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

30 June – 4 July 2025

Single Ion Detector I: How

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www.solid.unito.it

Summary

- ✓ **Ion-solid interaction: semiconductors as charge amplifiers**
- ✓ **Formation of the induced charge signal: The Gunn's theorem**
- ✓ **Principles of the Ion Beam Induced Charge (IBIC) technique: ion spectroscopy**
- ✓ **Examples of IBIC experiments to characterize semiconductors materials and devices.**

Ions to induce material modification/functionalization

↕

Ions as a probe for material characterization

Single keV-MeV ion detection

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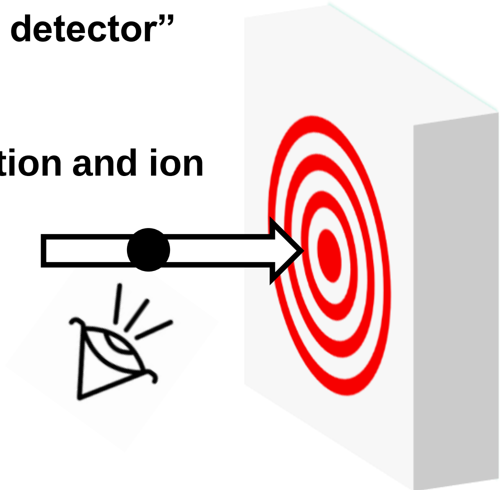
➢ Steven R Schofield et al" Roadmap on atomic-scale semiconductor devices 2025 Nano Futures 9 012001

Detection before the ion interact with the target
e.g. pre-implant determinism systems

➢ **Paul Trap «Concept of deterministic single ion doping with sub-nm spatial resolution"**
J. Meijer et al. Appl. Phys. A 83, 321–327 (2006), DOI: 10.1007/s00339-006-3497-0

➢ **"Image charge detection of ion bunches using a segmented, cryogenic detector"**
P. Räcke et al. J. Appl. Phys. 131, 204502 (2022); doi: 10.1063/5.0096094

Lecture 9: Deterministic single ion implantation using image charge detection and ion traps Speaker: Jan MEIJER (Leipzig University, Germany)

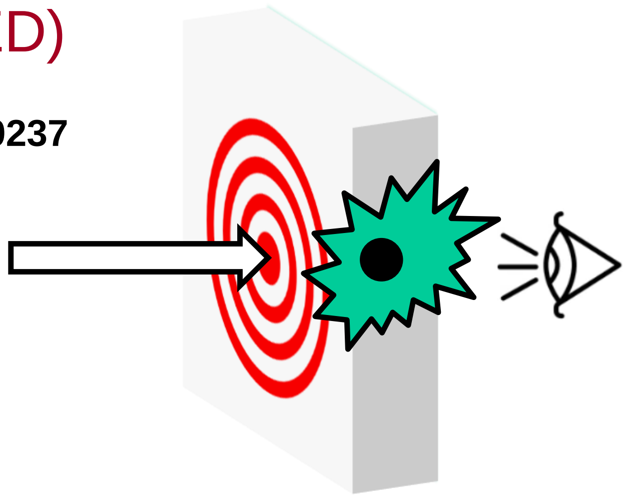


Detection of the ion interaction with the target

➢ Secondary electron detector (SED)

➢ **Single ion implantation of bismuth**
Cassidy N et al. 2021 Phys. Status Solidi a 218 2000237

➢ **Ion Beam Induced Charge (IBIC)**



- **Single ion implantation of bismuth**

Cassidy N et al. 2021 Phys. Status Solidi a 218 2000237

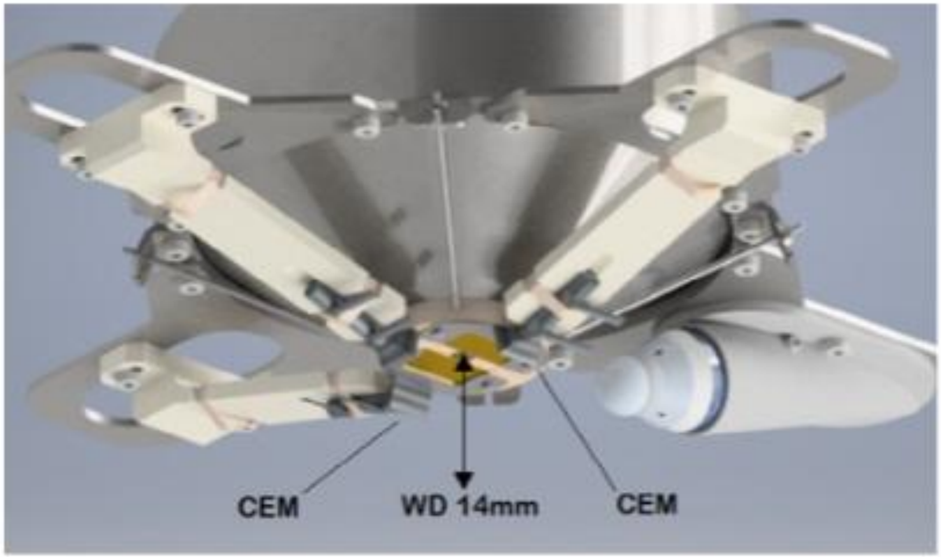


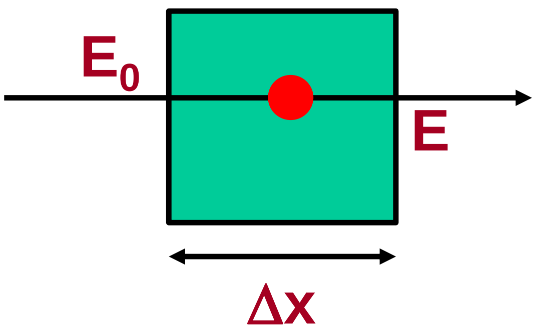
Figure 1. Ionoptika Ltd. detector array on the SIMPLE tool. Labelled are the CEMs that collect the SE signal. These are positioned on the nose cone of the ion gun at a 10 mm distance from the implant site. The working distance of the tool is 14 mm.

Ion induced secondary electron emission

Ion interaction with solids

SLOWING DOWN OF ENERGETIC IONS IN MATTER

Basic concepts



$\Delta E = E_0 - E$

Energy loss per distance Δx traversed

$$\lim_{\Delta x \to 0} \frac{\Delta E}{\Delta x} = \frac{dE}{dx}$$

Stopping power (S) or Specific energy loss

Units: [keV/μm]→ [J/m]=[N] → Stopping Force

Stopping power is the retarding force acting on charged particles

Stopping cross section $\varepsilon = \frac{1}{N}\frac{dE}{dx}$

N= atomic density

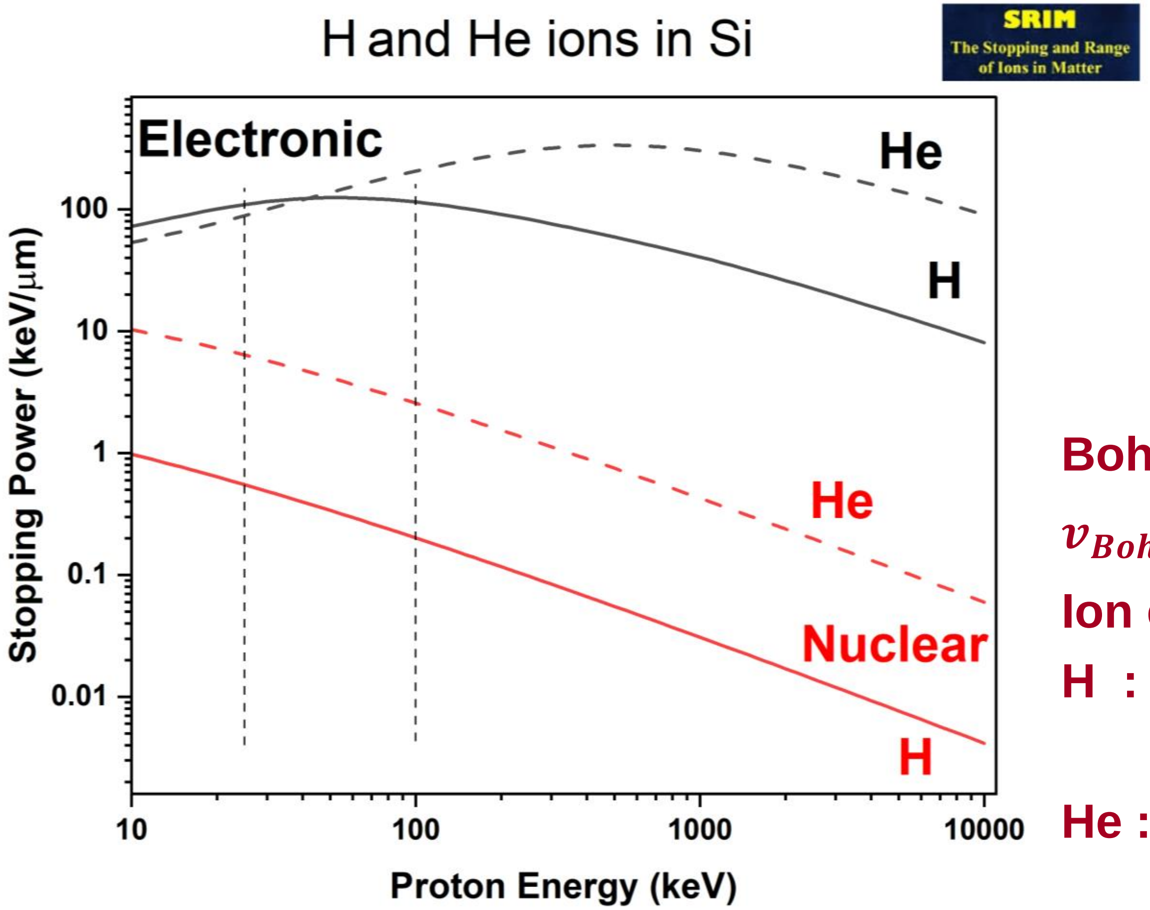
Units: [eV/(10^{15} atoms/cm^2)]

Interaction processes contributing to stopping power:

a) electronic (collision) stopping power →inelastic collisions with the atomic electrons

b) nuclear stopping power → elastic collisions with the target nuclei

~~c) radiative stopping power → Bremsstrahlung emission, Cerenkov radiation, nuclear reactions. These are important only at very high energies.~~



Bohr velocity

$$v_{Bohr} = \alpha c \cong \frac{c}{137} \cong 2.1 \cdot 10^6 m/s$$

Ion energies

H : $E = \frac{1}{2} M_H v_{Bohr}^2 \approx 25\ keV$

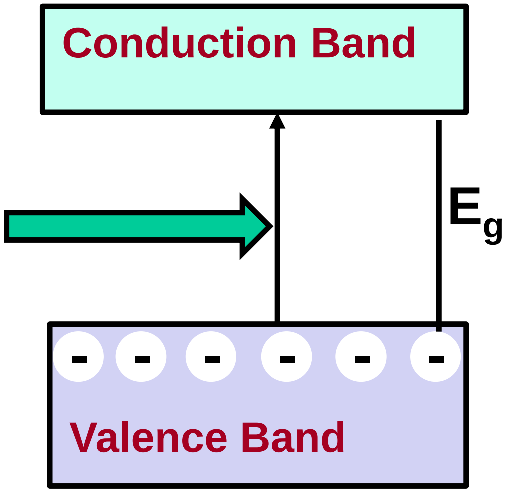
He : $E = \frac{1}{2} M_{He} v_{Bohr}^2 \approx 100\ keV$

Target: semiconductor

Ion energy loss converted into

Ionization
Electron/hole pairs

thermal energy
(phonons)



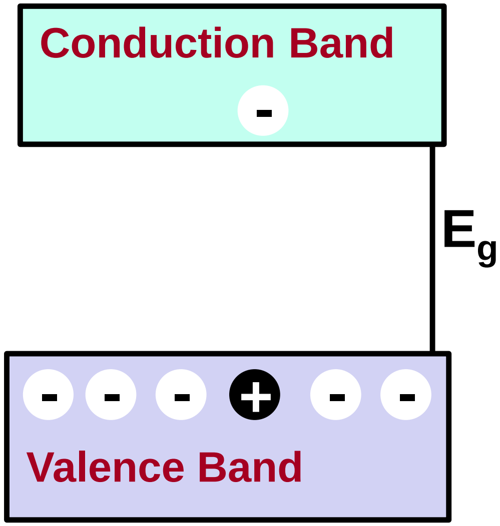
For a given radiation energy E_{Ion}

$N = \frac{E_{Ion}}{\varepsilon}$ = mean number of e/h pairs is

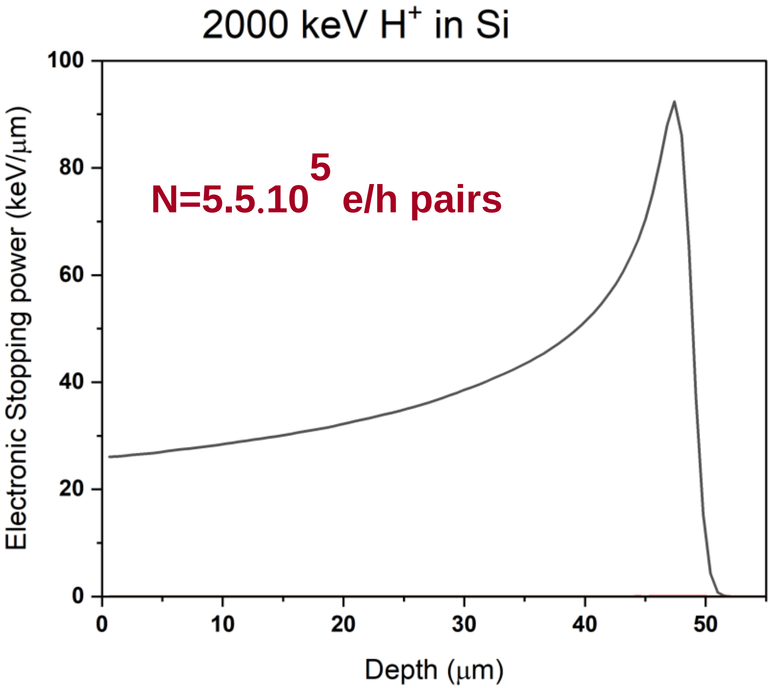
$\varepsilon =$ Mean energy spent for creating one e-h pair; weakly dependent on the type and energy of the radiation

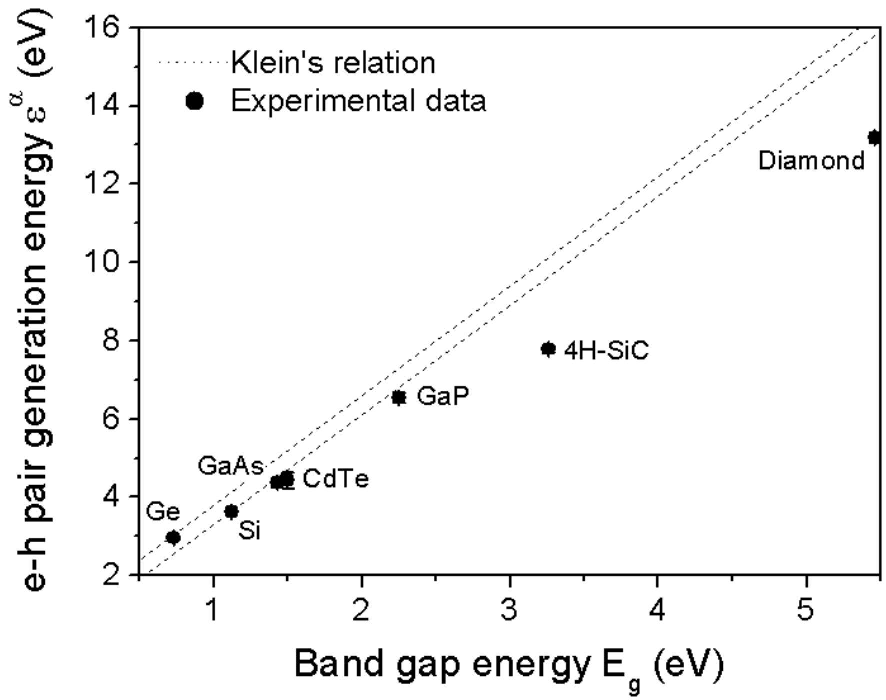
$\sigma^2 = F \cdot N = F \frac{E_{Ion}}{\varepsilon}$ = The variance in N

F is the Fano factor



G. Lutz, Semiconducto Radiation Detectors, ISBN 978-3-540-71678-5 Springer Berlin, 1999.
Jingtian Fang et al." Understanding the Average Electron–Hole Pair-Creation Energy in Silicon and Germanium Based on Full-Band Monte Carlo Simulations", IEEE TRANSACTIONS NS, VOL. 66, NO. 1, Jan. 2019





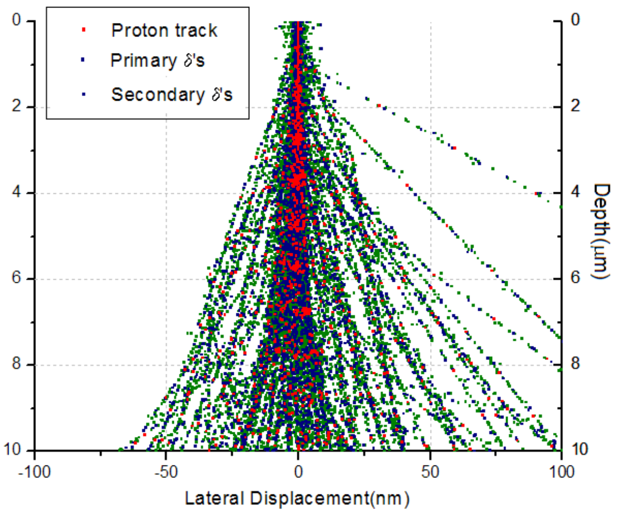


Figure 3.10: Simulation of the δ-rays generated when 1000, 2 MeV protons impinge on 10 µm thick PMMA.

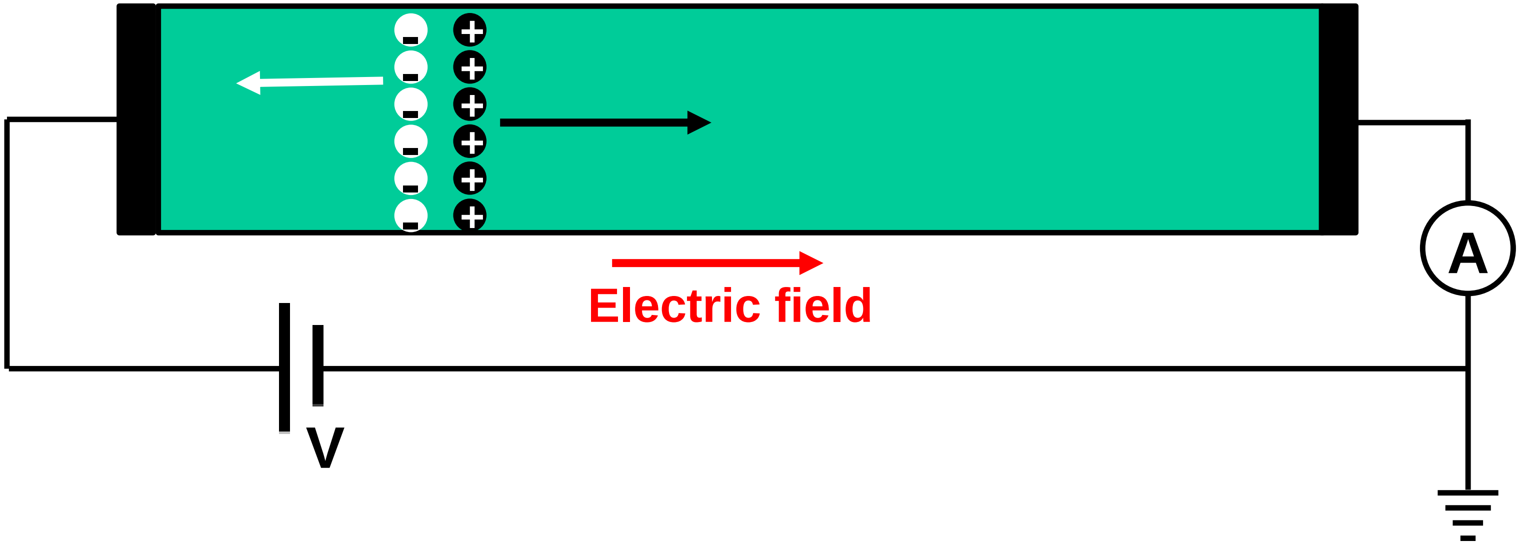
$$N = \frac{E_{Ion}}{\varepsilon} \qquad \Delta N = F\frac{E_{Ion}}{\varepsilon}$$

In Si ε=3.63 eV, F=0.115

CHAMMIKA N B UDALAGAMA PhD thesis
Optimization and Computer Control of the Sub-100 nm, Proton Beam Writing Facility at CIBA
https://scholarbank.nus.edu.sg/entities/publication/43db6390-fd43-4fe2-b729-cee6c6d9f681

Instantaneous charge injection in a semiconductor
What do we measure?

Current



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Physical observable

Instantaneous charge injection in a semiconductor
What do we measure?
Current:

The Haynes-Shockley experiment

https://www.youtube.com/watch?v=zYGHt-TLTl4

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J.R. Haynes, W. Shockley,
“The mobility and life of injecting holes and electrons in germanium,
Phys. Rev. 81, (1951), 835-843.

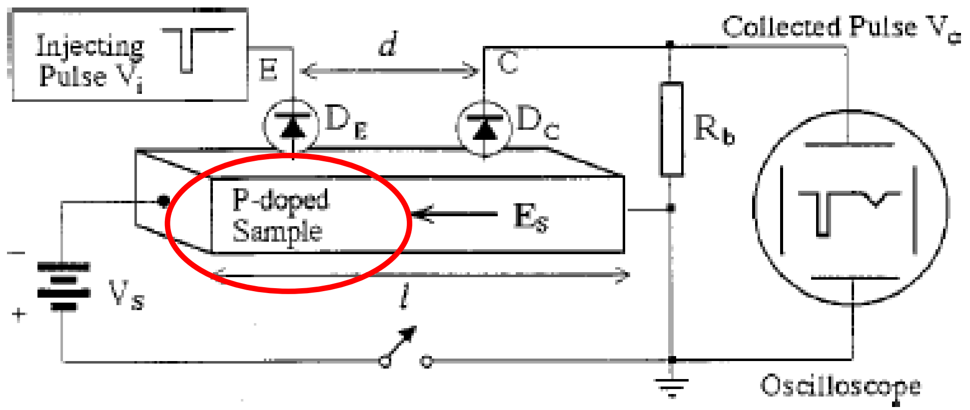


Fig. 1. Block diagram of the Haynes Shockley experiment: D_E and D_C are the emitter and collector point probes.

