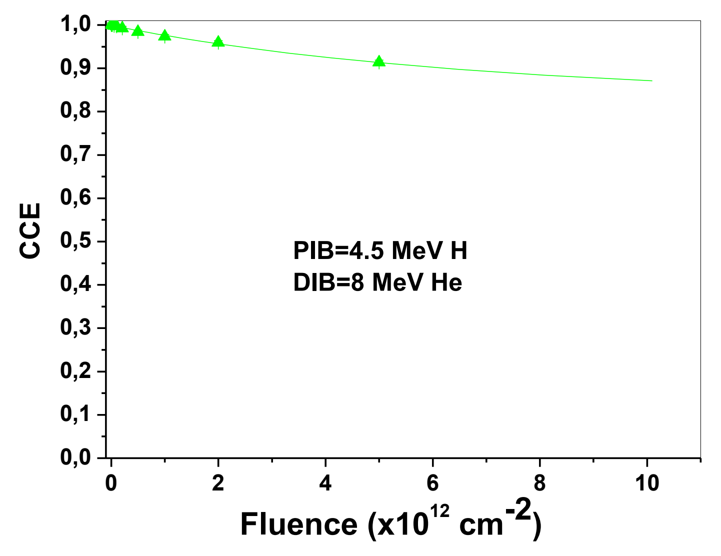
α_n Free parameter

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

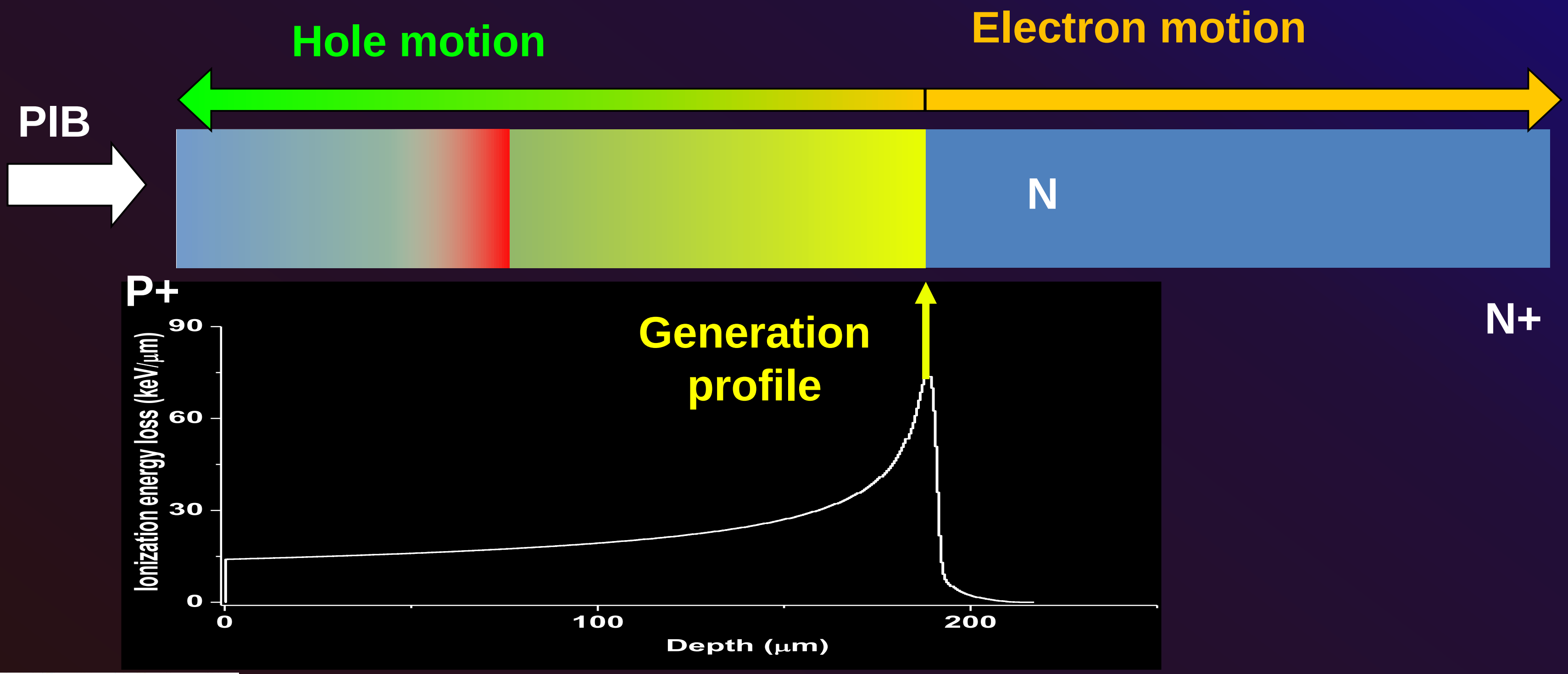

Vacancy profile
Vacancy/ion/μm
100
80
60
40
20
0
0
10
20
30
40
50
Depth (μm)
DIB
P+
N
N+