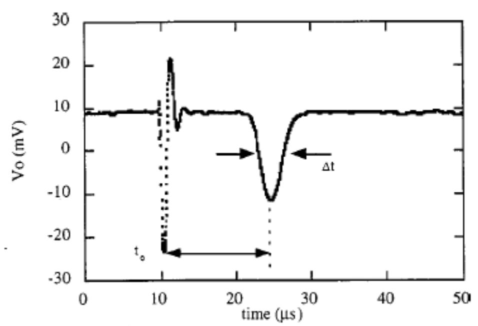
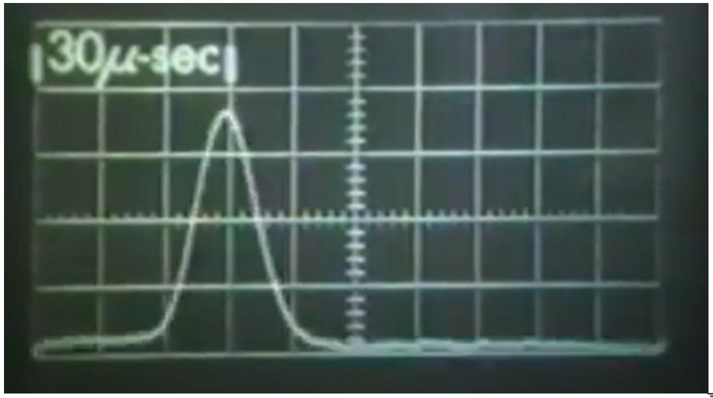
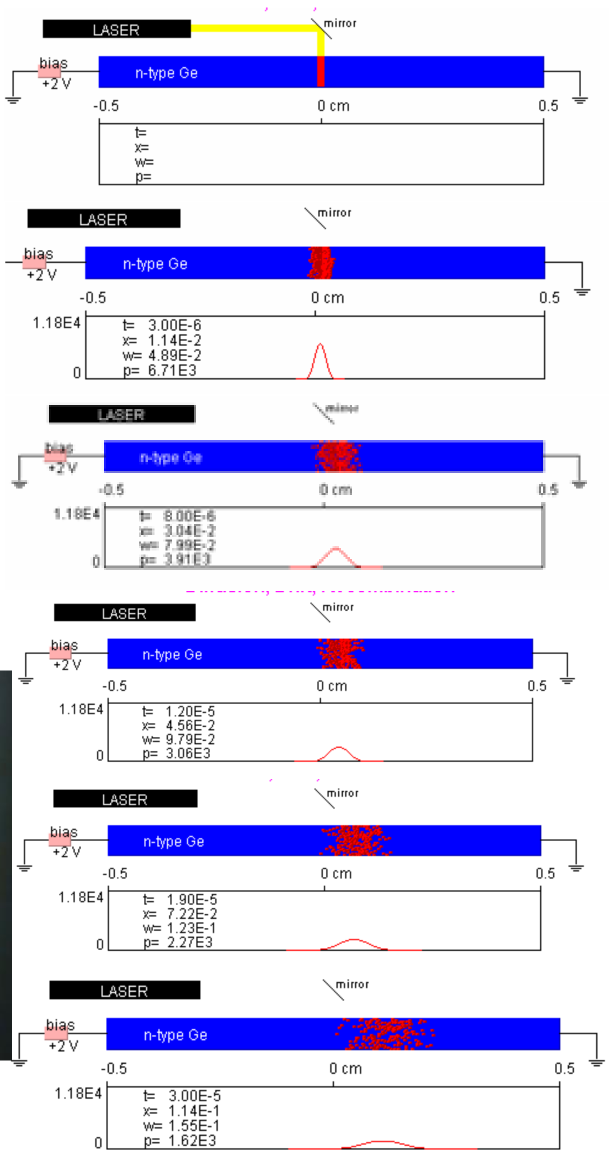


Fig. 11. Waveform observed in a P-doped Ge sample ($\rho = 15\ \Omega$ cm) with electrical injection.





If an amount of net charge is injected suddenly in a semiconductor, the free charge carriers of opposite sign try to balance the injected charge and establish charge neutrality.
How fast the charge neutrality can be achieved is determined by the dielectric relaxation time constant, τd.

$$\tau = \rho \cdot \varepsilon$$

$$\rho = resistivity\,;\varepsilon = dielectric\ constant$$

P-doped Ge;

resistivity about 15 Ω·cm;

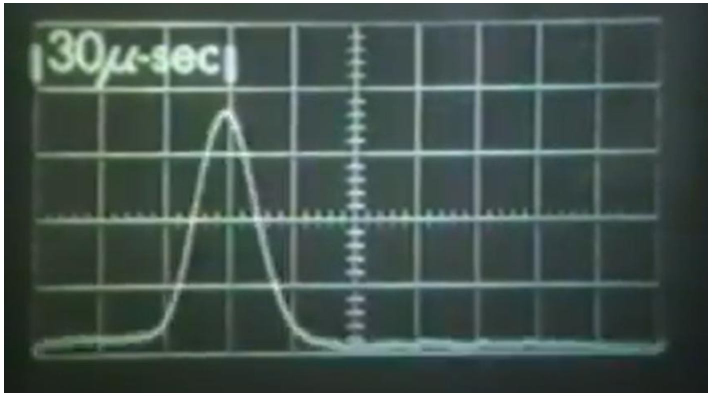
dielectric constant =1.4 pF/cm;

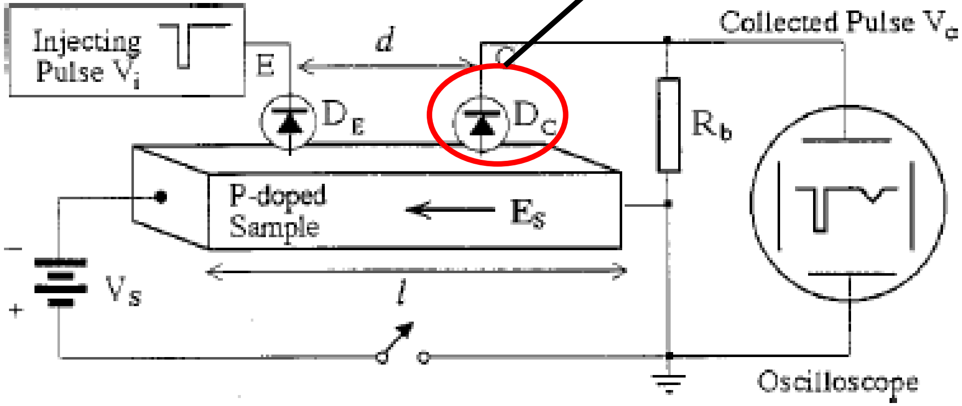
Dielectric relaxation time = 21 ps.

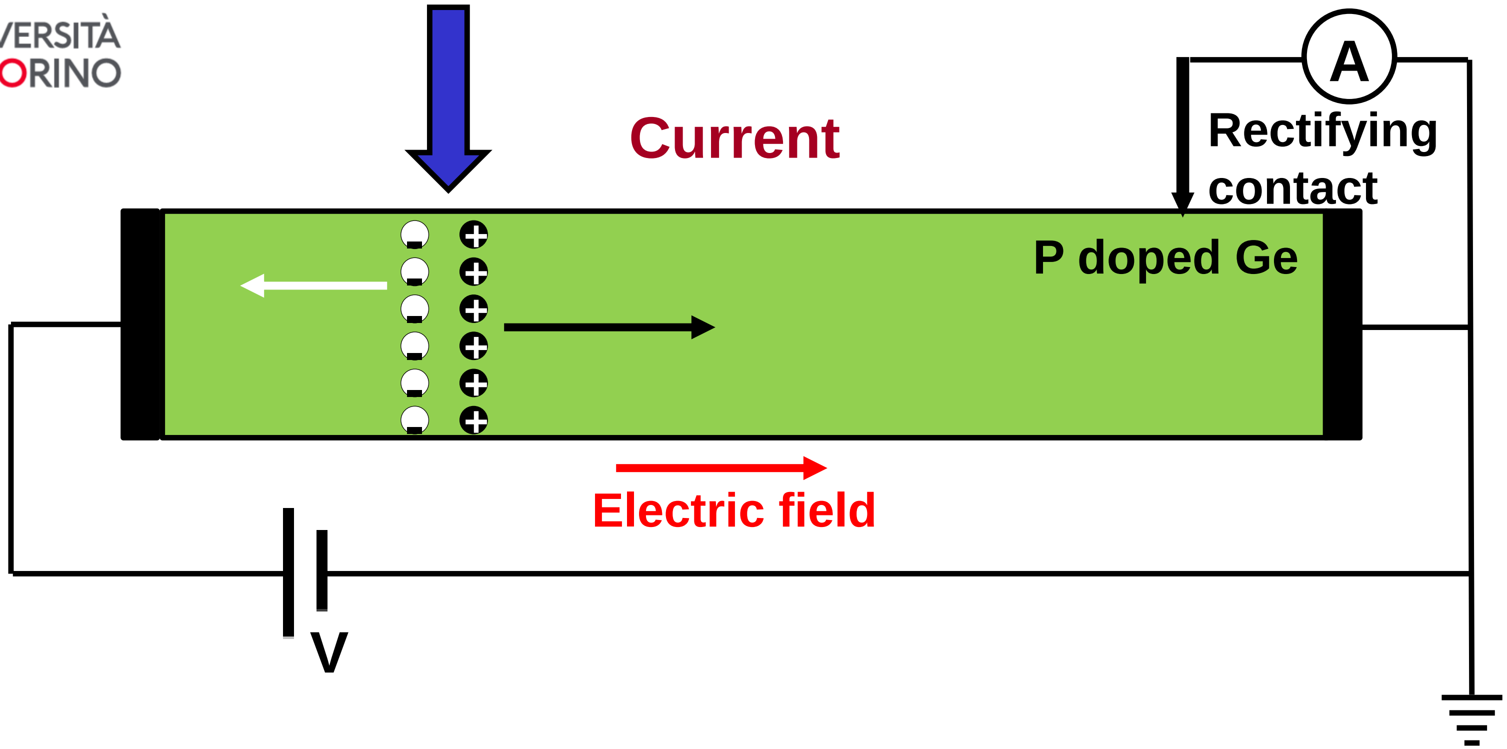
Charge neutrality maintained

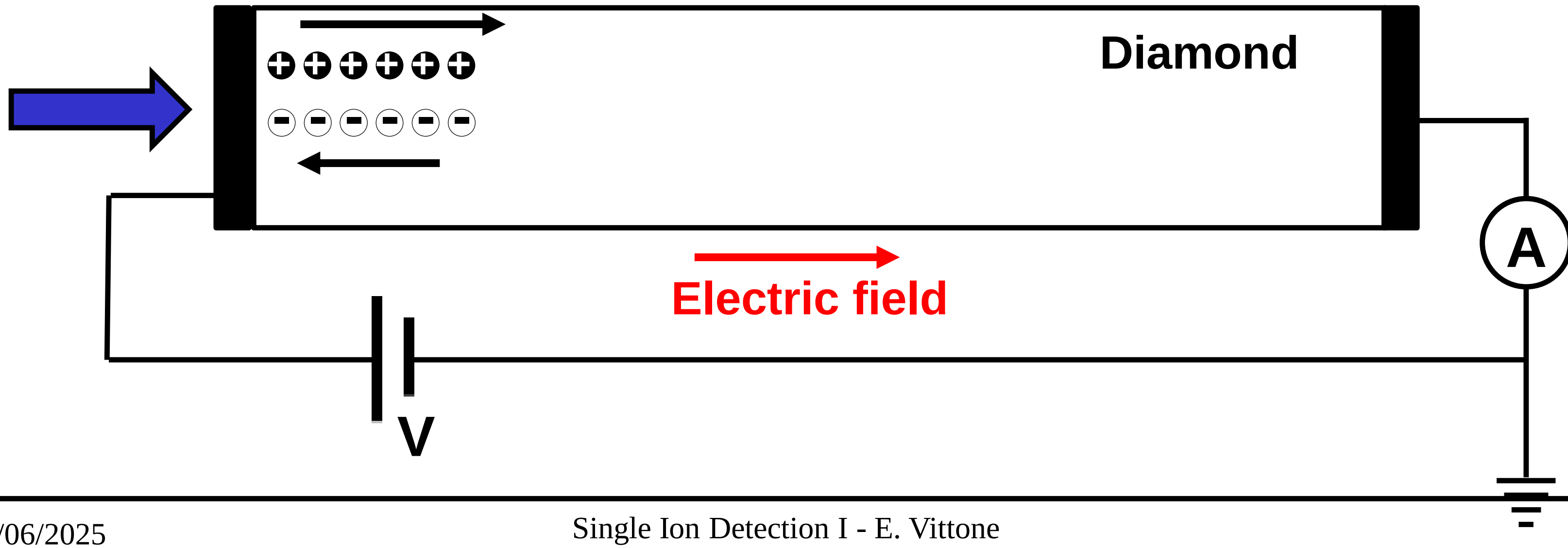
Ambipolar transport

Rectifying contact
Extraction of minority carriers






Current
A
Rectifying contact
P doped Ge
Electric field
V


Diamond
A
Electric field
V

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NIMB 93 (1979) 160, 73

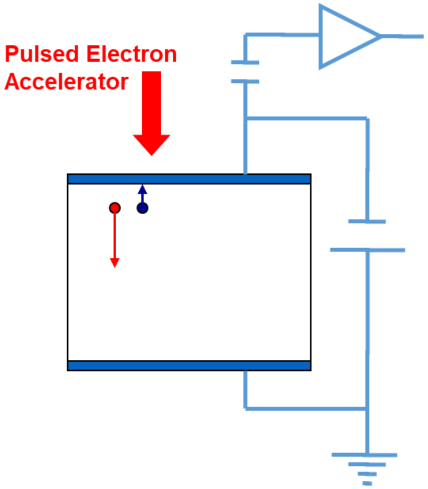
ELECTRICAL PROPERTIES AND PERFORMANCES OF NATURAL DIAMOND NUCLEAR RADIATION DETECTORS

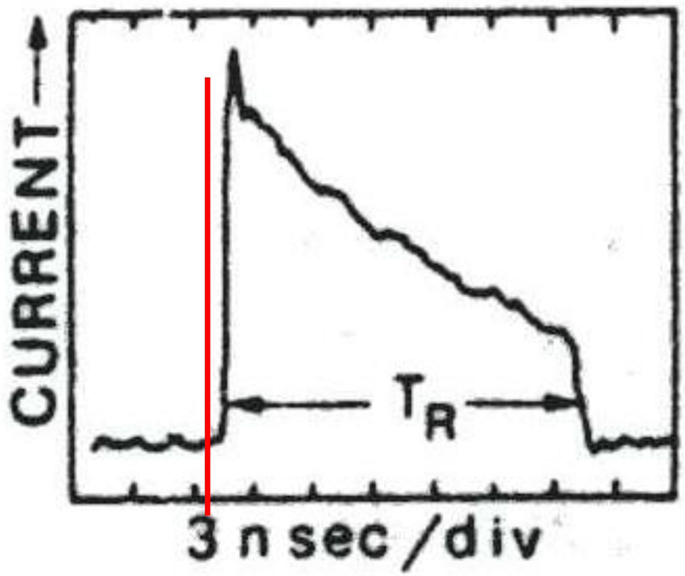
C. CANALI[1], E. GATTI[2], S. F. KOZLOV[4], P. F. MANFREDI[3], C. MANFREDOTTI[5], F. NAVA[1], and A. QUIRINI[5]

[1] *Institute of Physics, University of Modena, Modena, Italy*
[2] *Institute of Physics, Politecnico di Milano and INFN Milano, Milan, Italy*
[3] *Cesnef, Politecnico di Milano and INFN Milano, Milan, Italy*
[4] *Institute of Physics Lebedev, Academy of Sciences of U.S.S.R., Moscow, U.S.S.R.*
[5] *Institute of Physics, University of Bari, Bari, Italy*

40 keV pulsed electron accelerator, 70 ps ,

RevScInstr 41, 1205 (1970)





Natural IIa diamond from Yakutia (Siberia USSR)

400 µm thick

$\rho \approx 10^{15}$ Ω·cm; ε=0.5 pF/cm;

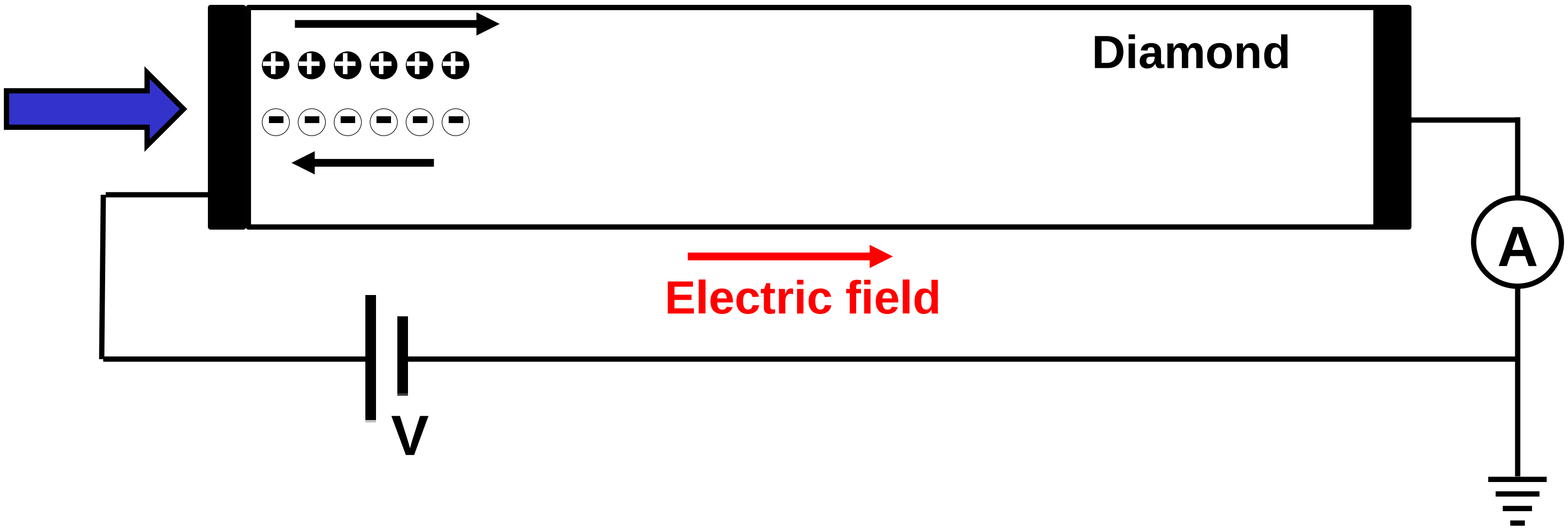
Dielectric relaxation time = 500 s.

Charge neutrality not maintained

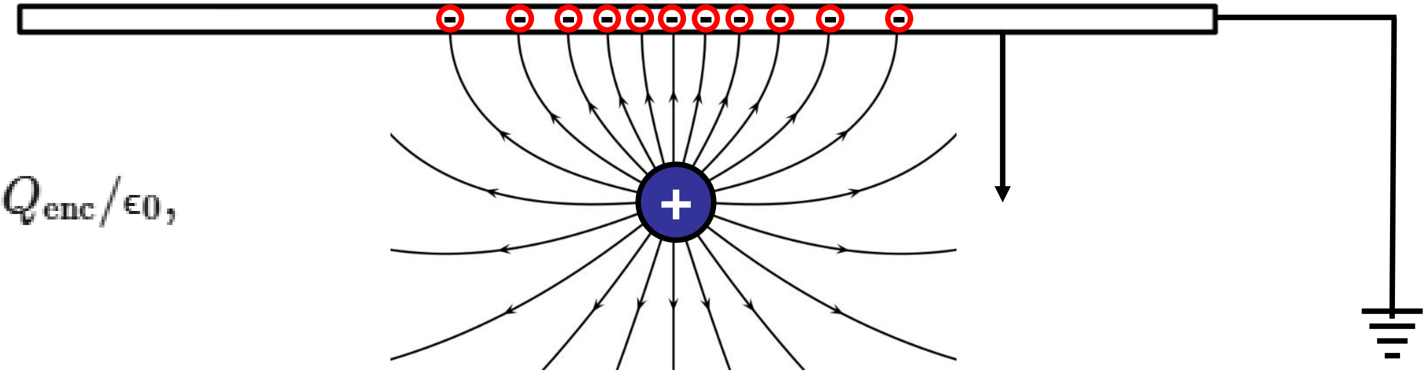
$$T_R = \text{drift time} = \frac{\text{Thickness}}{\text{Drift velocity}}$$

Current decay -> carrier lifetime

Solid state ionization chamber



Charge carriers (electrons-holes) generated by a ionizing particle move in an external electric field and induce charge on the electrodes



$$\oint_S \vec{E} \cdot \vec{da} = Q_{\text{enc}}/\epsilon_0,$$

Lecture 9: Deterministic single ion implantation using image charge detection and ion traps Speaker: Jan MEIJER (Leipzig University, Germany)

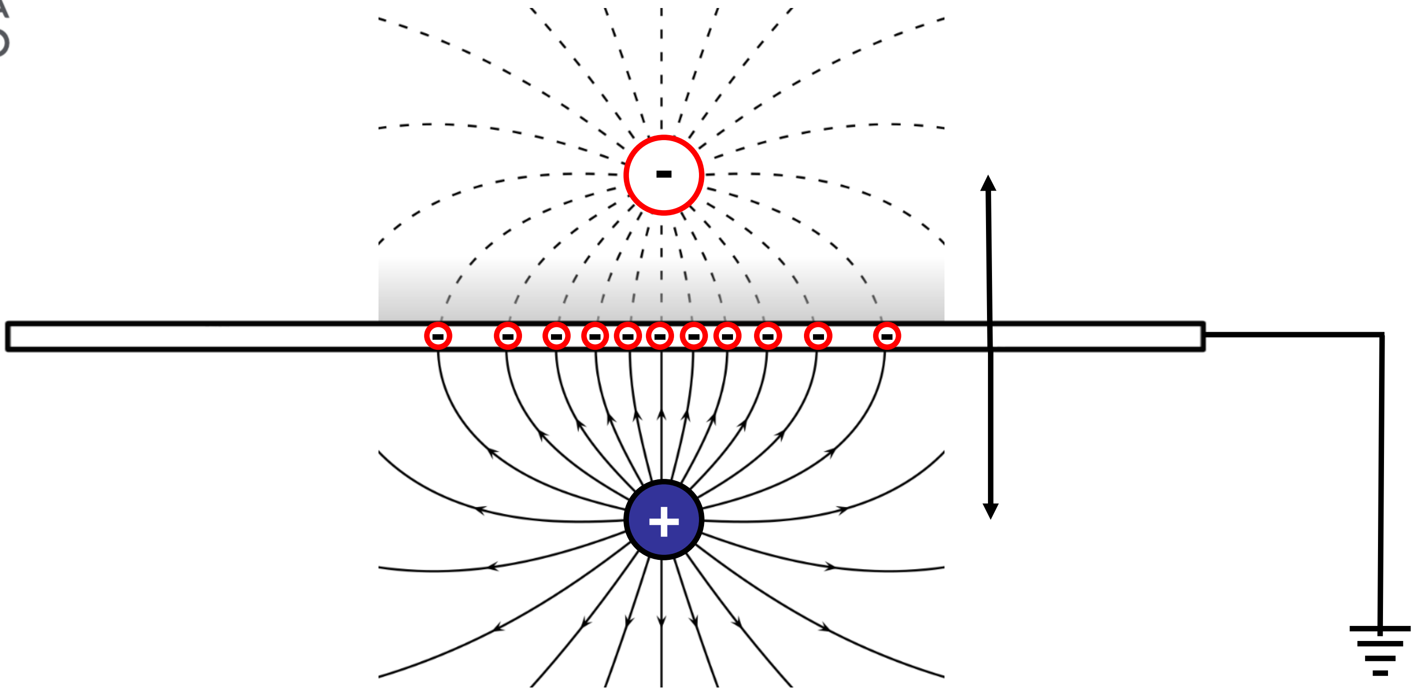


Image charge method

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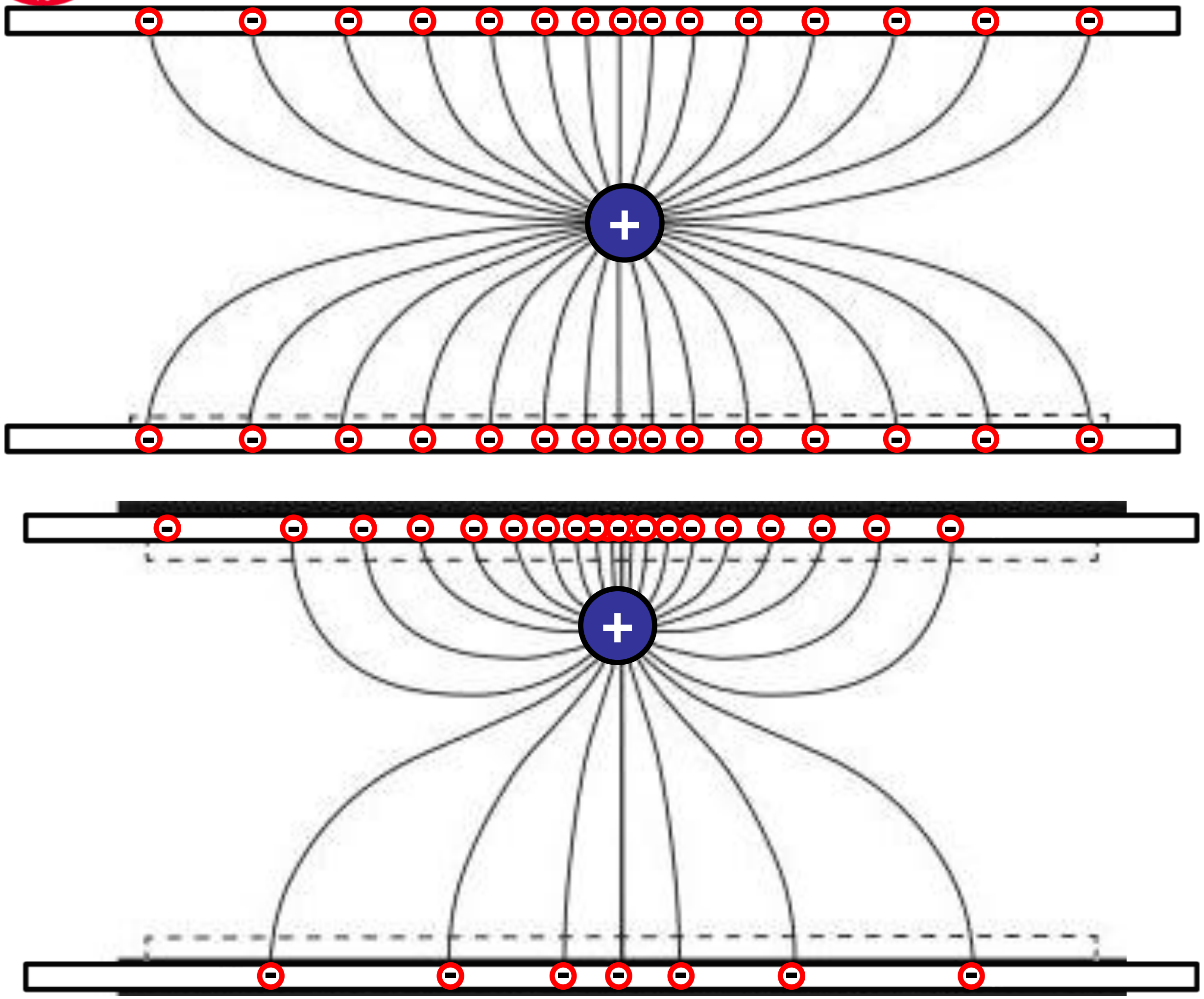


Gunn’s theorem

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

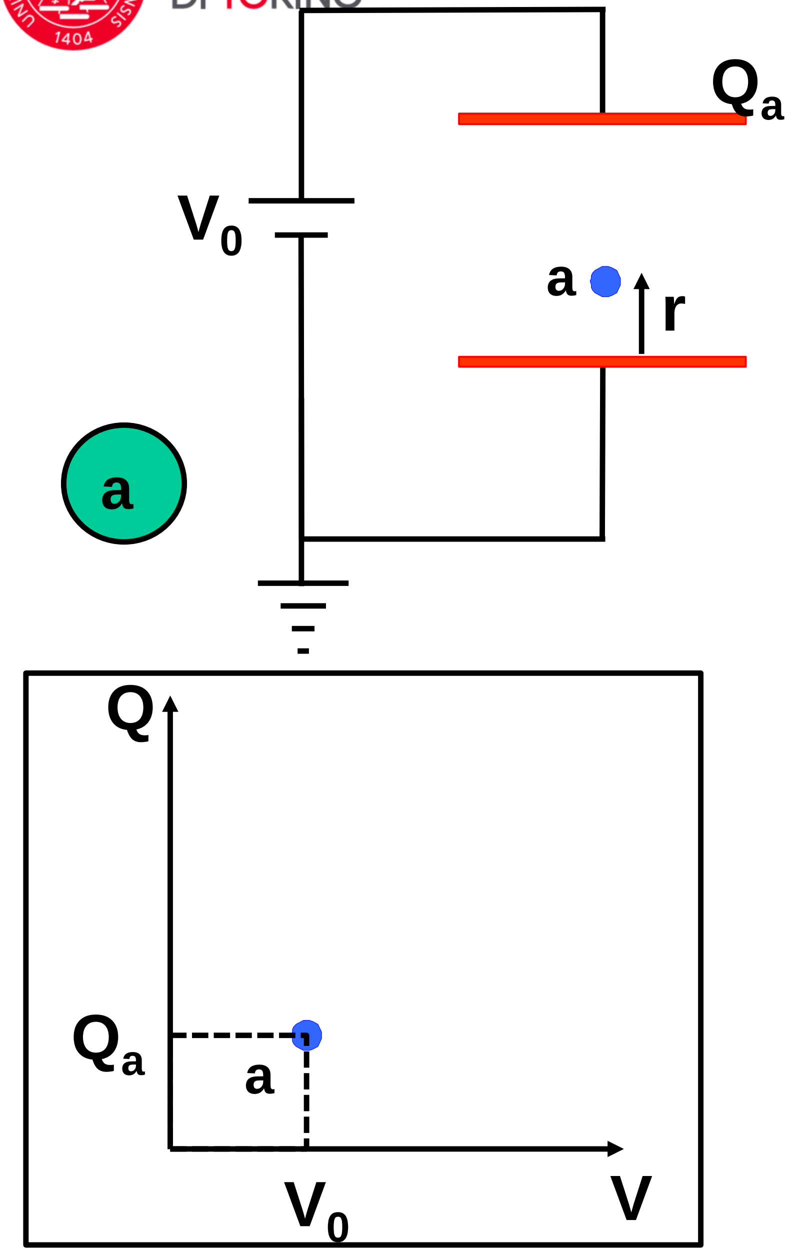
A GENERAL EXPRESSION FOR ELECTROSTATIC INDUCTION AND ITS APPLICATION TO SEMICONDUCTOR DEVICES

J. B. GUNN

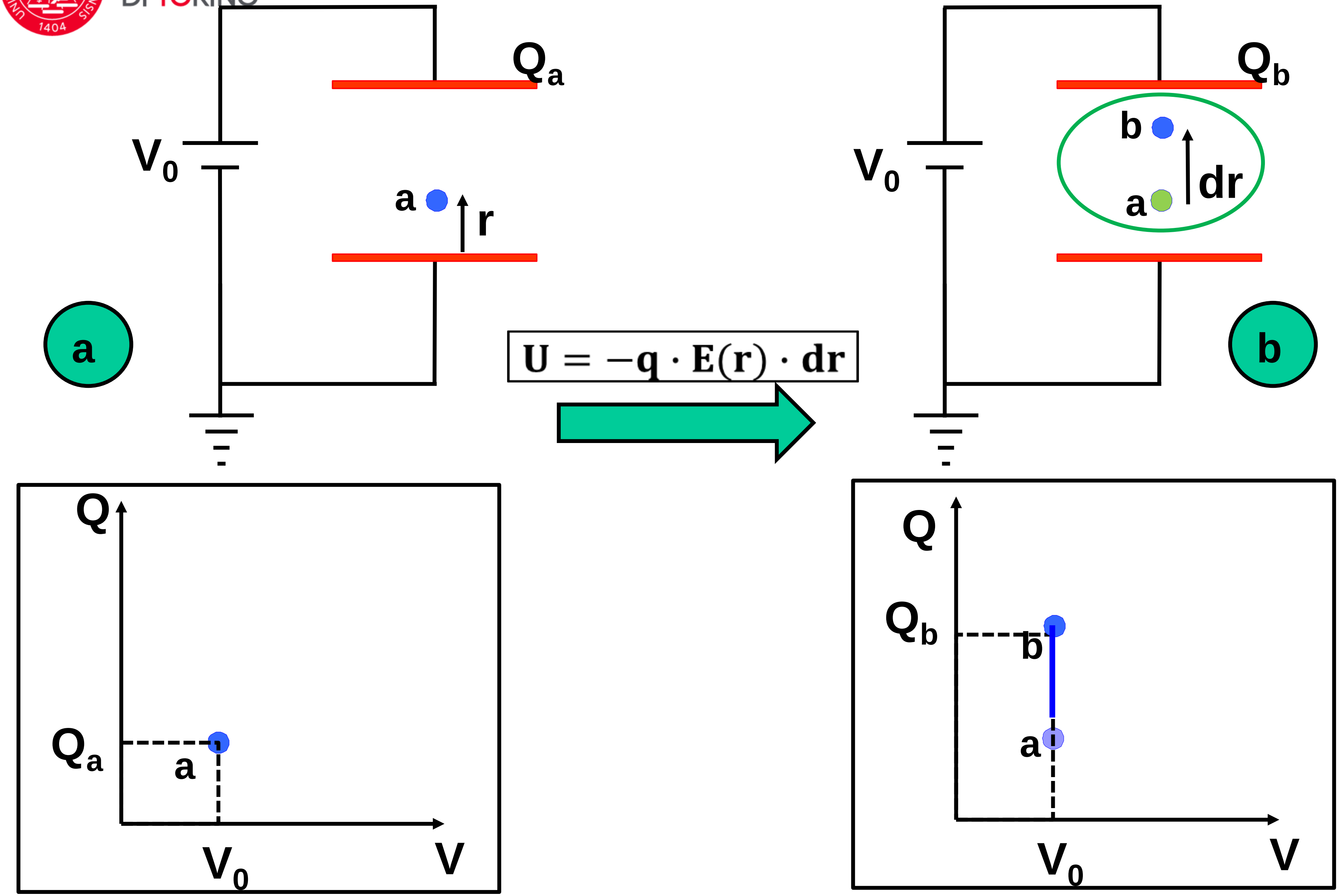
IBM Watson Research Center, Yorktown Heights, New York

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

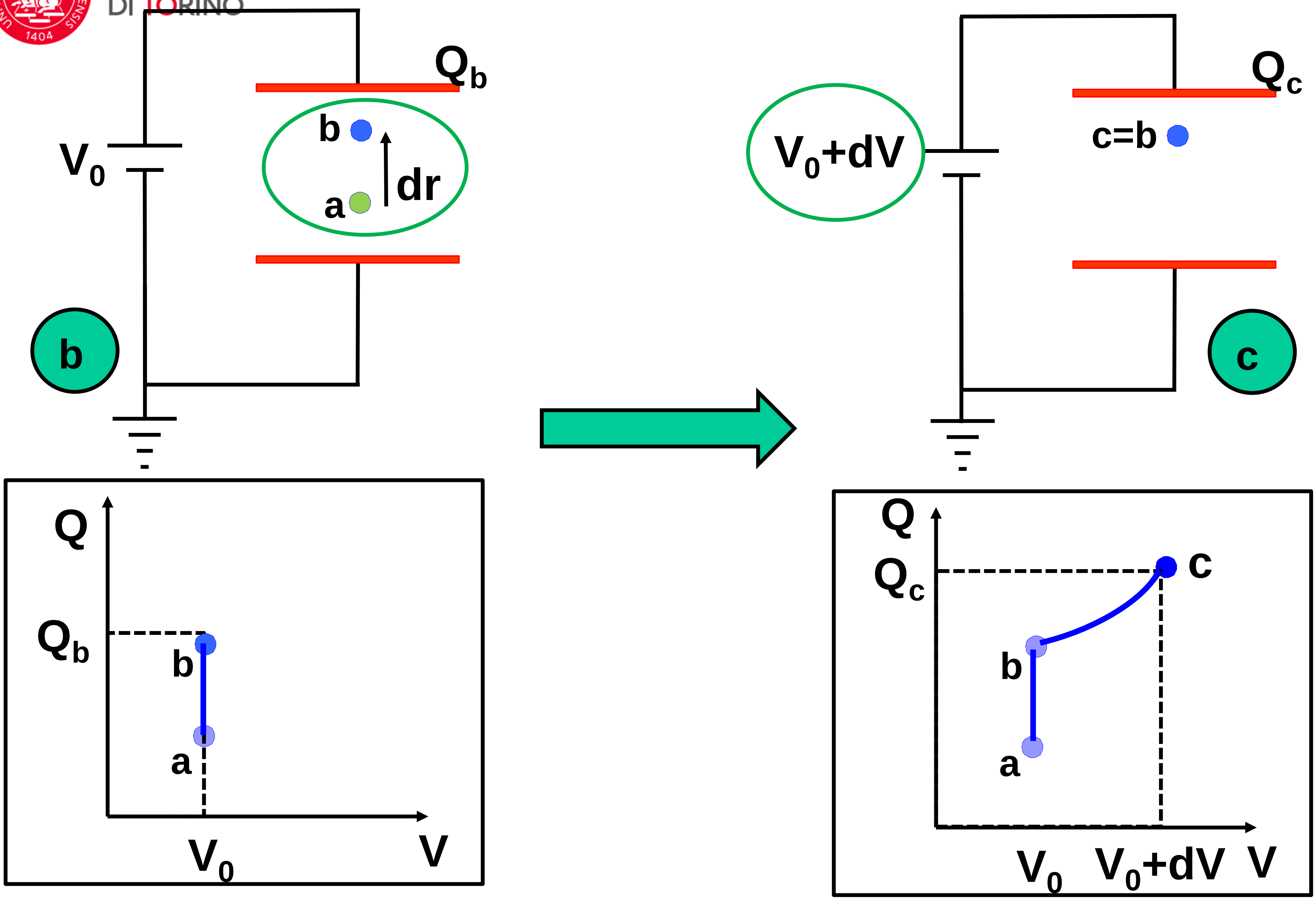
Abstract—A new formula is deduced, under rather general conditions, for the charges induced upon a system of conductors by the motion of a small charge nearby. The conditions are found under which this result can be simplified to yield various previously derived formulas applicable to the problem of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



Q_a
V_0
a
r
a
Q
Q_a
a
V_0
V



Q_a
V_0
a
r
a
$U = -q \cdot E(r) \cdot dr$
Q_b
V_0
b
a
dr
b
Q
Q_a
a
V_0
V
Q
Q_b
b
a
V_0
V



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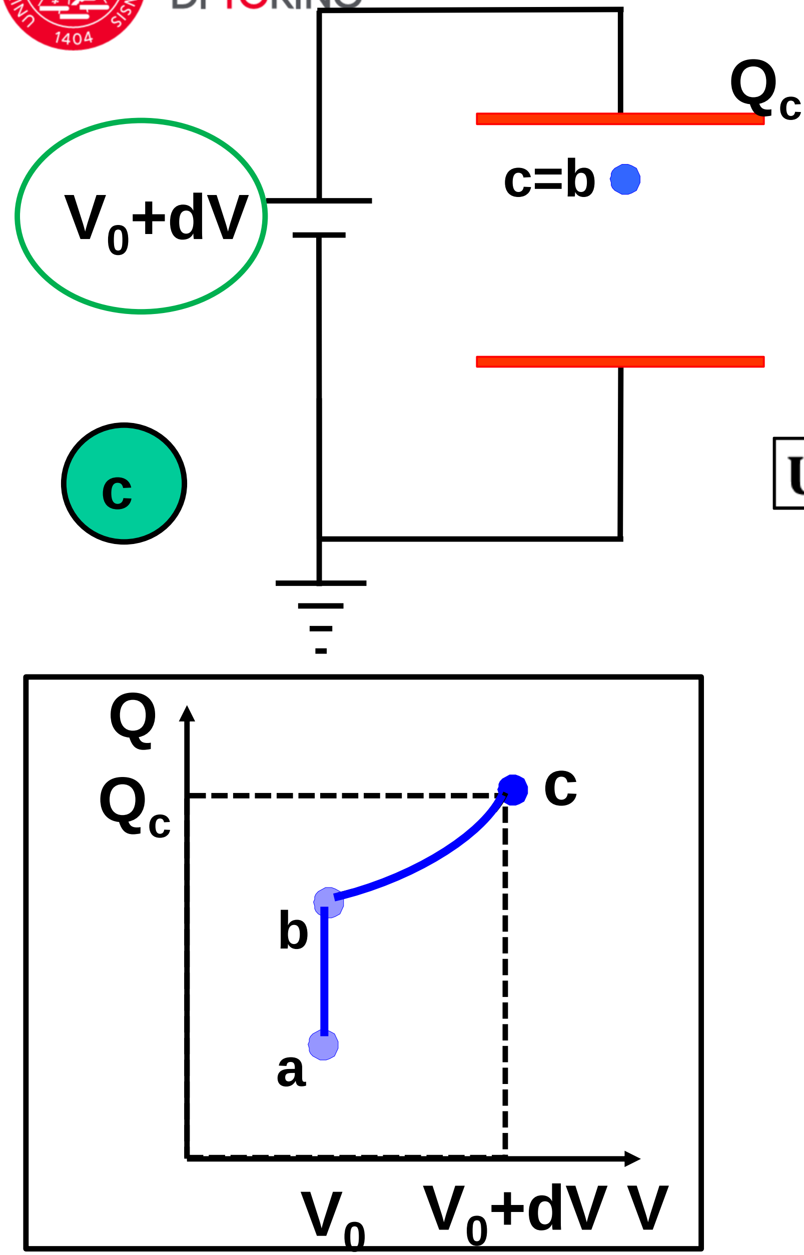
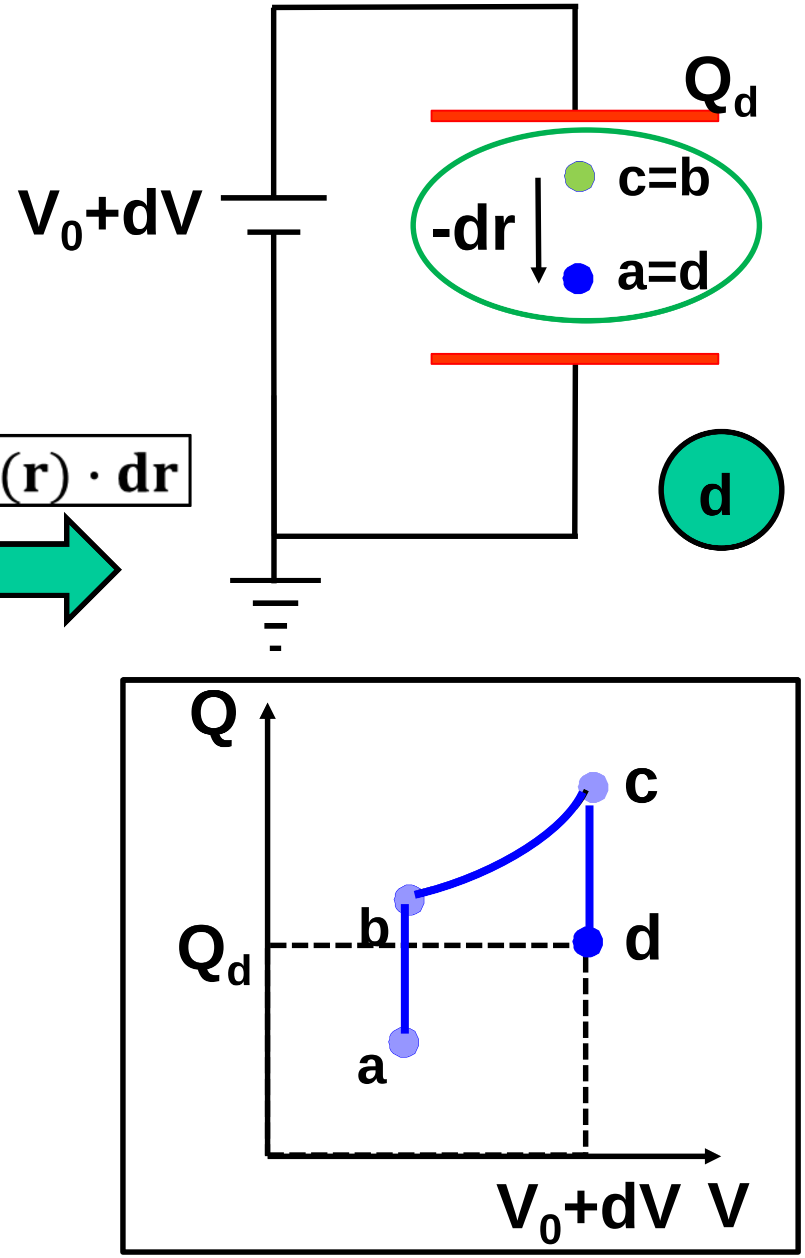
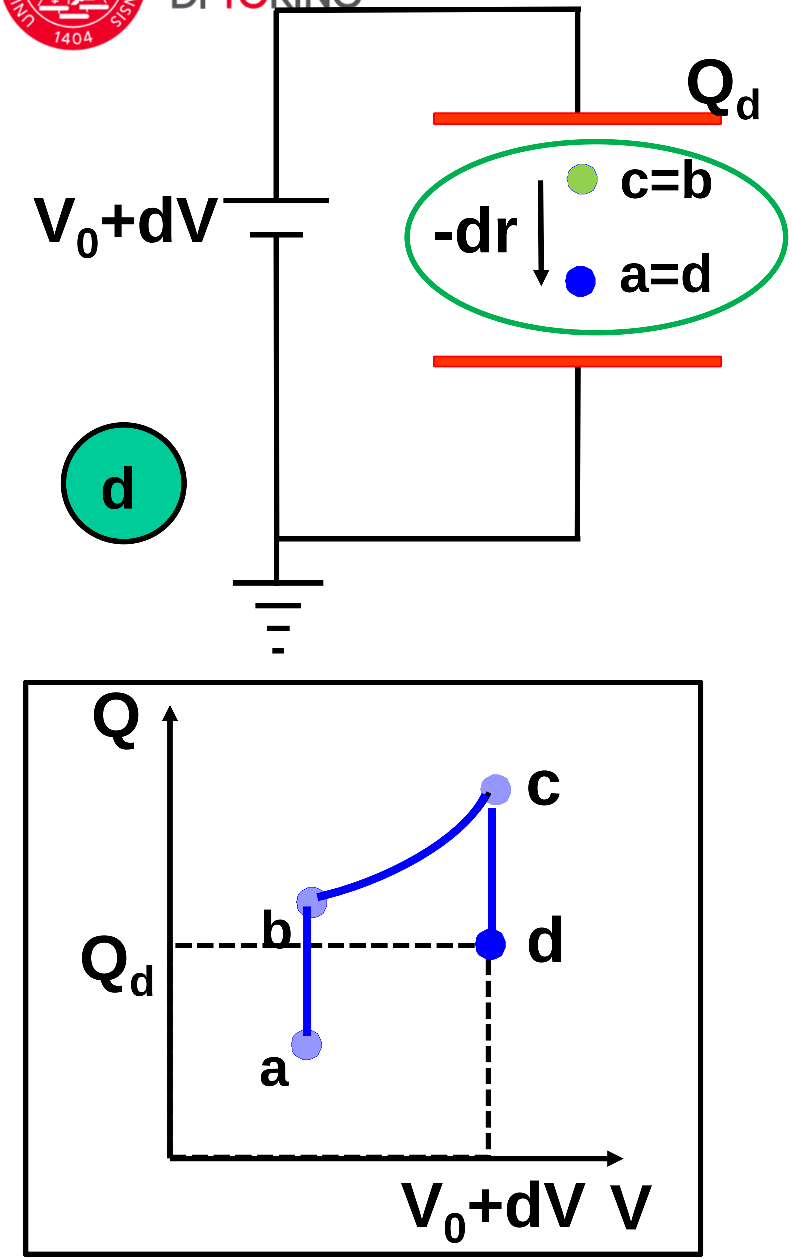
V0
Qb
b
a
dr
b
Q
Qb
b
a
V0
V
V0+dV
Qc
c=b
c
Q
Qc
c
b
a
V0
V0+dV
V