Long range PIB



PIB=4.5 MeV H
DIB=8 MeV He



Hole motion

Electron motion

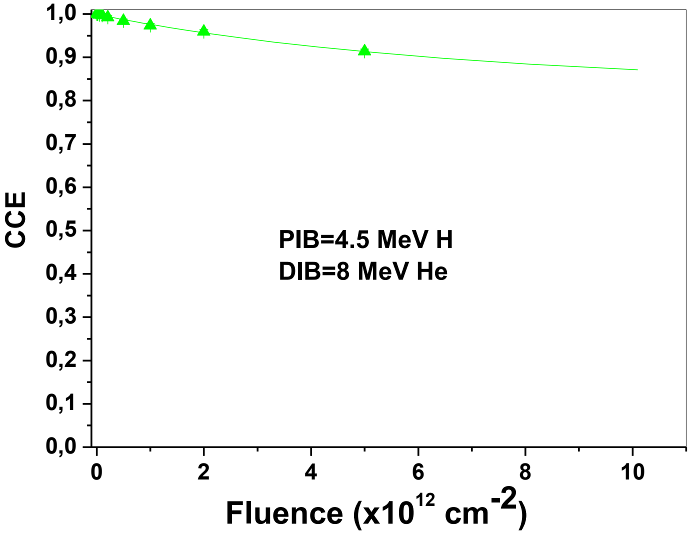
PIB

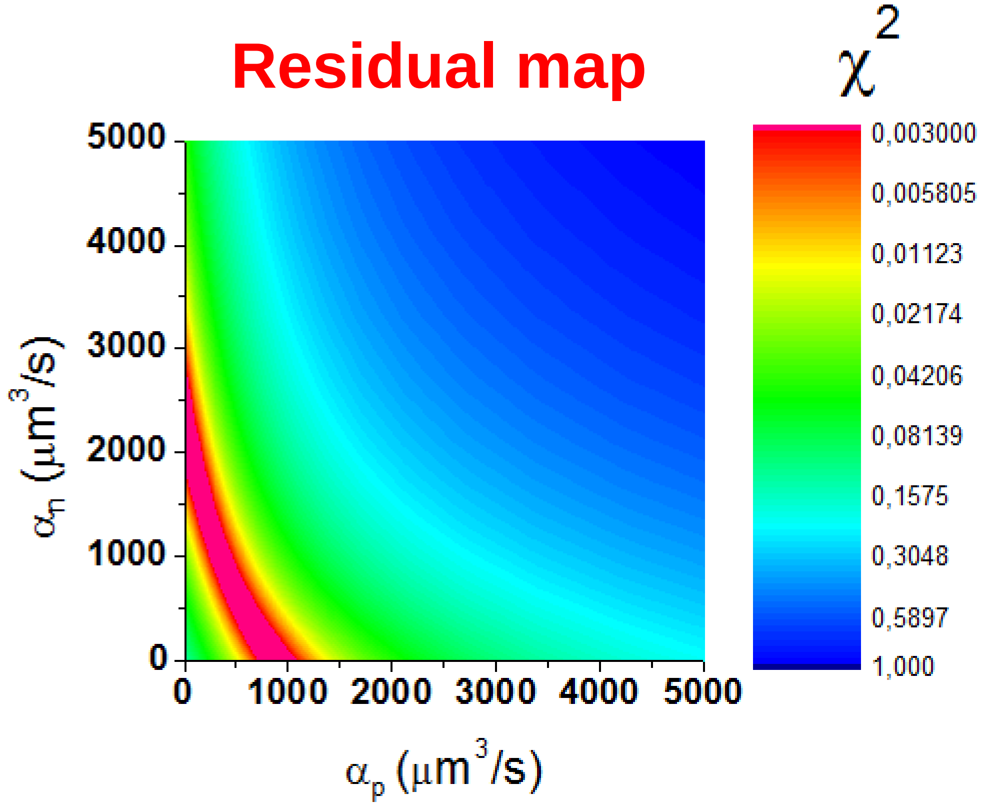
N

P+

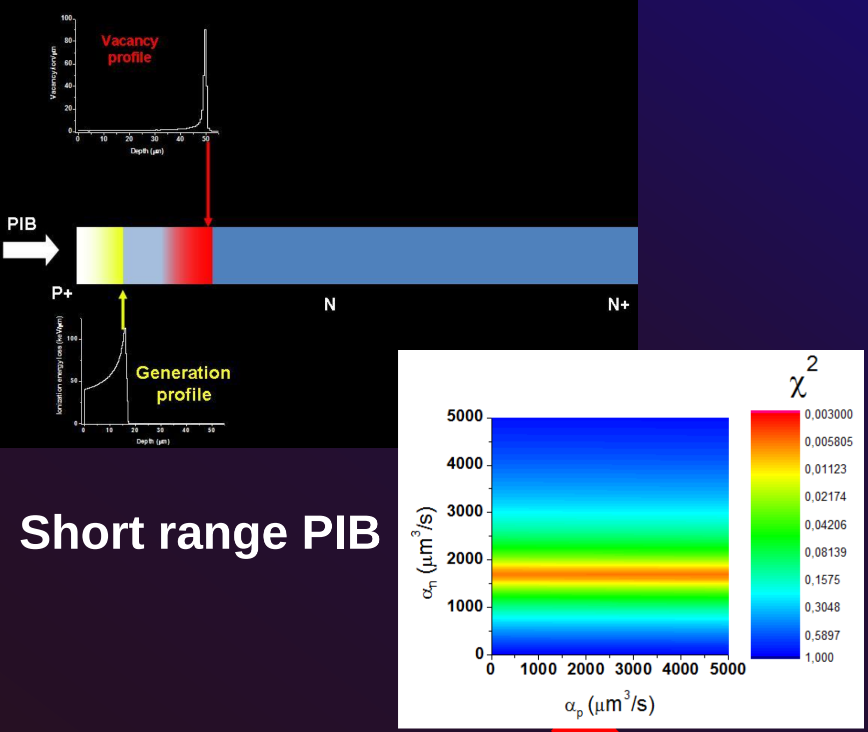
N+

Generation profile

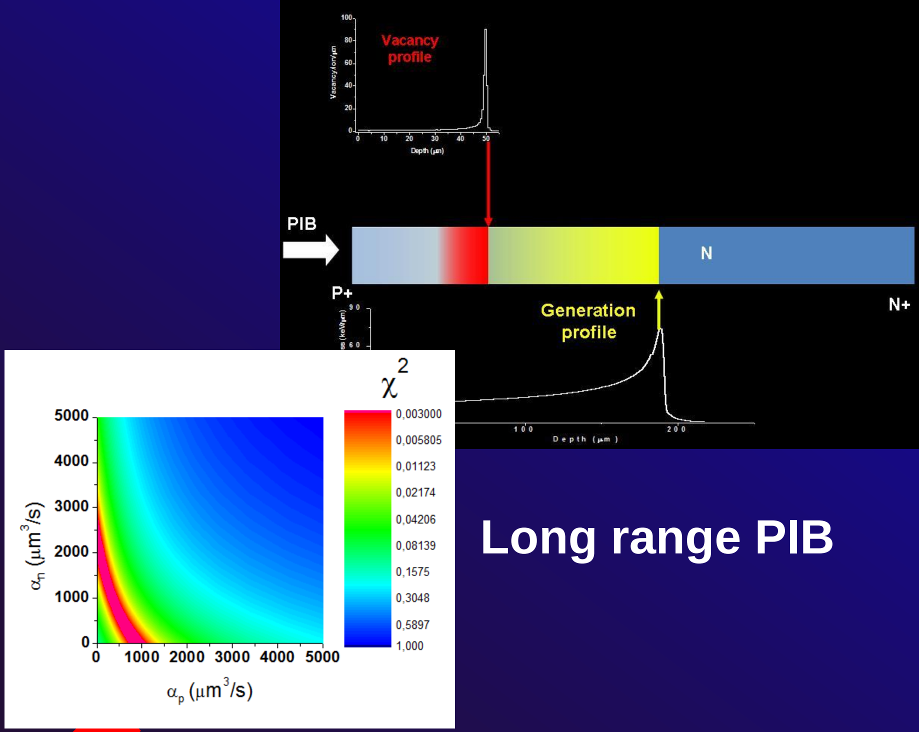



Residual map

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

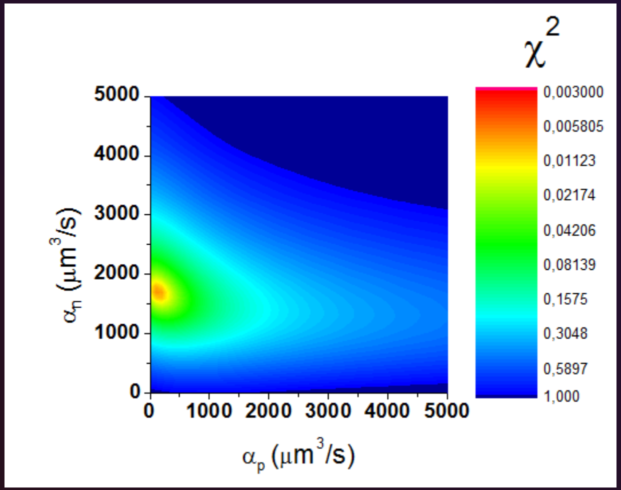


Short range PIB



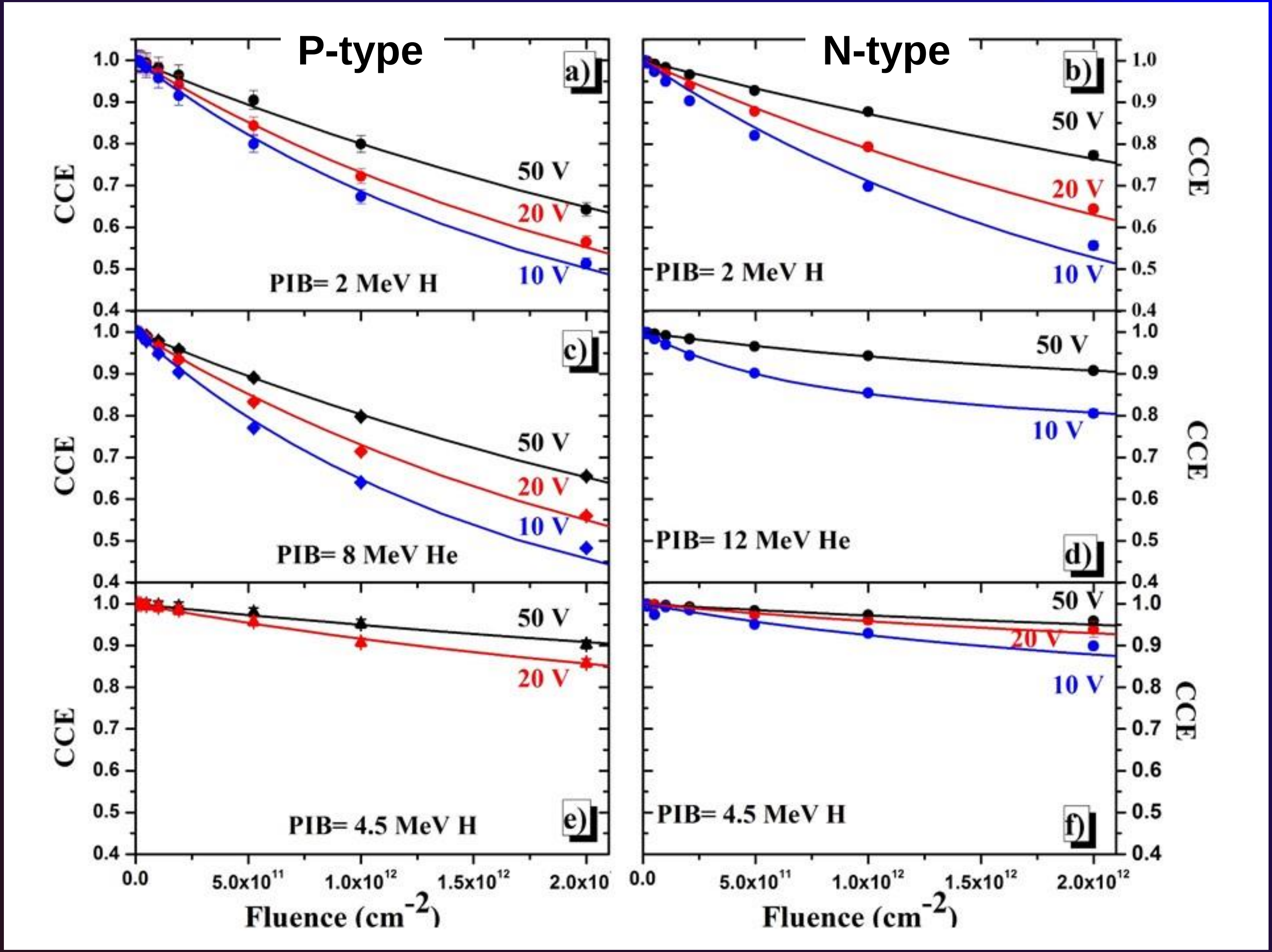
Long range PIB

Bias Voltage = 50 V