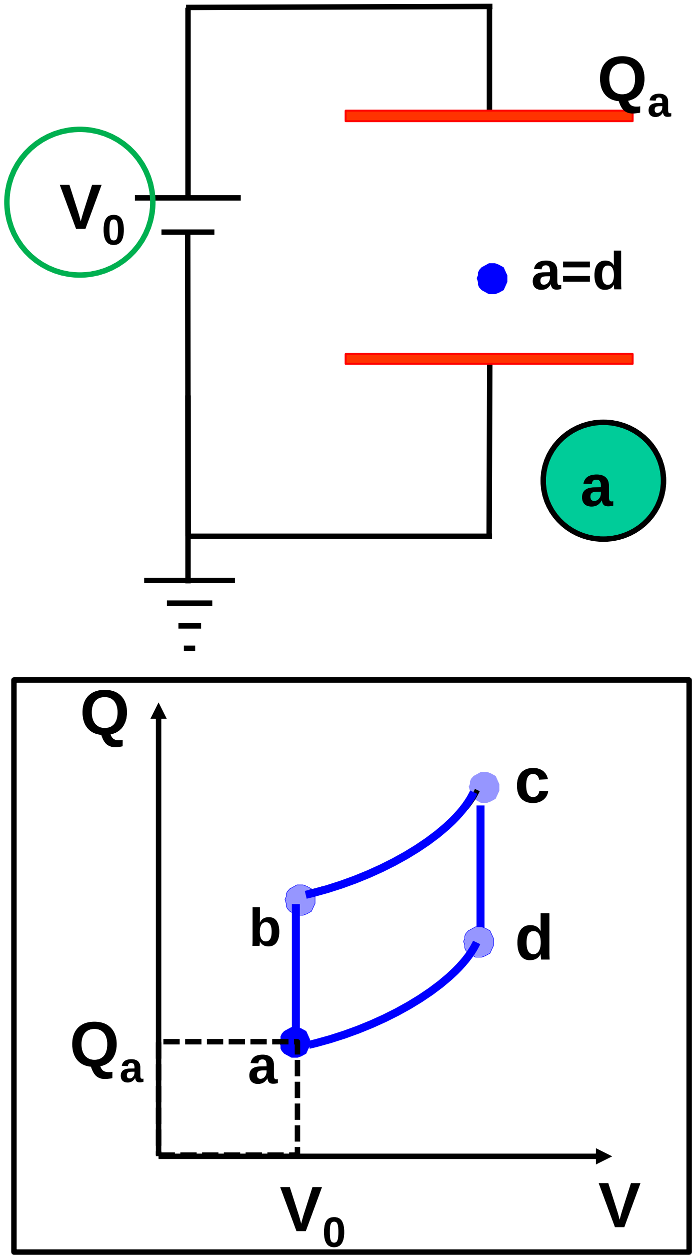


$$U = +q \cdot E'(r) \cdot dr$$





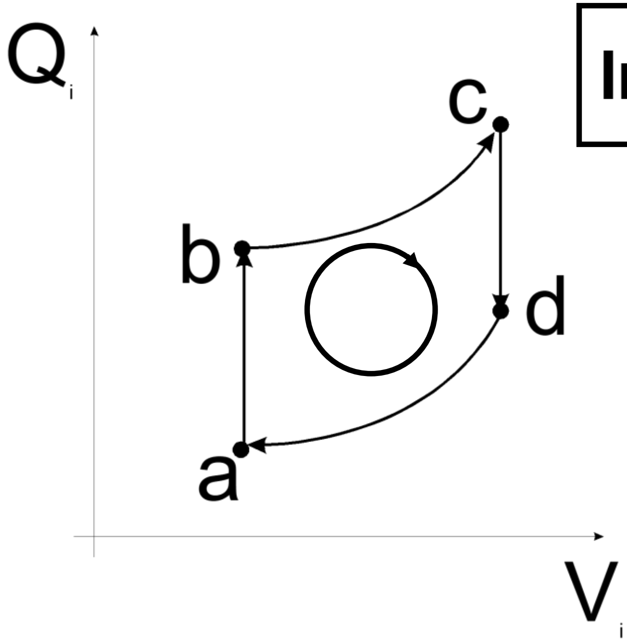
Q$_d$
V$_0$+dV
-dr
c=b
a=d
d
Q
c
b
Q$_d$
d
a
V$_0$+dV V



Q$_a$
V$_0$
a=d
a
Q
c
b
d
Q$_a$
a
V$_0$
V

$$U = \text{net work done upon } q = q \cdot \frac{\partial E(r)}{\partial V_i} \cdot dV_i \cdot dr$$

$$W = \text{net work done upon the system} = \oint V_i \cdot dQ_i = \nabla_r Q_i \cdot dr \cdot dV_i$$



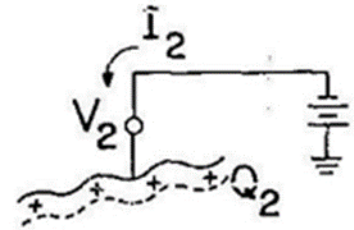
Initial conditions = Final conditions

$$\text{Total work} = U + W = 0$$

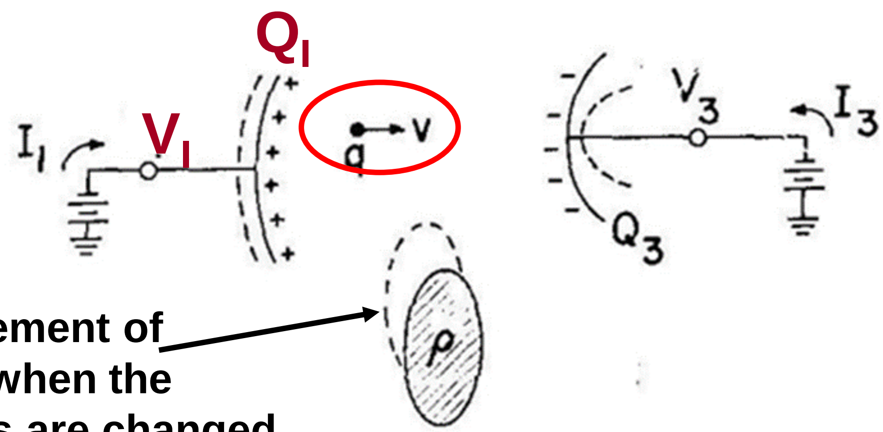
$$\nabla_r Q_i = -q \cdot \frac{\partial E(r)}{\partial V_i}$$

An arbitrary arrangement of conductors and of space charge ρ.

The sensing electrode (at potential V_l with a charge Q_l)



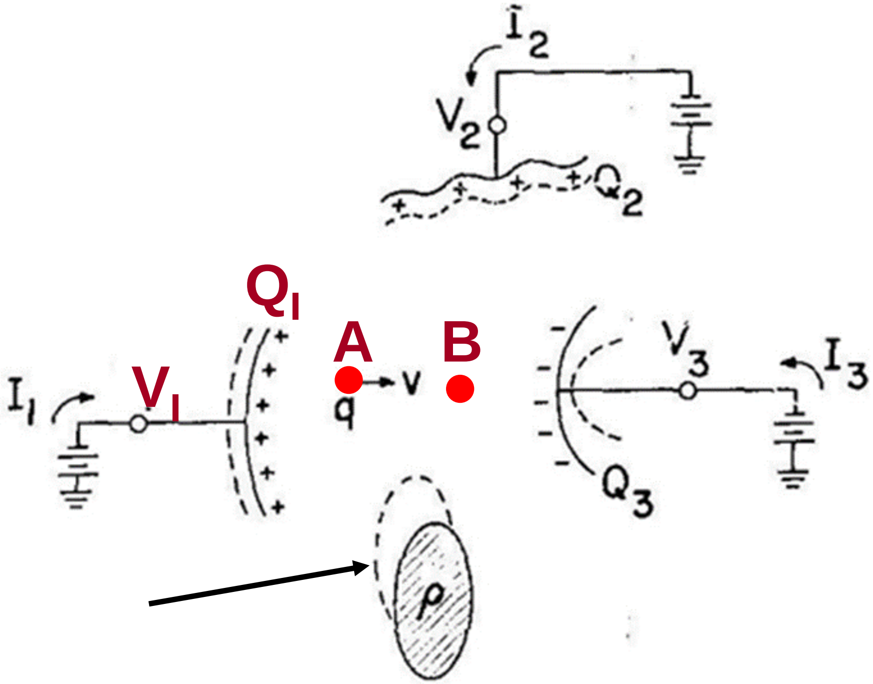
The potential of all the other conductors are held constant during the differentiation



$$\nabla_{\mathbf{r}} Q_i = -q \cdot \frac{\partial \mathbf{E}(\mathbf{r})}{\partial V_i}$$

Rate at which the charge induced upon the sensing electrode changes as the small charge q is moved

Rate at which the field experienced by the small charge changes when the potential of the sensing electrode is varied.



Electric potential ψ

Electric field $E(r) = -\nabla\psi$

Weighting field $E_w = \dfrac{\partial E}{\partial V_i}$;

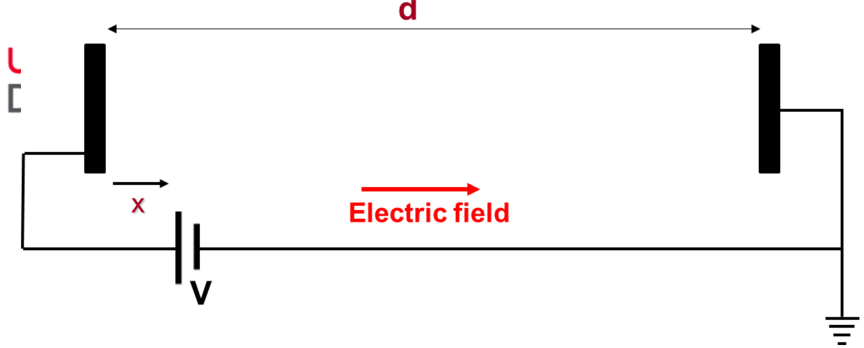
Weighting potential: $\psi_w = \dfrac{\partial \psi}{\partial V_i}$

$$Q = \int_A^B -q \cdot \frac{\partial E}{\partial V_i} dr = -q \cdot \frac{\partial}{\partial V_i} \int_A^B (-\nabla\psi) dr = q \cdot \frac{\partial}{\partial V_i} (\psi(B) - \psi(A)) =$$

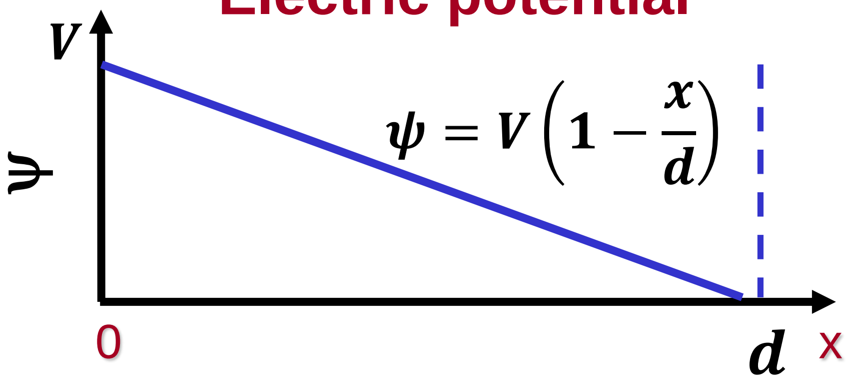
$$= q \cdot (\psi_w(B) - \psi_w(A))$$

<u>The induced charge Q at the sensing electrode</u> is given by the difference in the weighting potentials between any two positions (A and B) of the moving charge

Example: capacitor

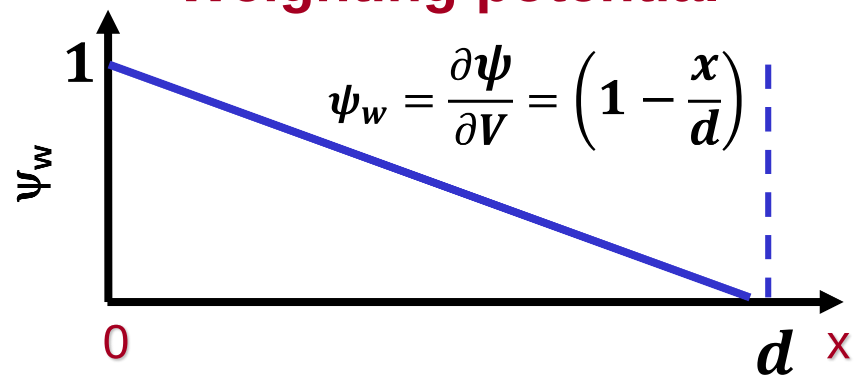


Electric potential



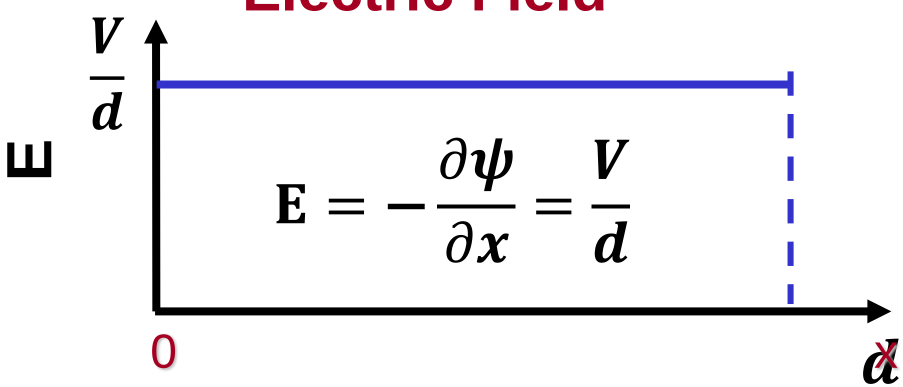
$$\psi = V\left(1 - \frac{x}{d}\right)$$

Weighting potential



$$\psi_w = \frac{\partial \psi}{\partial V} = \left(1 - \frac{x}{d}\right)$$

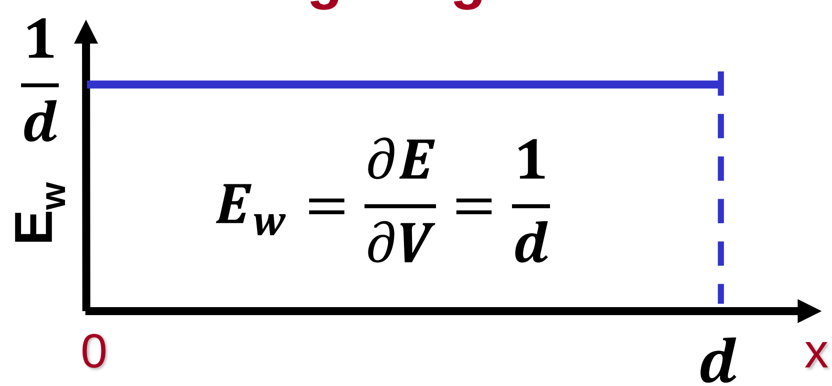
Electric Field



$$\frac{V}{d}$$

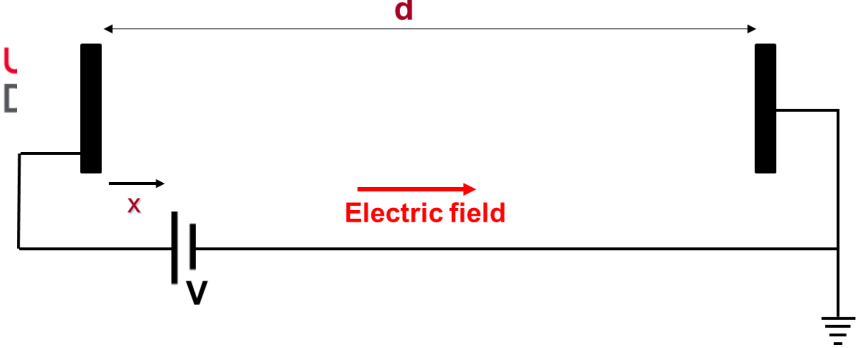
$$\mathrm{E} = -\frac{\partial \psi}{\partial x} = \frac{V}{d}$$

Weighting Field

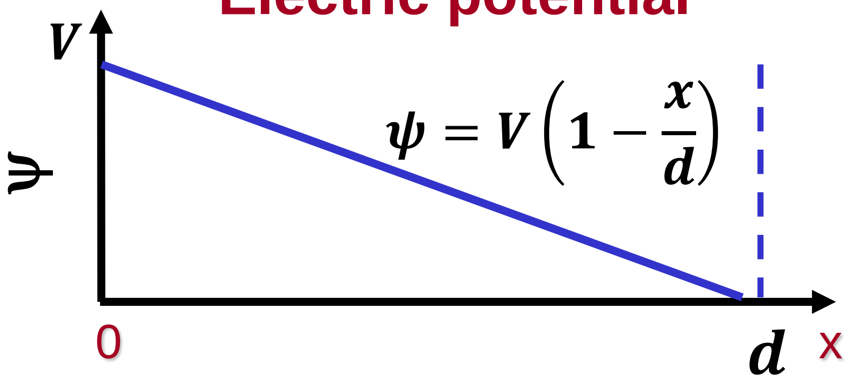


$$\frac{1}{d}$$

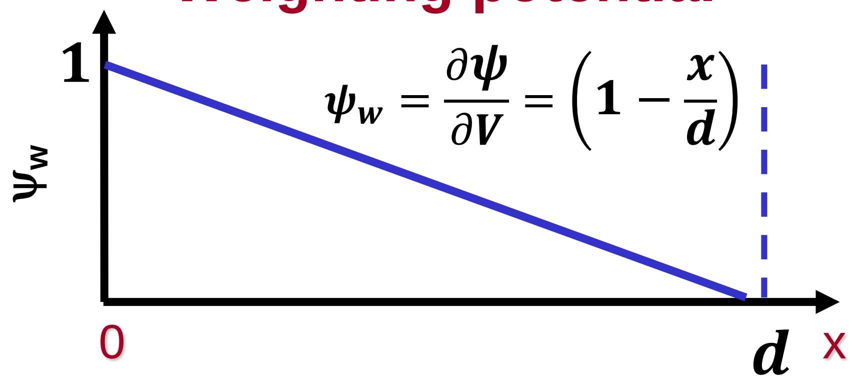
$$E_w = \frac{\partial E}{\partial V} = \frac{1}{d}$$

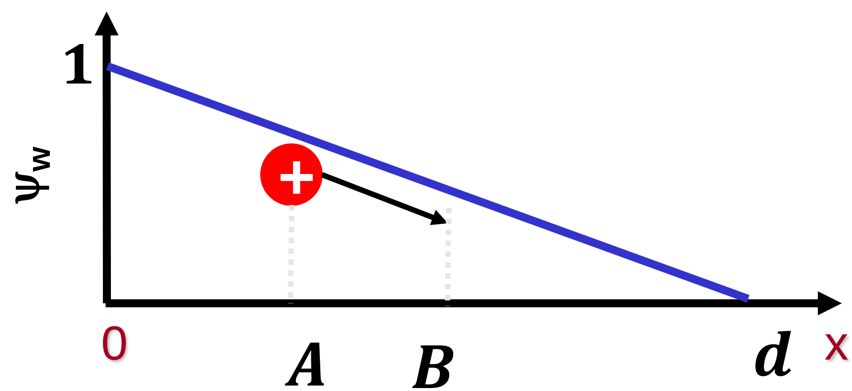


Electric potential

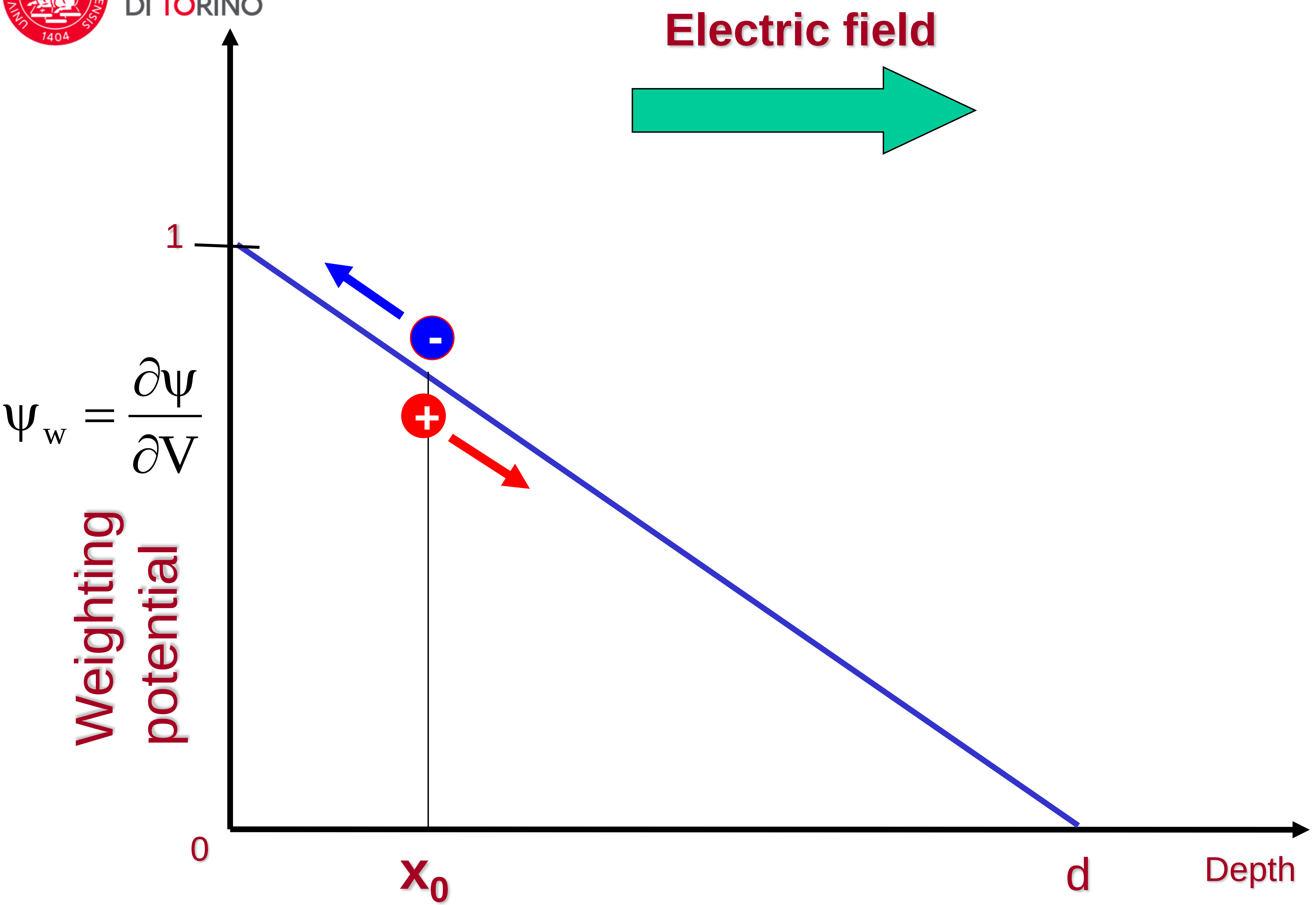


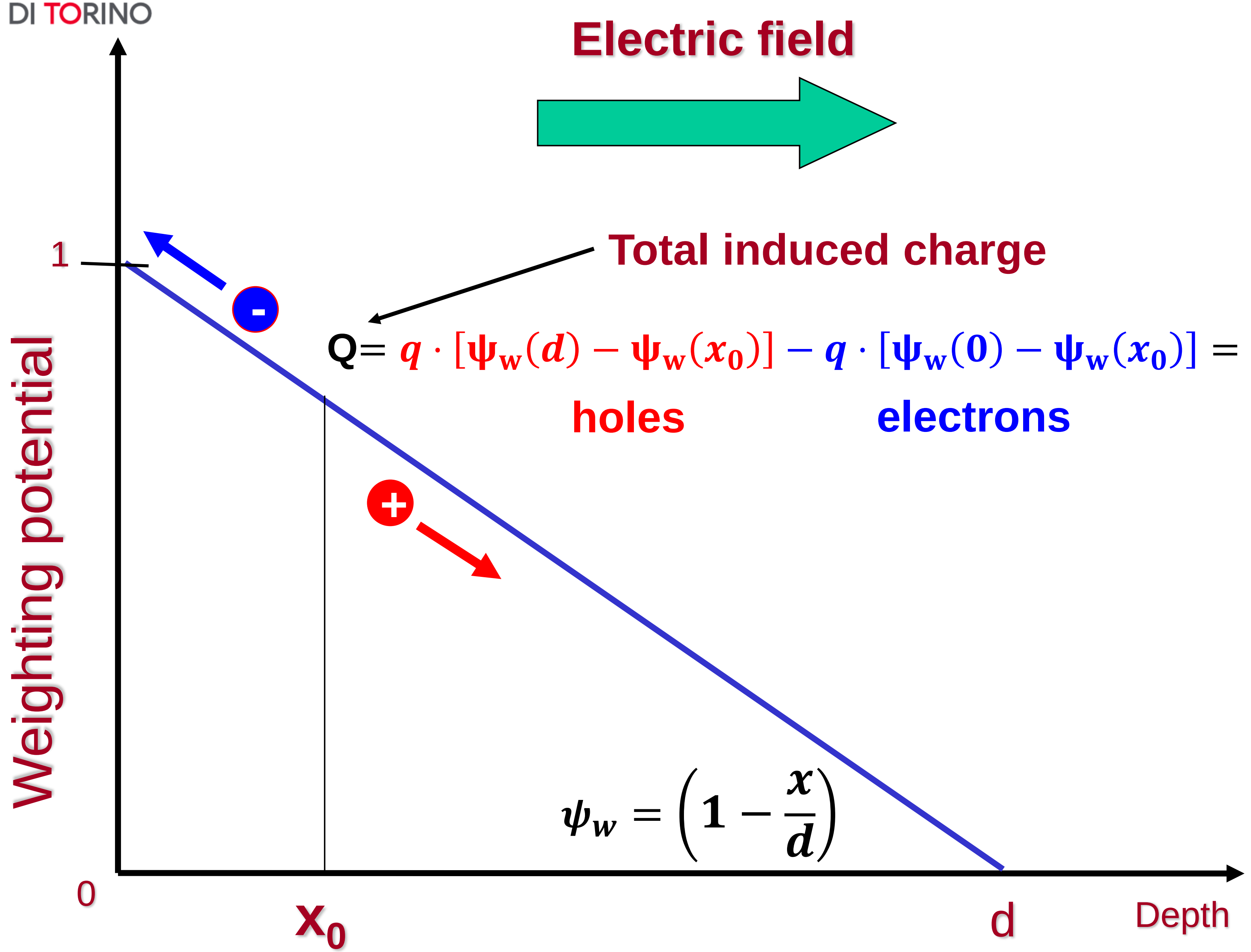
Weighting potential





$$\mathbf{Q = +q \cdot [\psi_w(B) - \psi_w(A)]}$$


Electric field
1
0
Weighting potential
$\psi_w = \frac{\partial \psi}{\partial V}$
-
+
x_0
d
Depth



$$Q = q \cdot [\psi_w(d) - \psi_w(x_0)] - q \cdot [\psi_w(0) - \psi_w(x_0)] = q$$

$$\psi_w = \left(1 - \frac{x}{d}\right)$$

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.

$$\nabla_r Q_i = -q \cdot \frac{\partial E(r)}{\partial V_i}$$

$$(\nabla_r Q_i) \cdot v = \frac{dQ_i}{dt} = I_i$$

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

$$\mathbf{E}_w = \frac{\mathbf{1}}{\boldsymbol{d}}$$

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

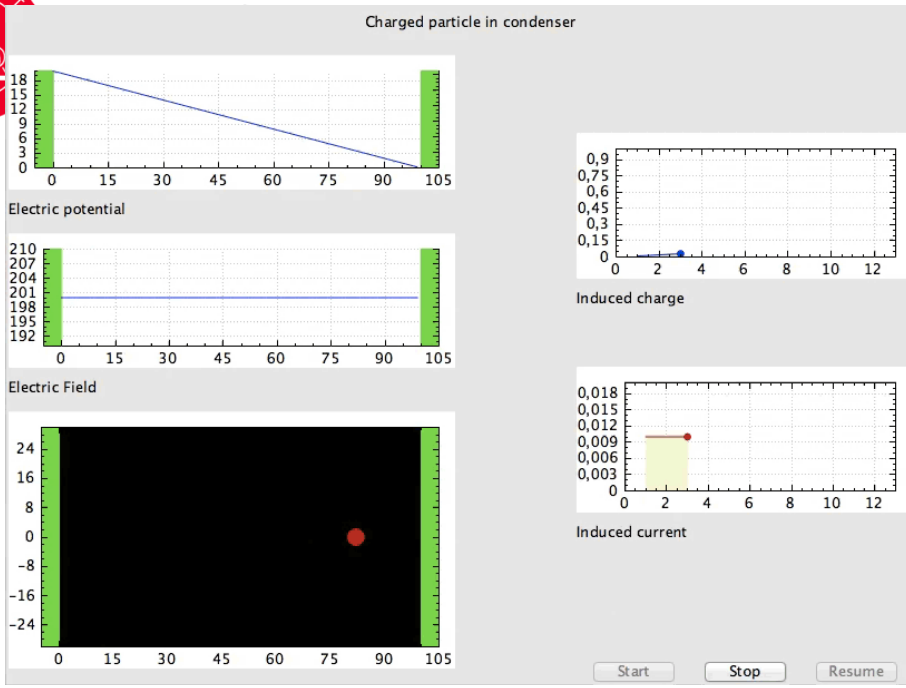
Shockley-Ramo theorem

Currents to Conductors Induced by a Moving Point Charge

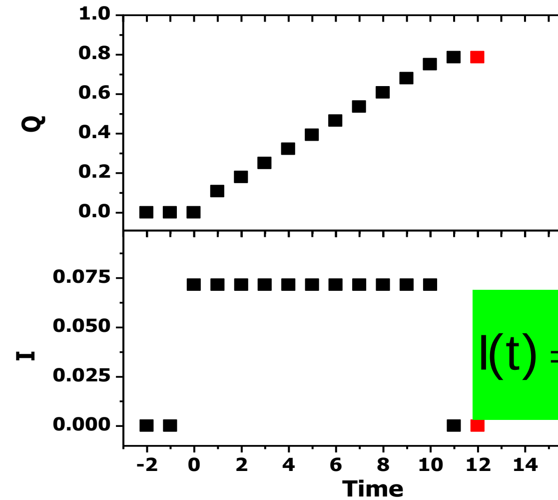
W. Shockley
Bell Telephone Laboratories, Inc., New York, N. Y.
(Received May 14, 1938)

Currents Induced by Electron Motion*

SIMON RAMO†, ASSOCIATE MEMBER, I.R.E.

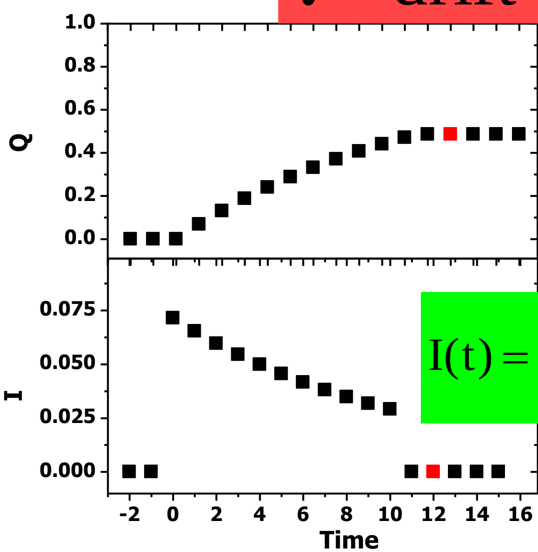


$$\tau \rightarrow \infty$$

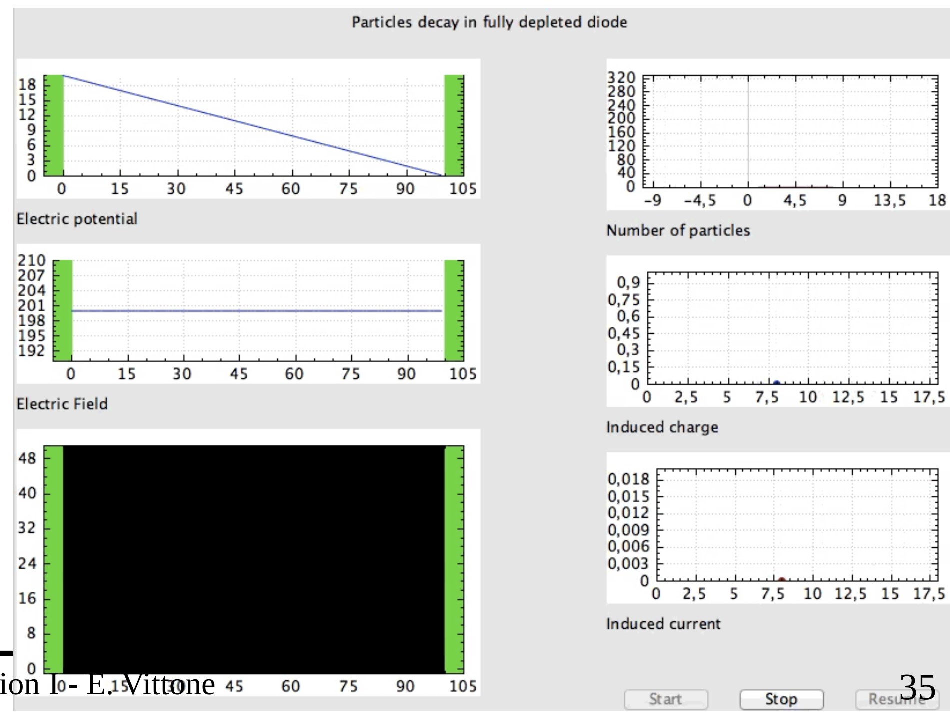


$$I(t) = q \cdot \frac{v}{d}$$

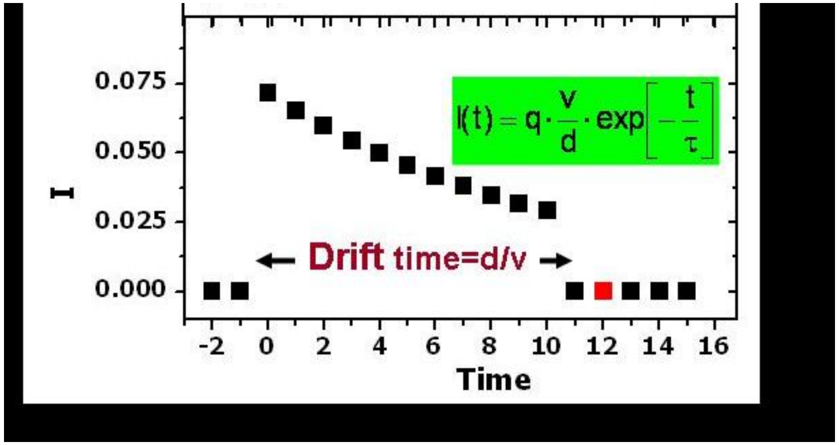
$$\tau \approx \text{drift time}$$



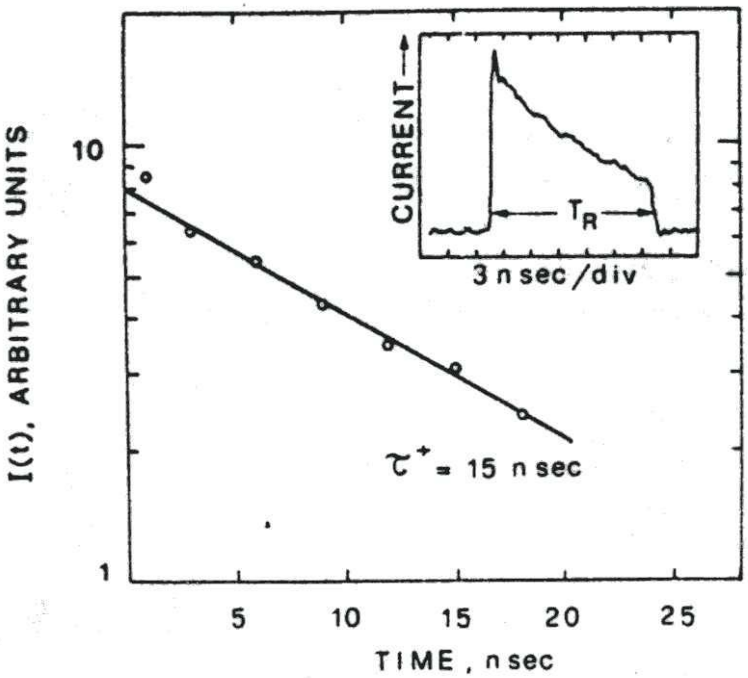
$$I(t) = q \cdot \frac{v}{d} \cdot \exp\left[-\frac{t}{\tau}\right]$$



Characterization of the transport properties in diamond

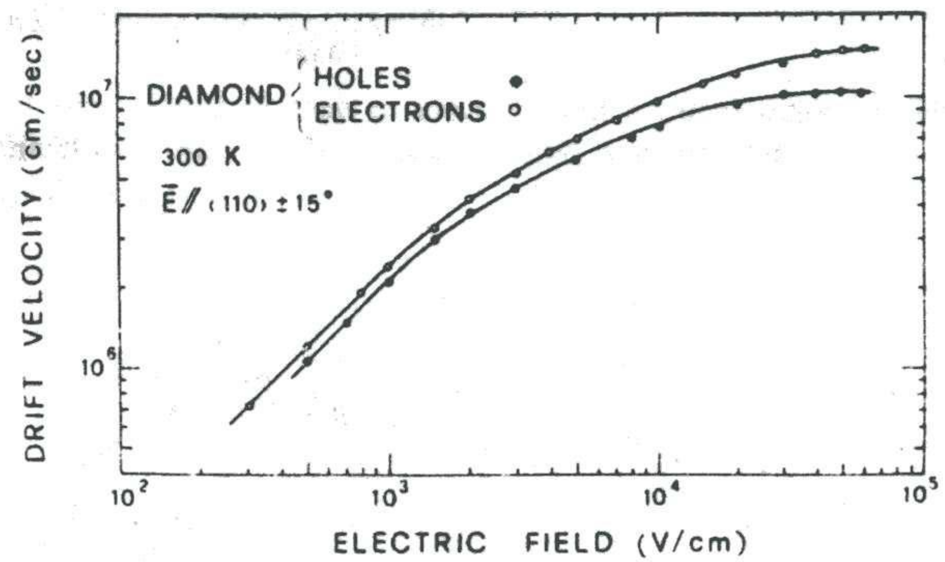


C. Canali, E. Gatti, S.F. Koslov, P.F. Manfredi, C. Manfredotti, F. Nava, A. Quirini
Nucl. Instr. Meth. 160 (1979) 73-77



400 μm thick natural diamond,

biased at 40 V @ RT

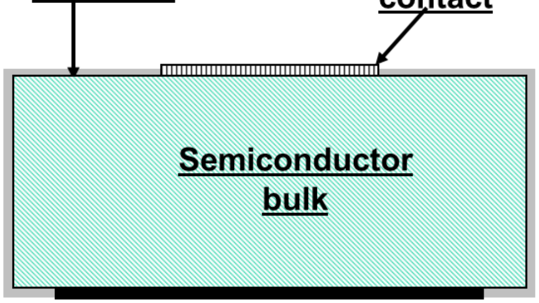


Drift velocity; $v = \mu E = d/T_R$

Mobility; $\mu = d^2/(T_R * V_{Bias})$

Evaluation of the induced charge at the sensing electrode

1. Definition of the study domain



2. Calculation of the electrostatics and of the evolution in time and space of the electron (n) - hole (p) densities generated by ionization

Continuity equations

Electrons

Holes

Poisson's equation

$$\begin{cases} \dfrac{\partial n}{\partial t} = +\vec{\nabla} \cdot \left(-\mu_n \cdot \vec{\nabla}\boldsymbol{\psi} \cdot n + D_n \cdot \vec{\nabla} n\right) + G_n - \dfrac{n}{\tau_n} \\ \dfrac{\partial p}{\partial t} = -\vec{\nabla} \cdot \left(+\mu_p \cdot \vec{\nabla}\boldsymbol{\psi} \cdot p - D_p \cdot \vec{\nabla} p\right) + G_p - \dfrac{p}{\tau_p} \\ \Delta\boldsymbol{\psi} = -\dfrac{\rho}{\varepsilon} \end{cases}$$

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Evaluation of the induced charge at the sensing electrode

3. Evaluate the Gunn′s weighted potential ψ_w and weighting field $\mathbf{E}_w$

$$\psi_w = \frac{\partial\psi}{\partial V_i}; \boldsymbol{E}_w = -\nabla\psi_w \rightarrow V_i\text{=potential at the sensing electrode}$$

The potentials of all the other conductors are held constant

4. Evaluate the induced current

$$I_i(t) = -q \int_\Omega dr \{[n(r,t';r_0) \cdot v_n(r) + p(r,t';r_0) \cdot v_p(r)] \cdot \mathbf{E_w}\}$$

5. Evaluate the induced charge

$$Q_i(t) = -q \int_0^t dt' \int_\Omega d\mathbf{r} \{[n(\mathbf{r},t';r_0) \cdot \mathbf{v}_n(\mathbf{r}) + p(\mathbf{r},t';r_0) \cdot \mathbf{v}_p(\mathbf{r})] \cdot \mathbf{E_w}\}$$

Adjoint equation Method **Short-cut**

Charge Induced from electrons

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

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.