α_n=1700 μm^3/s

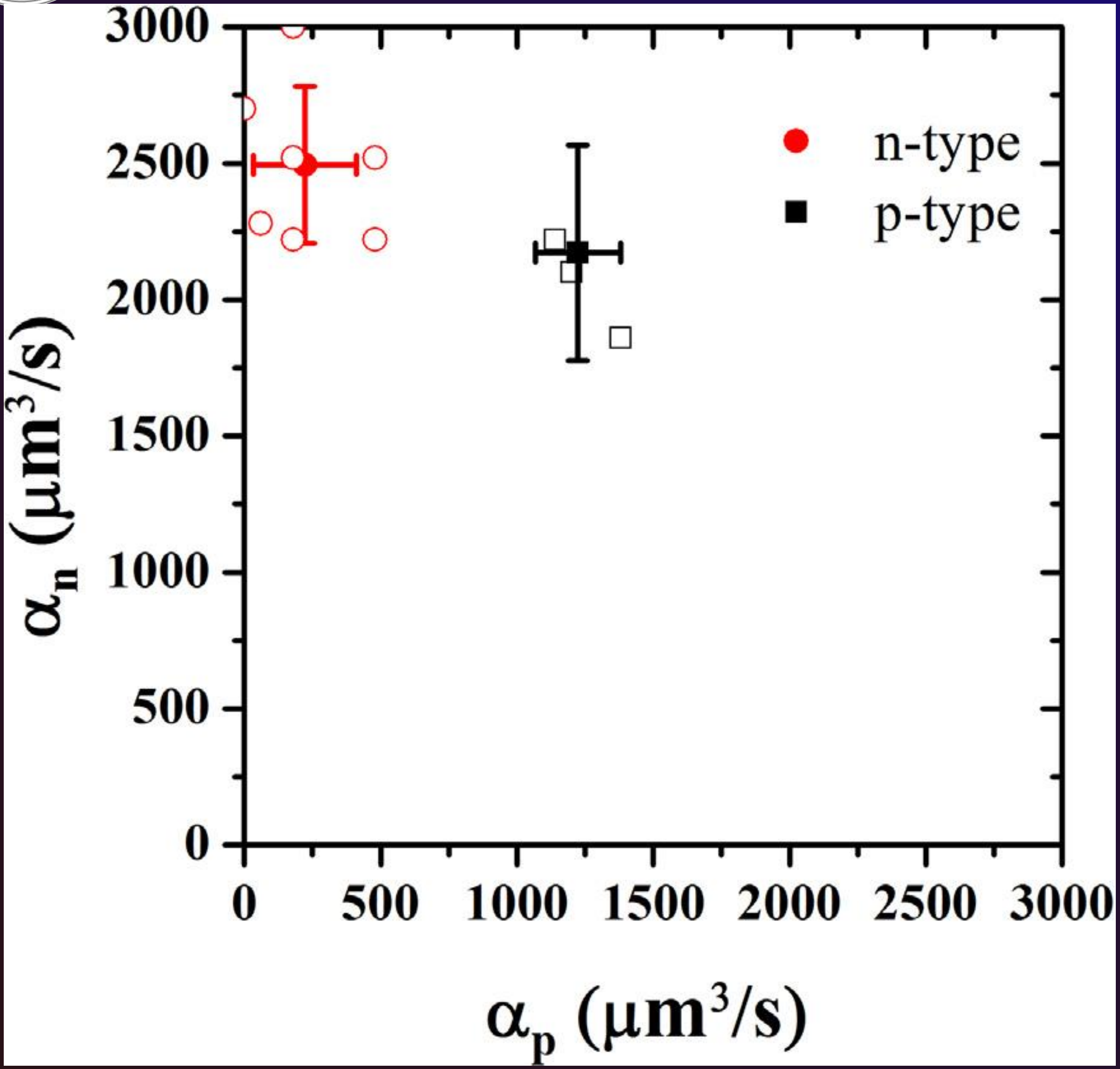
α_p=130 μm^3/s



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

Fz silicon diode Capture coefficient



n-type

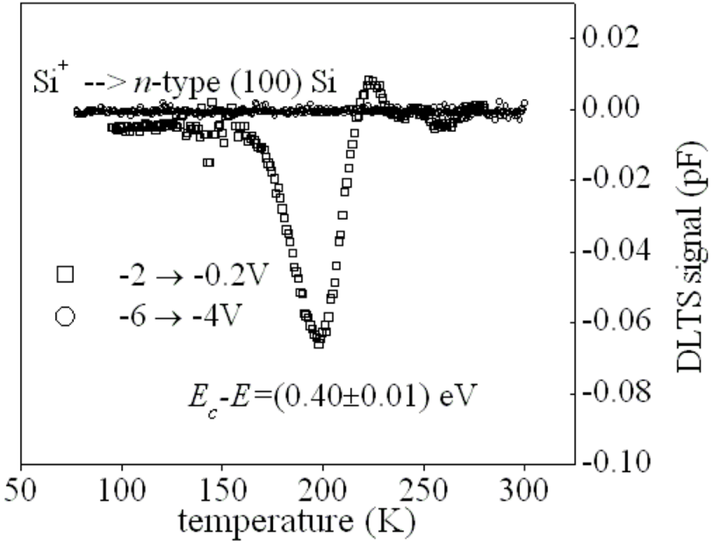
α_n = (2500±300) μm³/s

α_p = (210±160) μm³/s

p-type

α_n = (1310± 90) μm³/s

α_p = (2200±300) μm³/s

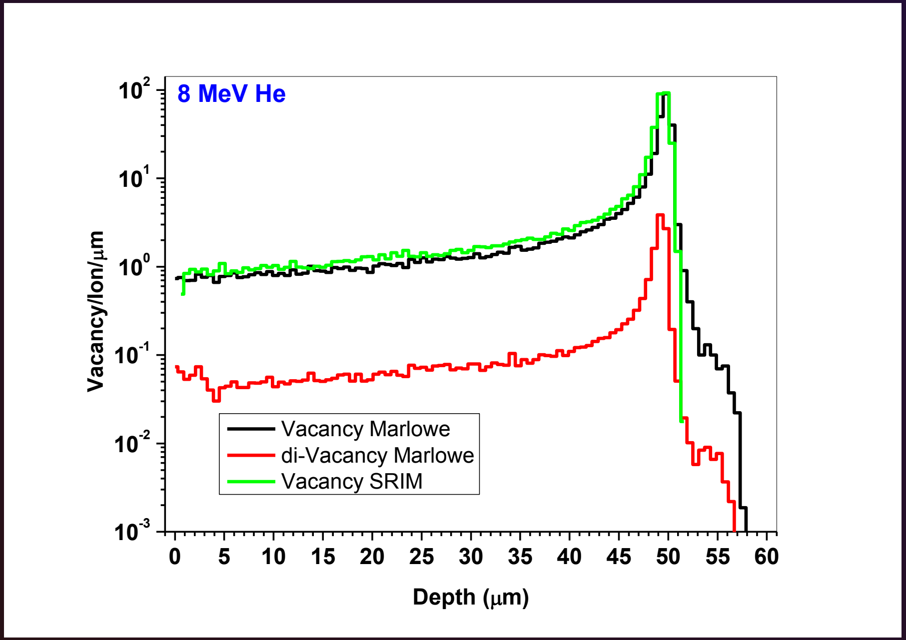


N-type silicon

DLTS measurements

singly V2(−/0) negatively charged divacancy