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

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

$$G_n^+ = \mu_n \cdot \nabla\phi \cdot \frac{\partial E}{\partial V_i}$$

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

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Monte Carlo Method

Short-cut

Shockley-Ramo-Gunn Theory

A charge moving in a non-zero electric field induces a current to the sensitive electrode.
$\partial\psi/\partial V$ is the **Gunn's weighting potential**, where ψ is the electric potential and V the bias voltage

$$Q = q\left[\left.\frac{\partial\psi}{\partial V}\right|_{r} - \left.\frac{\partial\psi}{\partial V}\right|_{r}\right]$$

Follow the carrier trajectories by a Monte Carlo approach
Taking into account
- ❖**physical parameters** (geometry, electric field, transport properties)
- ❖**experimental set-up** (noise, threshold, beam spot size)

P. Olivero et al., Nucl. Instr. Meth. B 269 (2011) 2350

Single ion detection for the functional characterization of semiconductors

Physical observable: charge induced at the sensing electrode by the motion of carriers moving in an electric field

$$Q_i(t) = -q \int_0^t dt' \int_\Omega d\mathbf{r} \left\{ \left[n(\mathbf{r}, t'; r_0) \cdot \mathbf{v}_n(\mathbf{r}) + p(\mathbf{r}, t'; r_0) \cdot \mathbf{v}_p(\mathbf{r}) \right] \cdot \mathbf{E_w} \right\}$$

Space/time evolution of carriers
Continuity equations

Electrostatics

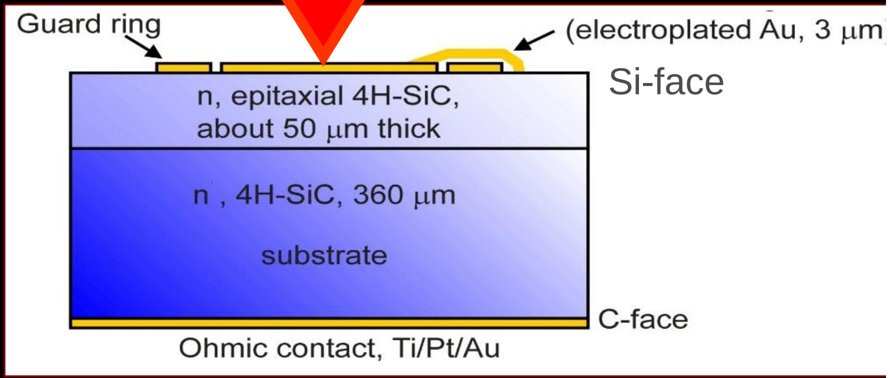
$$\mathbf{v}_{n,p} = \boldsymbol{drift\ velocities} = \boldsymbol{\mu}_{n,p} \cdot \boldsymbol{E}$$

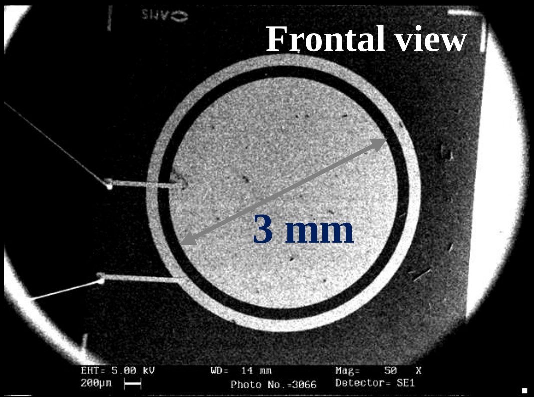
4H-SiC Schottky diode

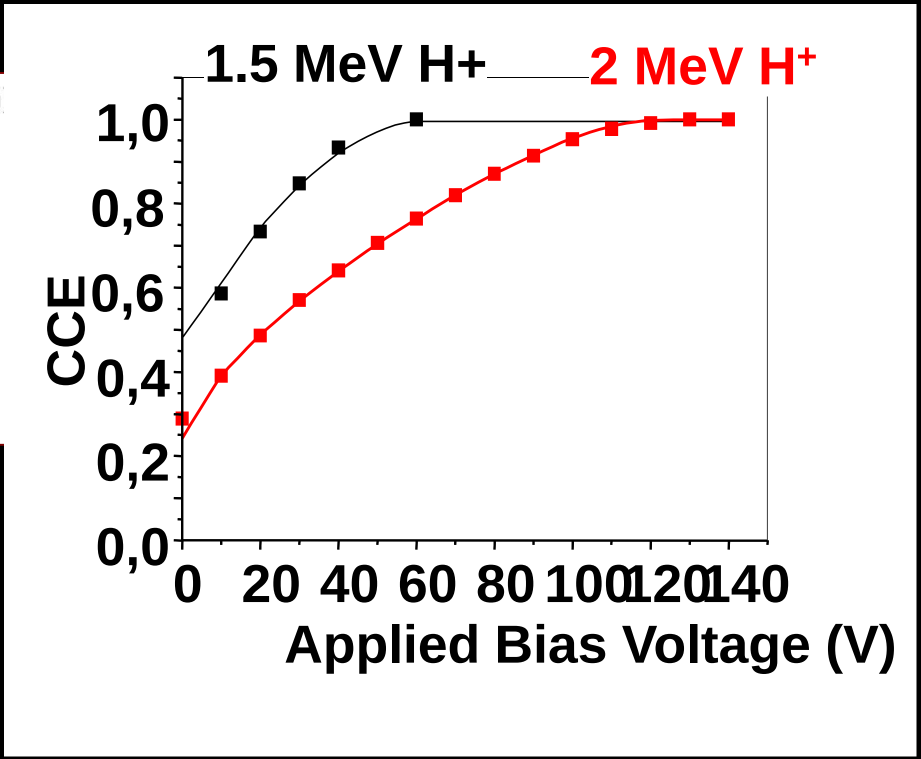
Starting Material: 360 μm n-type 4H-SiC by CREE (USA)
Epitaxial layer from Institute of Crystal Growth (IKZ), Berlin, Germany
Devices from Alenia Marconi System

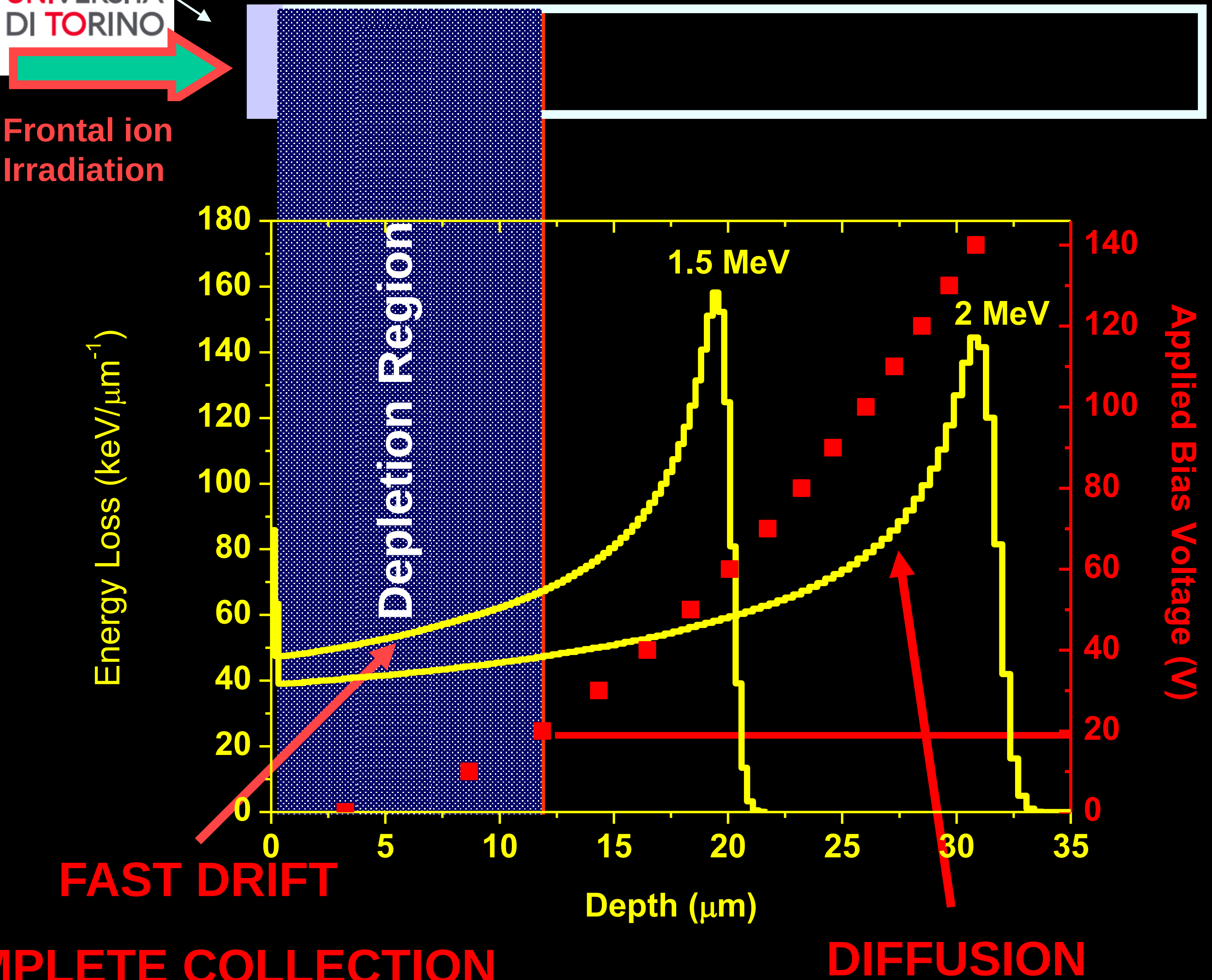
CCE=Charge Collection Efficiency
=
(Charge collected)/(Charge generated)

1.5 or 2.0 MeV H+







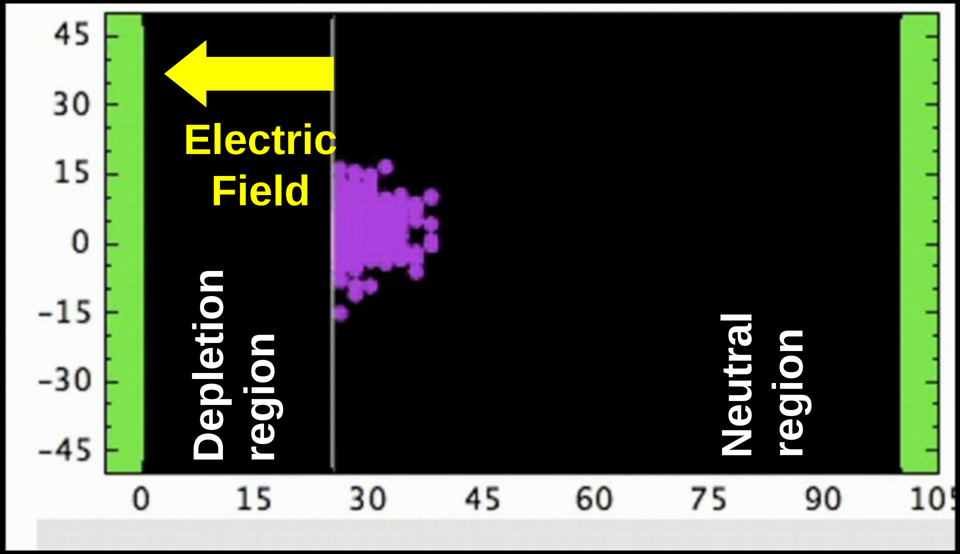

Schottky electrode
50 μm thick N-type epitaxial 4H-SiC layer
DI TORINO
Frontal ion
Irradiation
Depletion Region
1.5 MeV
2 MeV
Energy Loss (keV/μm-1)
Applied Bias Voltage (V)
Depth (μm)
0
5
10
15
20
25
30
35
180
160
140
120
100
80
60
40
20
0
FAST DRIFT
COMPLETE COLLECTION
DIFFUSION

Generation of electrons and holes in the

Depletion Region

Electrons

Holes

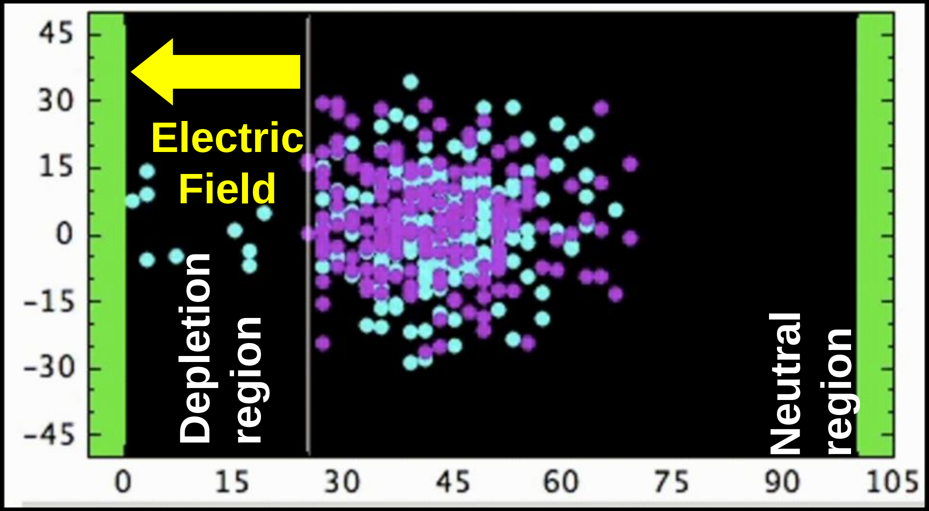


Complete charge collection

Neutral Region

Electrons

Holes



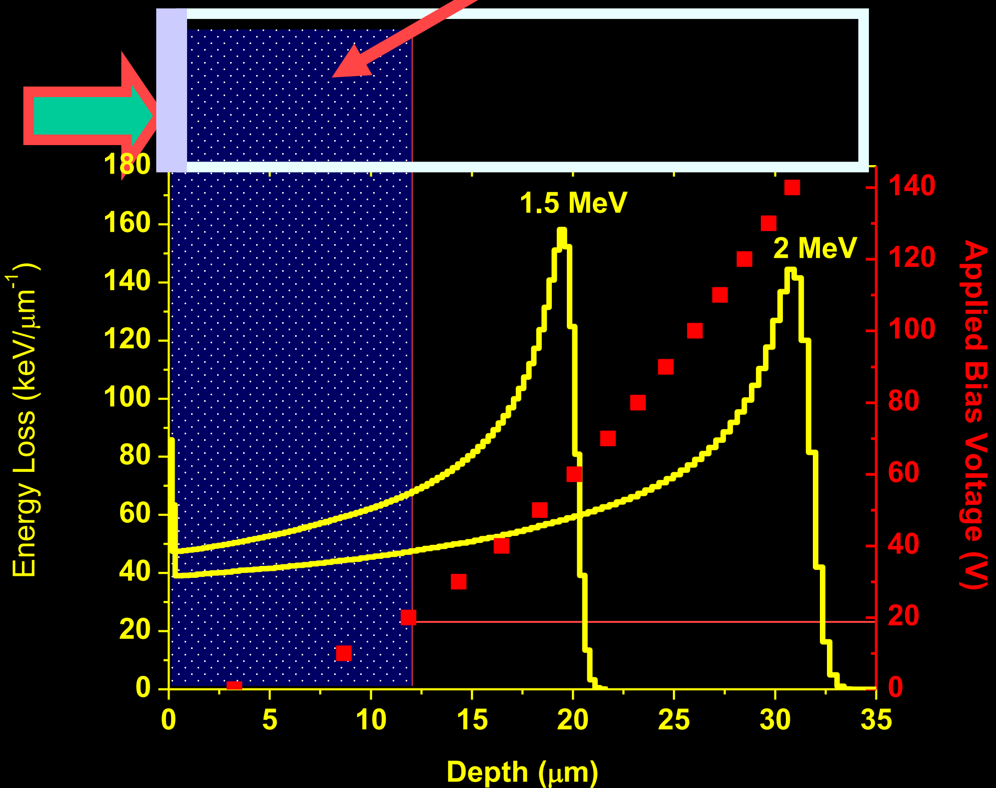
Only holes injected in the depletion region by diffusion induce a charge

Contribution from the neutral region

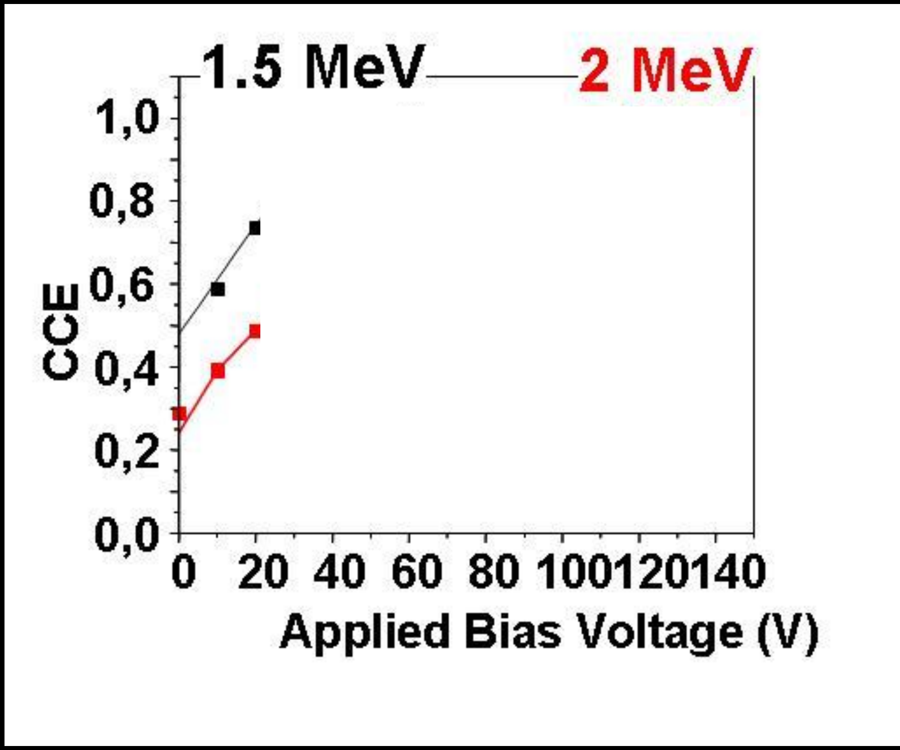
Contribution from the depletion layer

$$Q = Q_{Depl} + Q_{Neutr} \propto \left[\int_0^W \left(\frac{dE}{dx}\right)\cdot dx\right] + \left[\int_W^d \left(\frac{dE}{dx}\right)\cdot \exp\left[-\frac{x-W}{L_p}\right]\cdot dx\right]$$

Frontal ion Irradiation



4H-SiC Schottky diode

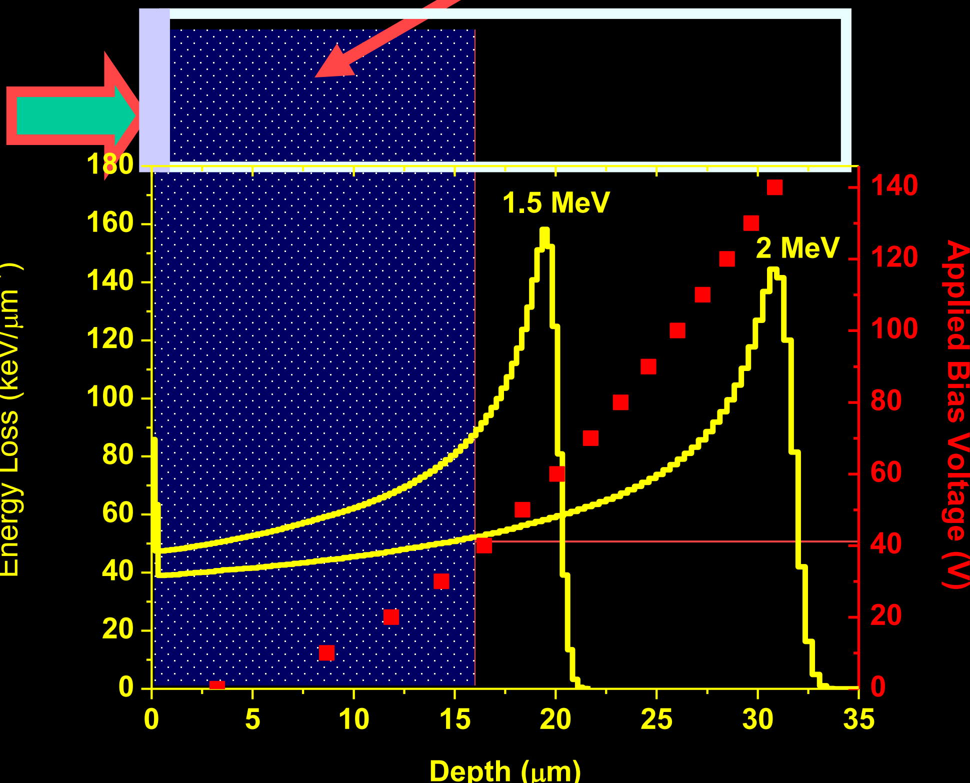


Contribution from the neutral region

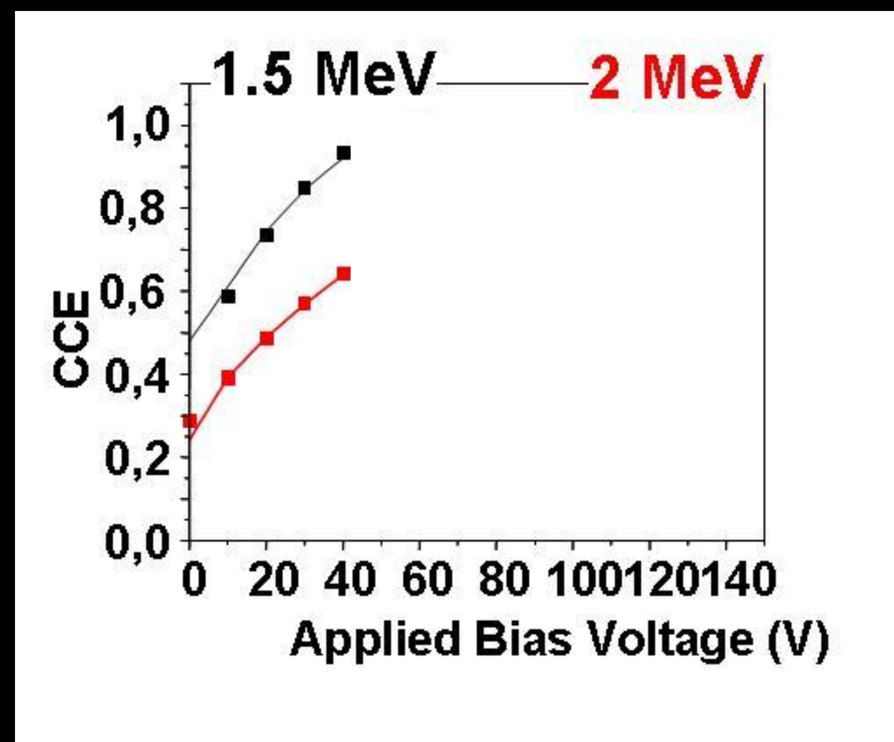
Contribution from the depletion layer

$$Q = Q_{Depl} + Q_{Neutr} \propto \left[\int_0^w \left(\frac{dE}{dx}\right) \cdot dx\right] + \left[\int_w^d \left(\frac{dE}{dx}\right) \cdot \exp\left[-\frac{x-W}{L_p}\right] \cdot dx\right]$$