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



From MARLOWE simulation

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

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

$\sigma_n \approx (3.6 \pm 0.4) \cdot 10^{-15}$ cm^2

Solution of the adjoint equations

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

For very low level of radiation

⬇

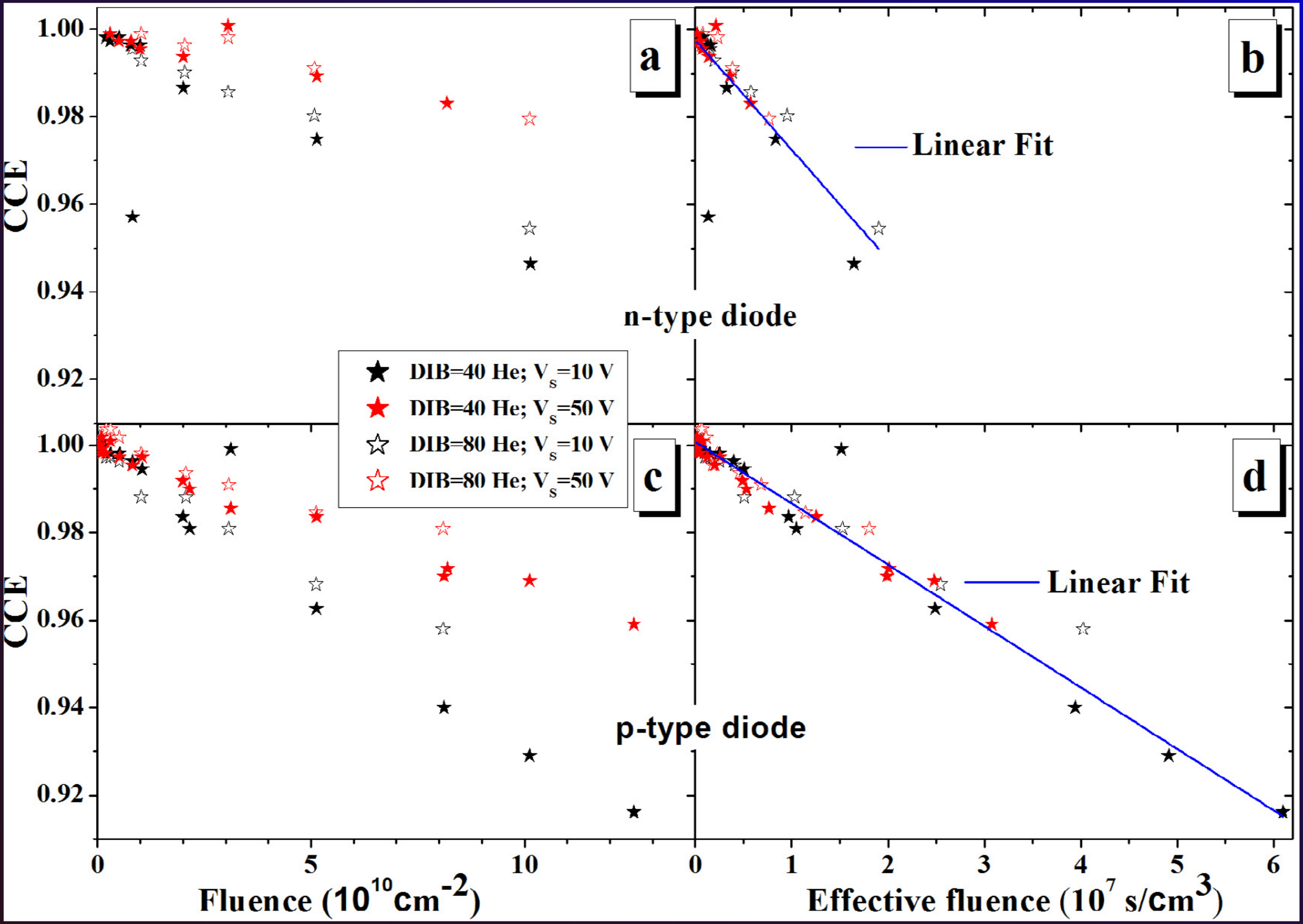
Linearization vs. Φ

⬇

Effective fluence Φ*

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