Frontal ion Irradiation



4H-SiC Schottky diode

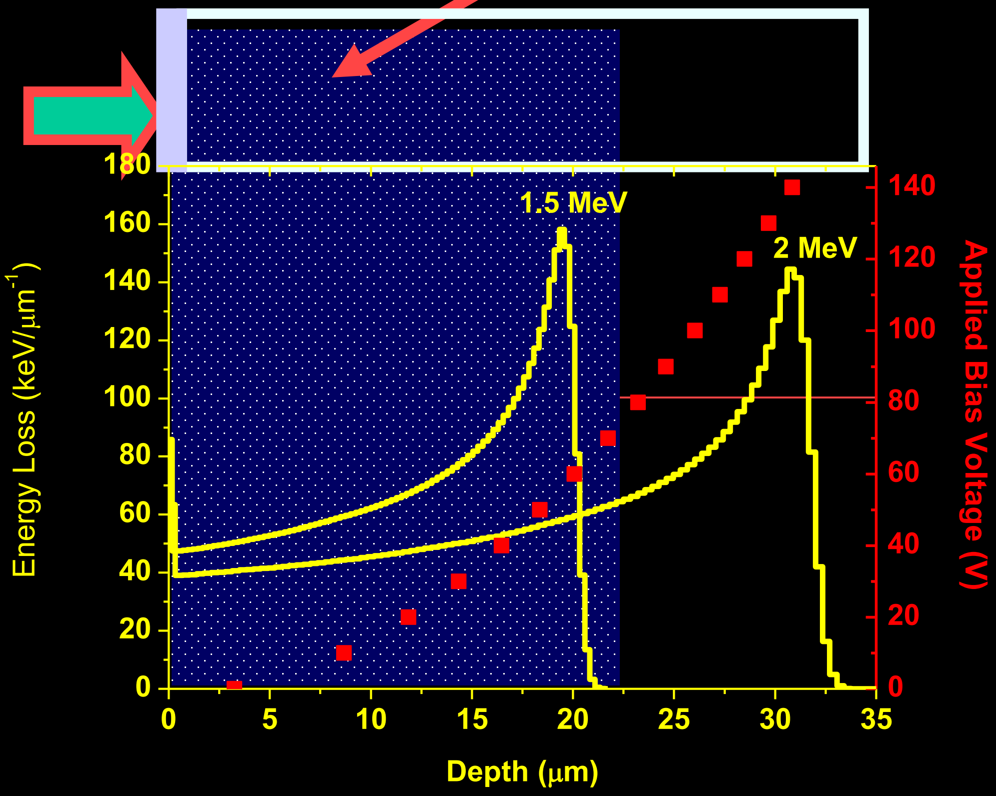


Contribution from the neutral region

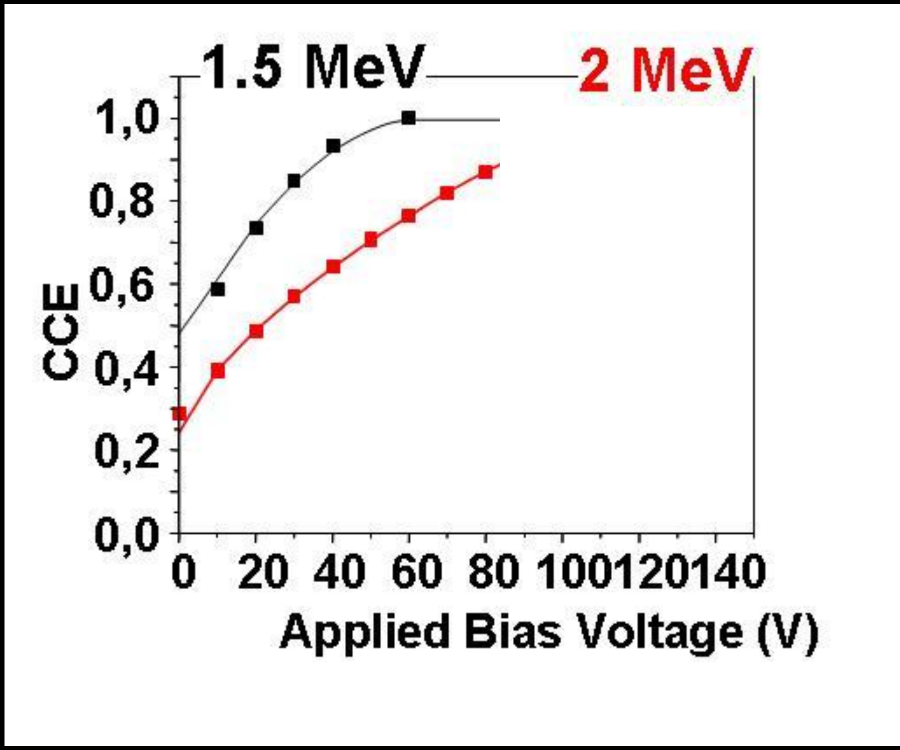
Contribution from the depletion layer

$$Q = Q_{Depl} + Q_{Neutr} \propto \left[\int_0^w \left(\frac{dE}{dx}\right) \cdot dx\right] + \left[\int_w^d \left(\frac{dE}{dx}\right) \cdot \exp\left[-\frac{x-W}{L_p}\right] \cdot dx\right]$$

Frontal ion Irradiation



4H-SiC Schottky diode

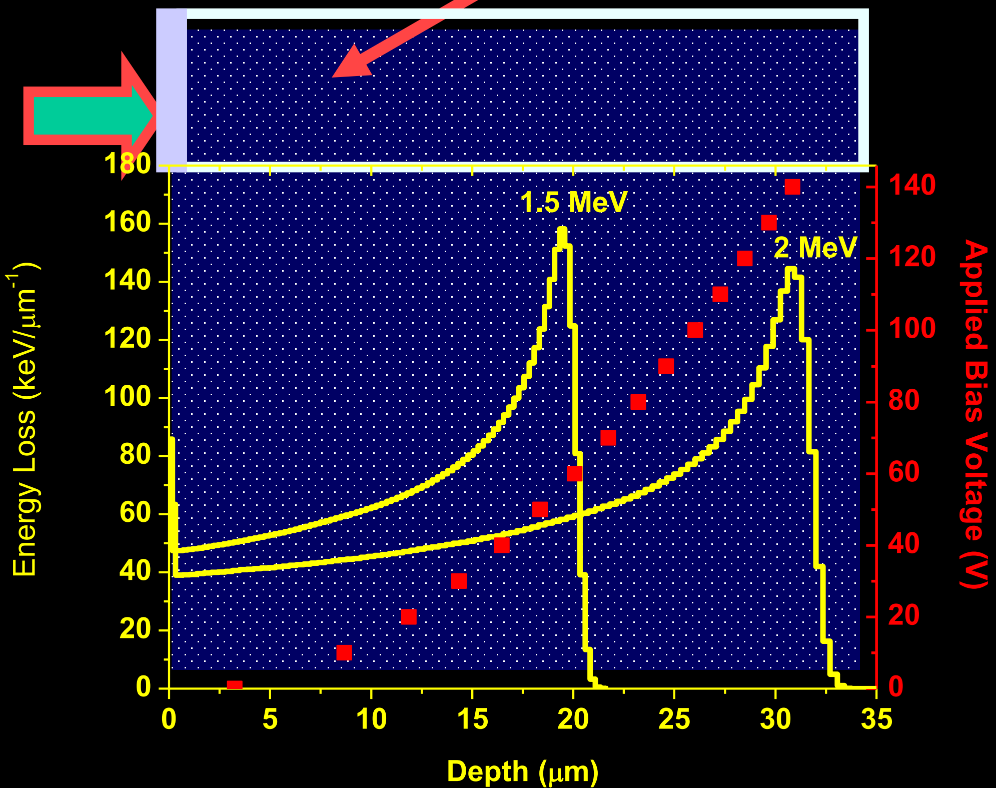


Contribution from the neutral region

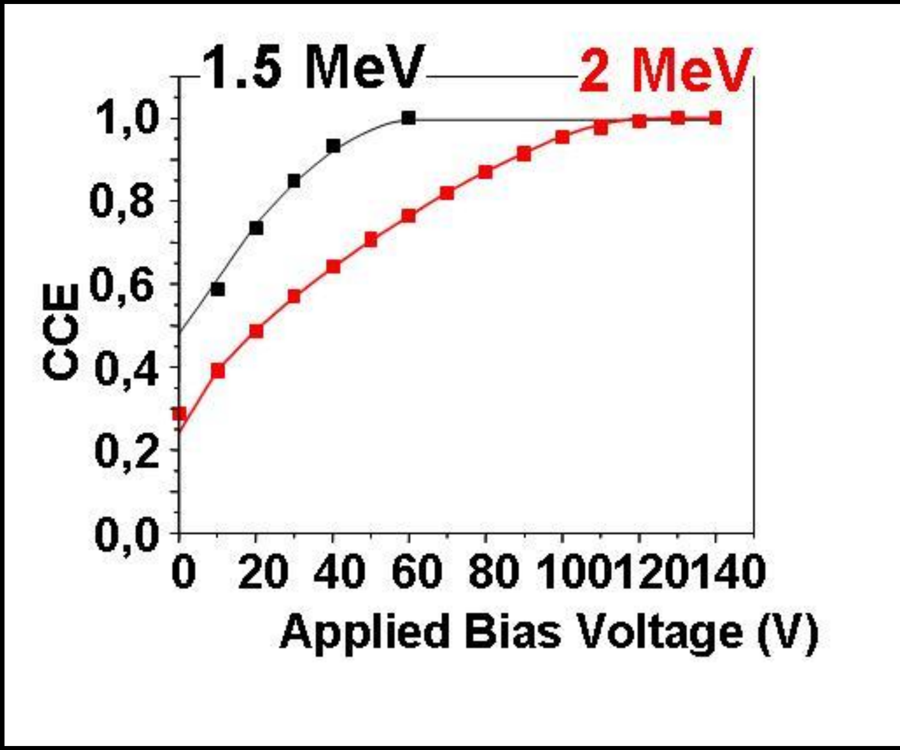
Contribution from the depletion layer

$$Q = Q_{Depl} + Q_{Neutr} \propto \left[\int_0^w \left(\frac{dE}{dx}\right) \cdot dx\right] + \left[\int_w^d \left(\frac{dE}{dx}\right) \cdot \exp\left[-\frac{x-W}{L_p}\right] \cdot dx\right]$$

Frontal ion Irradiation



4H-SiC Schottky diode



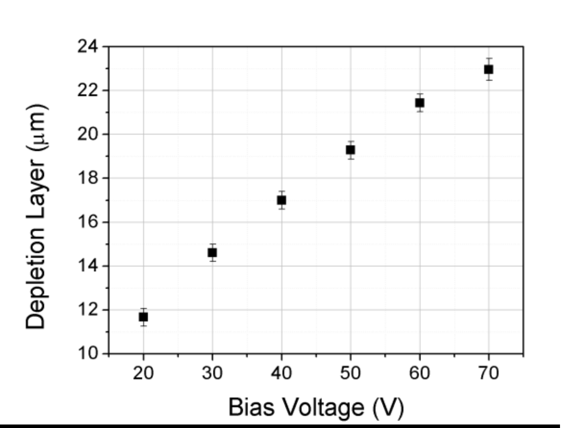
Contribution from the neutral region

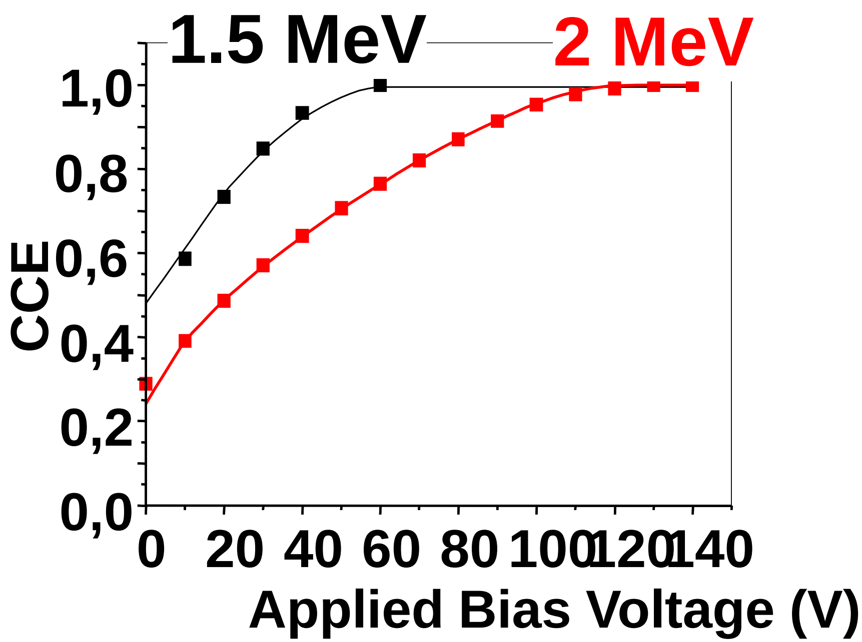
Contribution from the depletion layer

$$Q = Q_{Depl} + Q_{Neutr} \propto \left[\int_0^w \left(\frac{dE}{dx}\right)\cdot dx\right] + \left[\int_w^d \left(\frac{dE}{dx}\right)\cdot \exp\left[-\frac{x-W}{L_p}\right]\cdot dx\right]$$

Active region width

minority carrier diffusion length





$L_p = (9.0 \pm 0.3)\ \mu m$

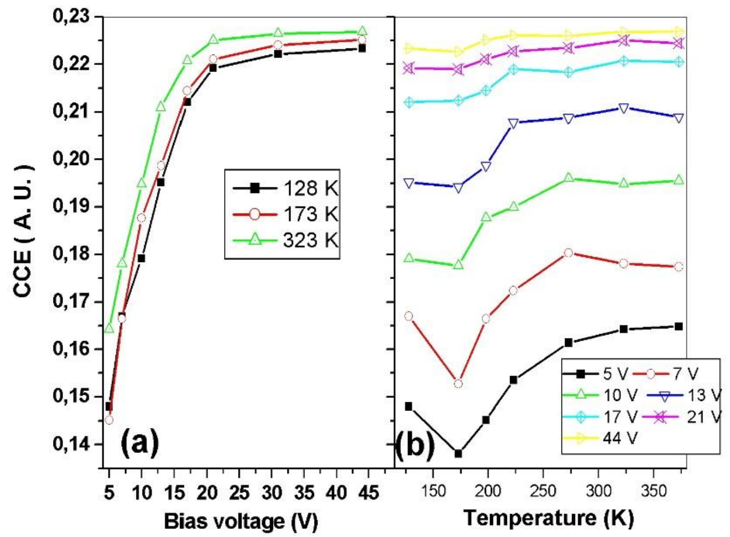
$D_p = 3\ cm^2/s$

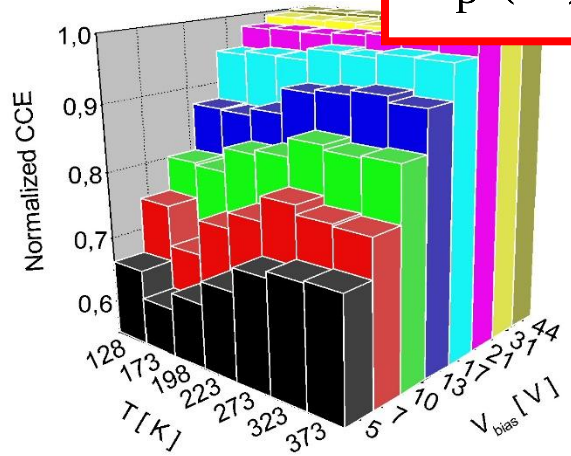
$\tau_p = 270\ ns$

Functional characterization

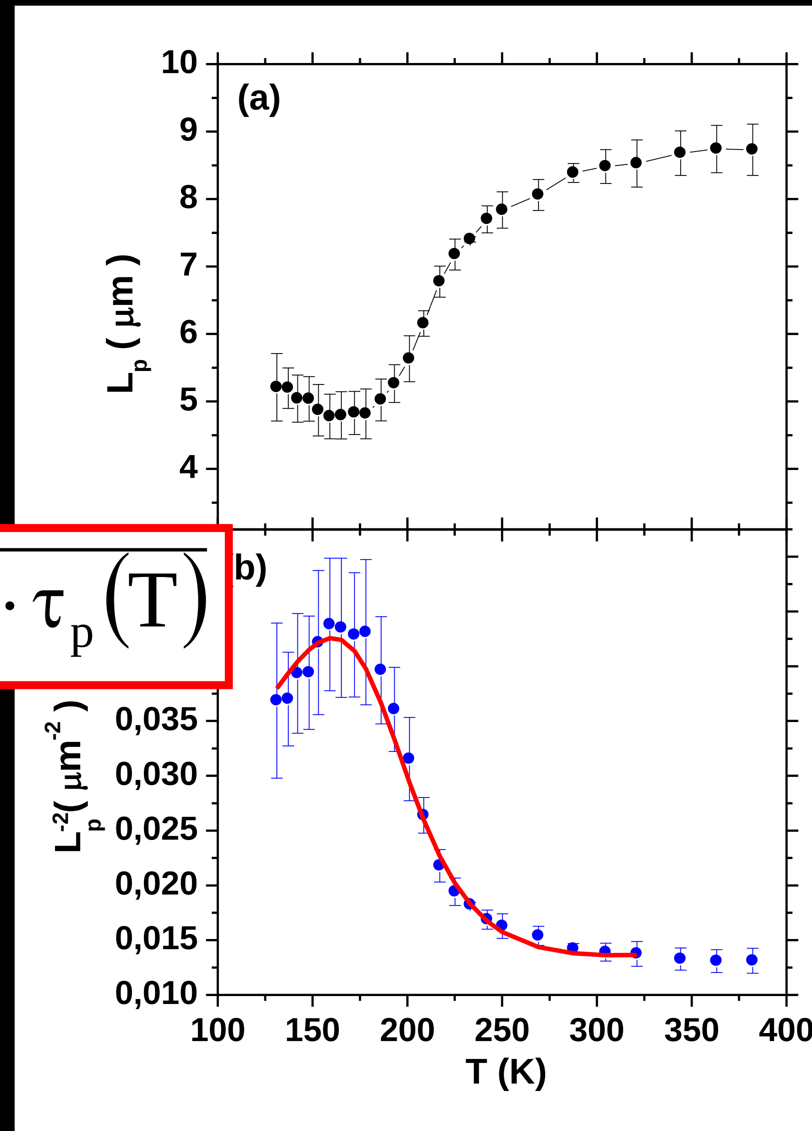
4H-SiC Schottky diode

Temperature dependent IBIC (TIBIC)

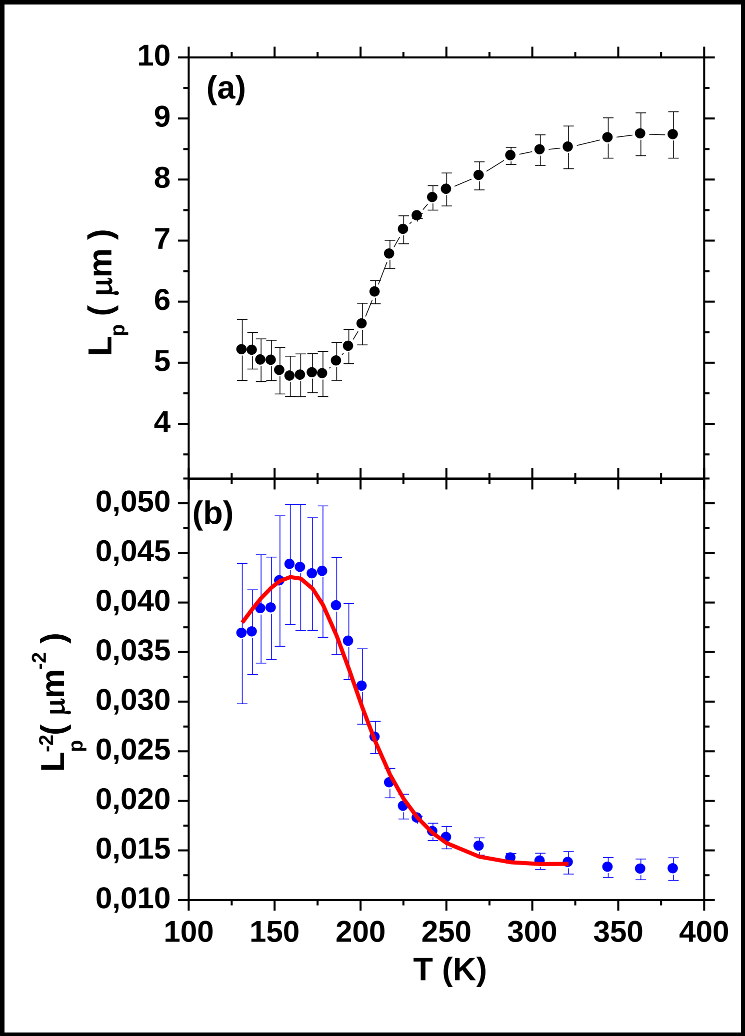




$$L_p(T) = \sqrt{D_p(T) \cdot \tau_p(T)}$$



Temperature dependent IBIC (TIBIC)



Two trapping levels

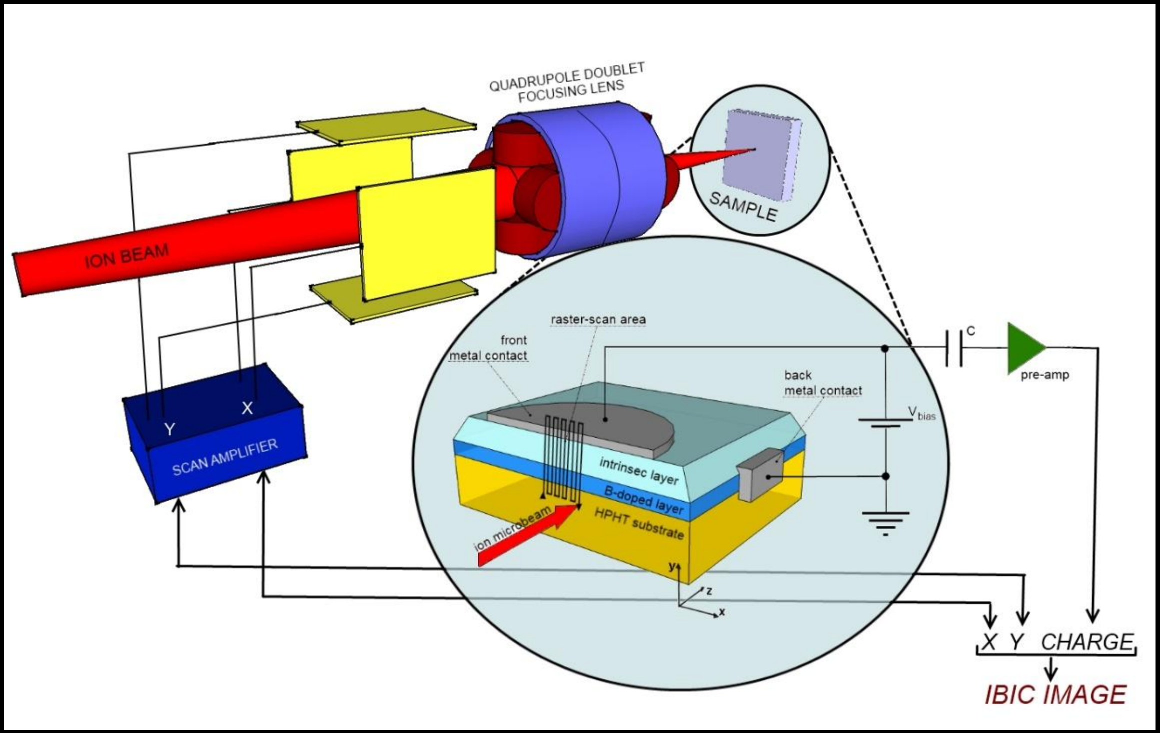
SRH recombination model

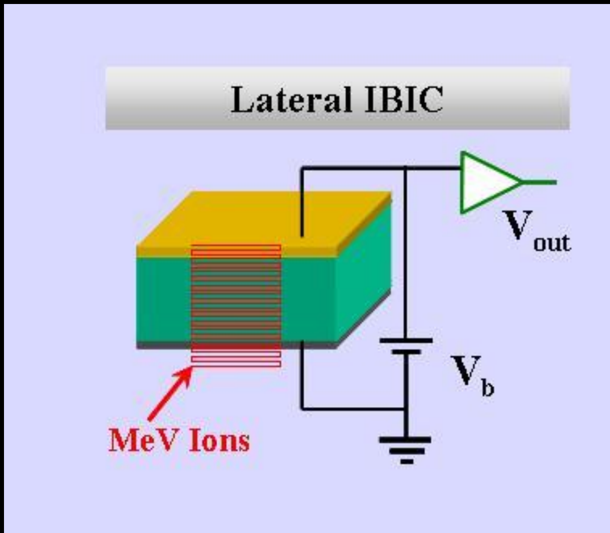
$$\frac{1}{L_p^2} = \frac{1}{D_p \cdot \tau} = \frac{1}{D_p} \cdot \left(\frac{1}{\tau(T)} + \frac{1}{\tau_B} \right) = A \cdot \frac{1}{T^{-0.5}} \cdot \left[\frac{1}{T^{-0.5} + \frac{B}{N_D} \cdot T \cdot \exp\left(-\frac{E_t}{k_B T} \right)} + \frac{1}{\tau_B} \right]$$

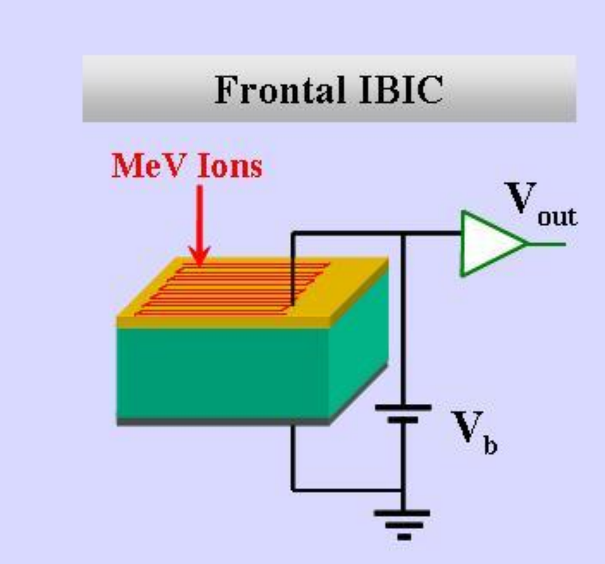
The fitting procedure provides a trapping level of about 0.163 eV which is close to the value found in similar 4H SiC Schottky diodes by DLTS technique (S1 level).