Very low level of damage



E. Vittone et al. / Nuclear Instruments and Methods in Physics Research B 372 (2016) 128–142

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

Constant vacancy profile
Low displacement damage

$$\mathrm{CCE} = 1 - \mathrm{K}_{\mathrm{ed}} \cdot \mathrm{D}_{\mathrm{d}}$$

$$\mathrm{K}_{\mathrm{ed}} = \frac{\rho}{\mathrm{M}} \cdot \int_0^{\mathrm{R}} \mathrm{dz} \cdot \left\{ \mathrm{k}_{\mathrm{n}} \cdot \sigma_{\mathrm{n}}^{\mathrm{eff}}(\mathrm{z}) \cdot \int_{\mathrm{z}}^{\mathrm{d}} \mathrm{dy} \cdot \frac{\partial \mathrm{F}(\mathrm{y})}{\partial \mathrm{V}_{\mathrm{S}}} \cdot \int_0^{\mathrm{z}} \mathrm{dx} \cdot \gamma(\mathrm{x}) + \mathrm{k}_{\mathrm{p}} \cdot \sigma_{\mathrm{p}}^{\mathrm{eff}}(\mathrm{z}) \cdot \int_0^{\mathrm{z}} \mathrm{dy} \cdot \frac{\partial \mathrm{F}(\mathrm{y})}{\partial \mathrm{V}_{\mathrm{S}}} \cdot \int_{\mathrm{z}}^{\mathrm{d}} \mathrm{dx} \cdot \gamma(\mathrm{x}) \right\}$$

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

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

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

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 approach:

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

Characterization of radiation induced damage:

Induced Charge after irradiation

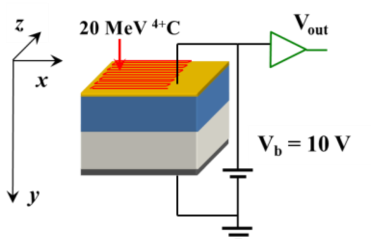
$$\eta = CCE = \frac{Q}{Q_0} = 1 - K \cdot \Phi = 1 - K_{ed} \cdot D_d$$

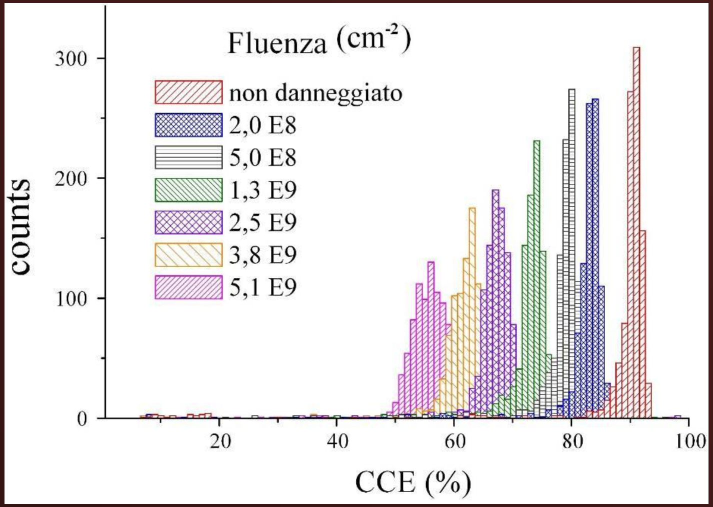
Induced Charge before irradiation

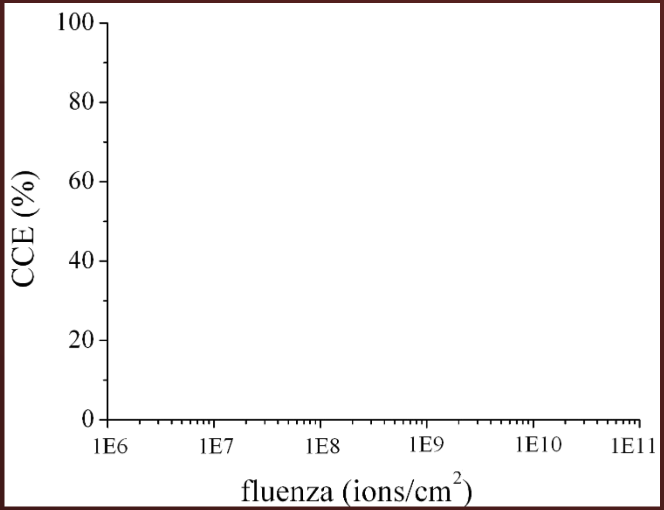
Particle Fluence

Equivalent damage factor

Displacement dose







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

Excess carrier lifetime

$$\tau = \frac{1}{N_{trap}\cdot\sigma\cdot v_{th}}$$

Trap density

Thermal velocity

Capture cross section

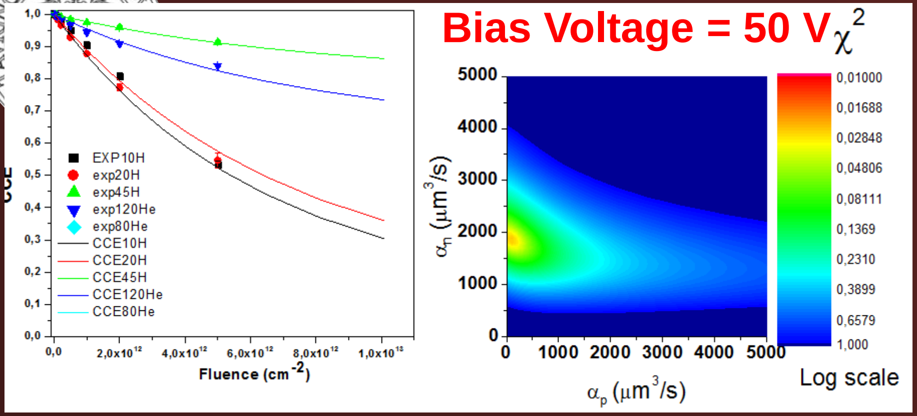
$$N_{trap} = N^0_{trap} + k\cdot\Phi$$

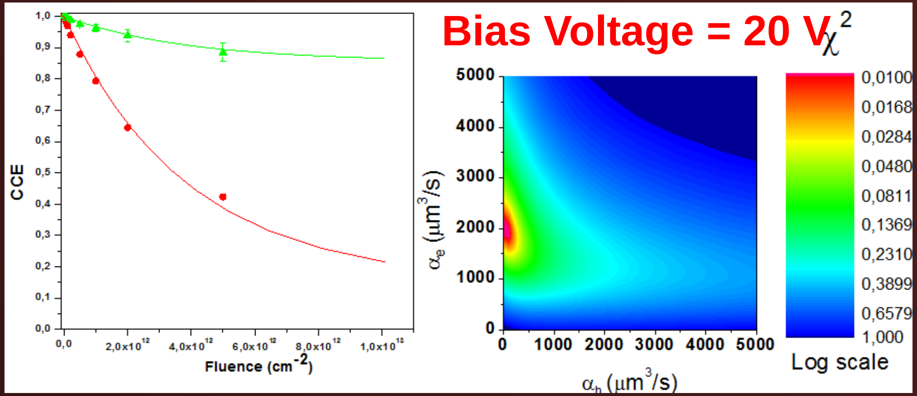
Trap density induced by radiation

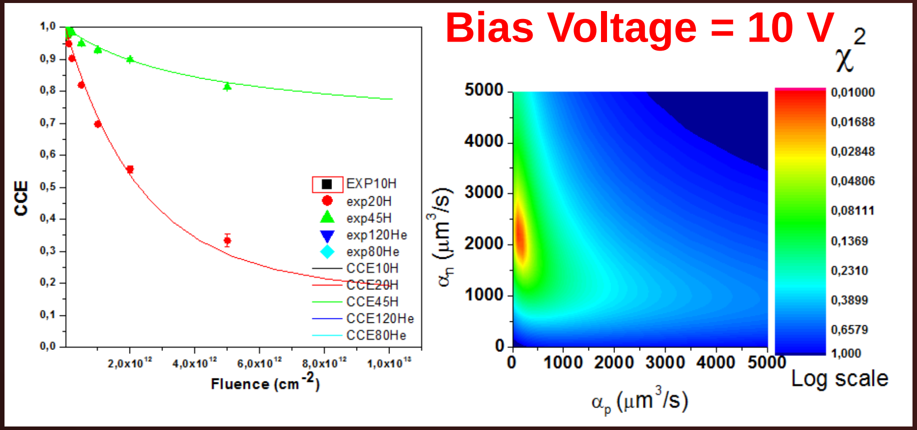
Trap density in pristine material

$$\frac{1}{\tau(\Phi)} = \frac{1}{\tau_0} + K\cdot\Phi$$

n-type Fz silicon diode


Bias Voltage = 50 V


Bias Voltage = 20 V


Bias Voltage = 10 V

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

CAPTURE COEFFICIENTS

$$\alpha_n = (2500 \pm 300)\ \mu m^3/s$$
$$\alpha_p = (210 \pm 160)\ \mu m^3/s$$