E. Vittone et al., NIM-B 231 (2005) 491.

From Spectroscopy to micro-spectroscopy



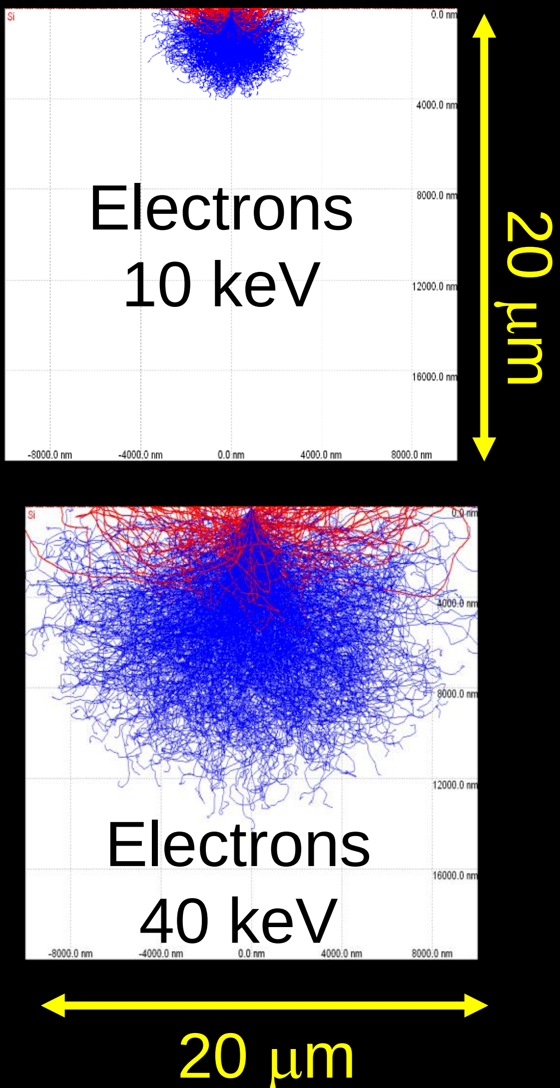


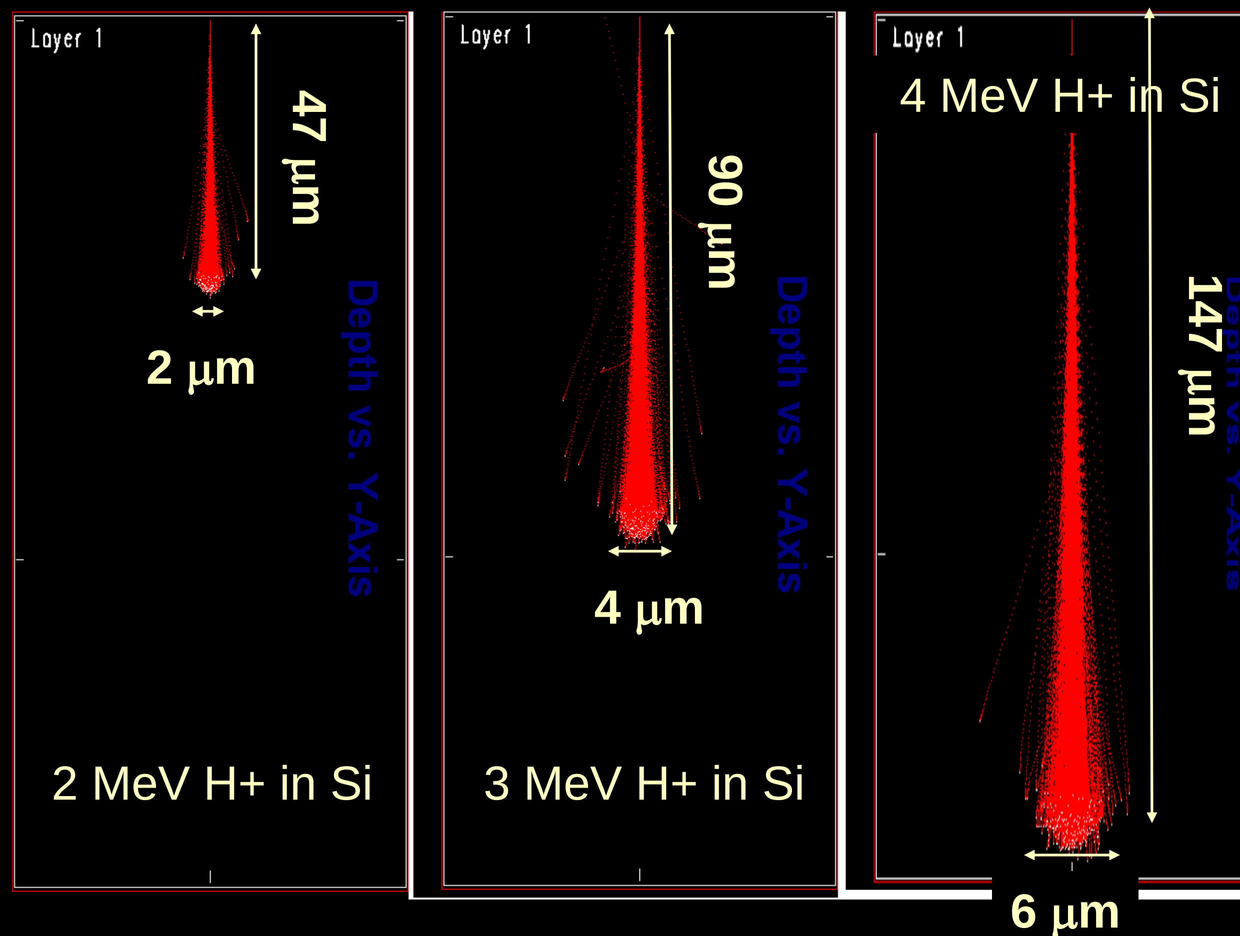


Use of focused ion beams

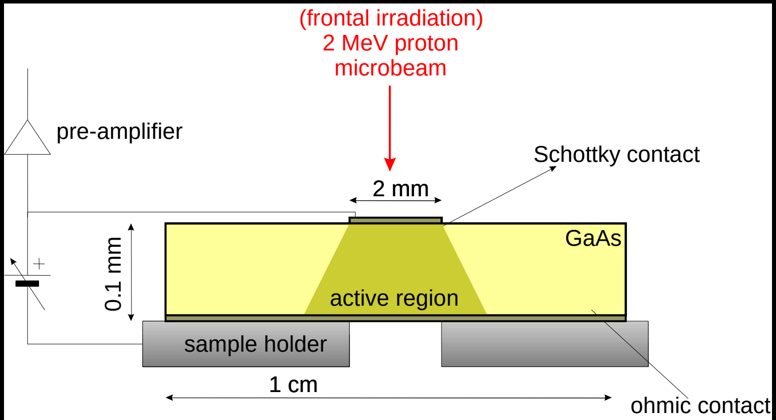
Trajectories

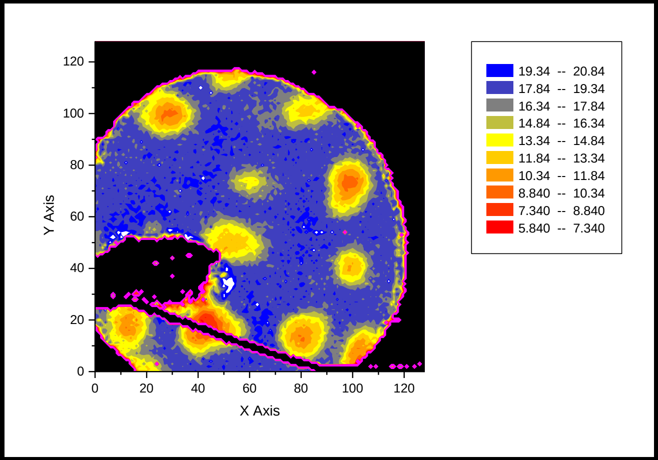
One advantage of IBIC over other forms of charge collection microscopy is that it provides high spatial resolution analysis in thick layers since the focused MeV ion beam tends to stay 'focused' through many micrometers of material.

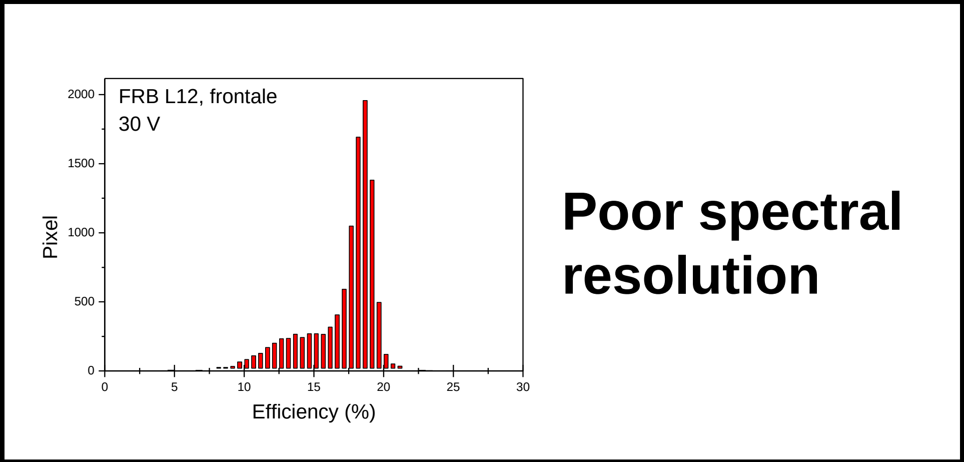




GaAs Schottky diode
Frontal IBIC



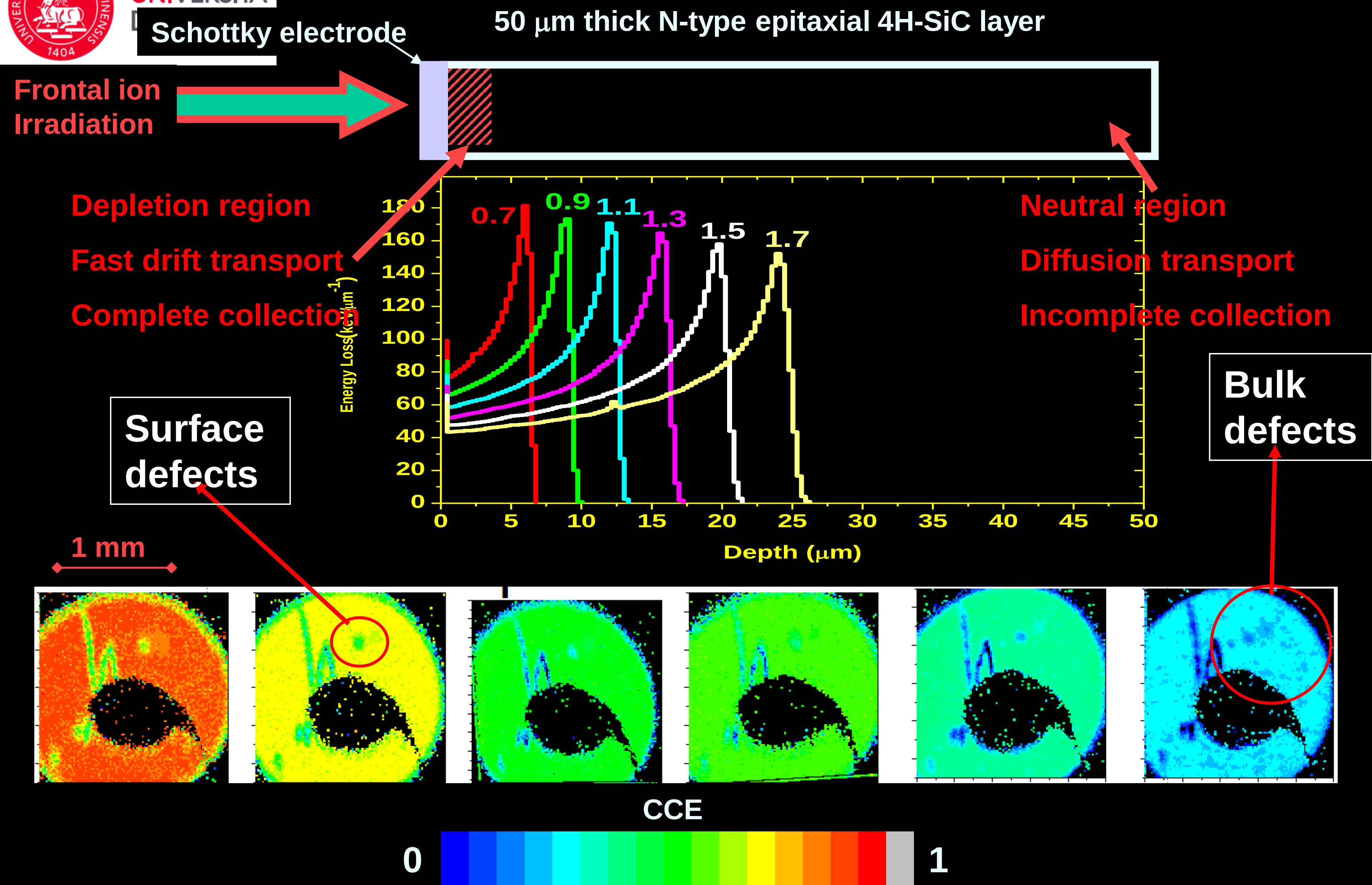




Poor spectral resolution

Effects of inhomogeneous cabon doping

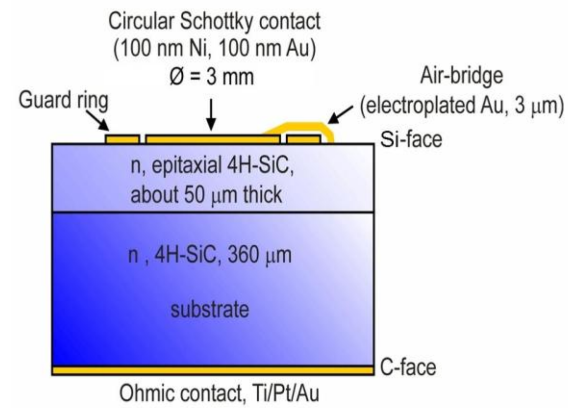
E. Vittone et al., Nuclear instruments and Methods in Physics Research B 158 (1999) 470-47

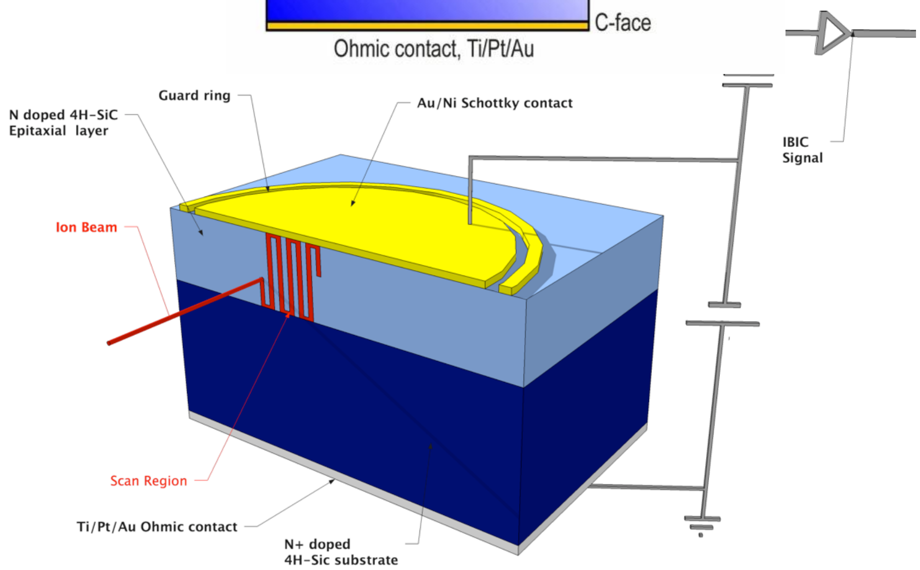


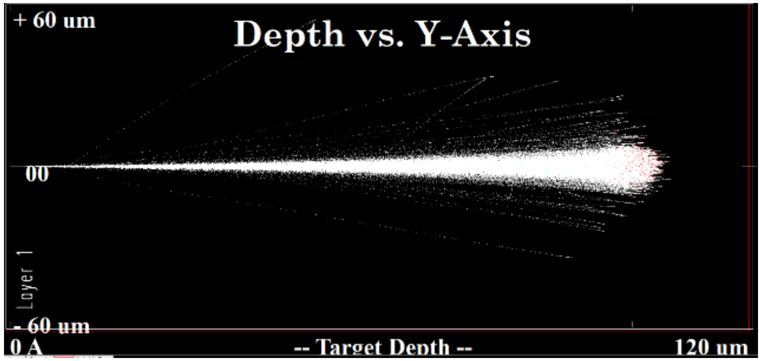
M. Jaksic et al.Nuclear Instruments and Methods in Physics Research B 188(1-4) (2002) 130-134

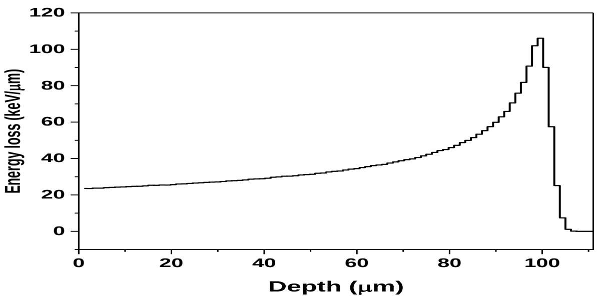
Lateral IBIC

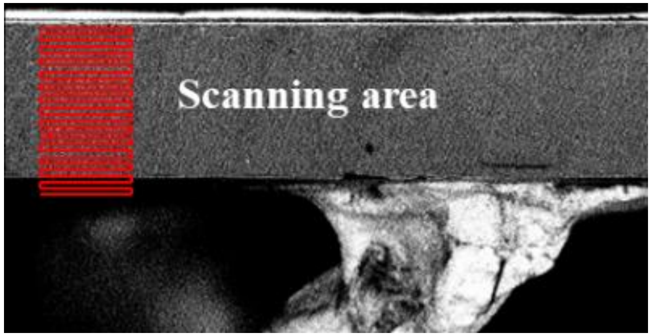
4 MeV protons
2 μm beam spot size (FWHM)
Charge sensitivity 1800 electrons/channel -> 14 keV in SiC
Spectral resolution: 12000 electrons (FWHM) ->94 keV in SiC



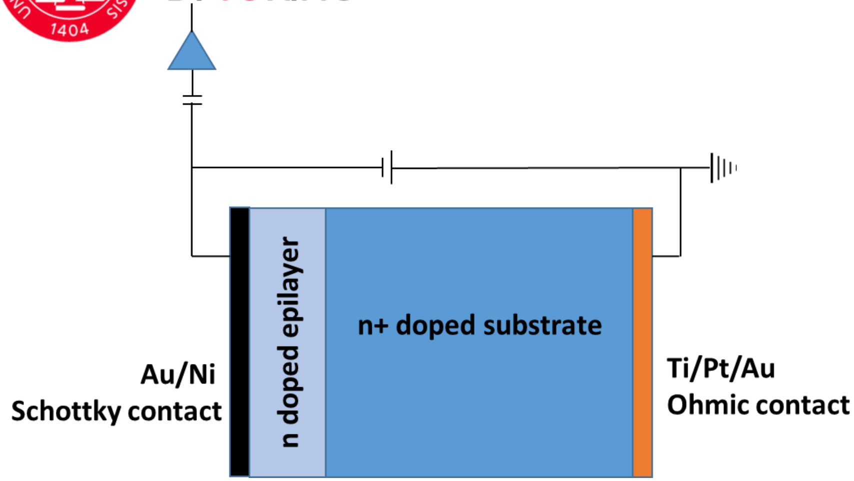


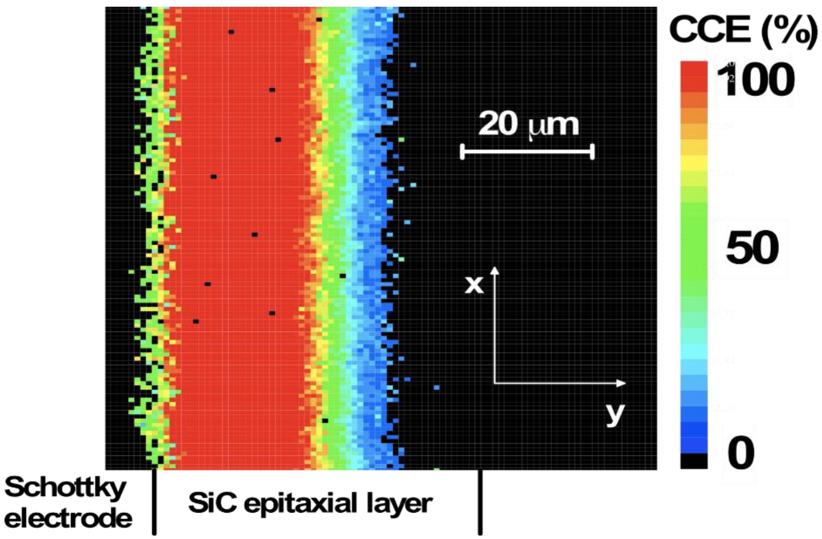


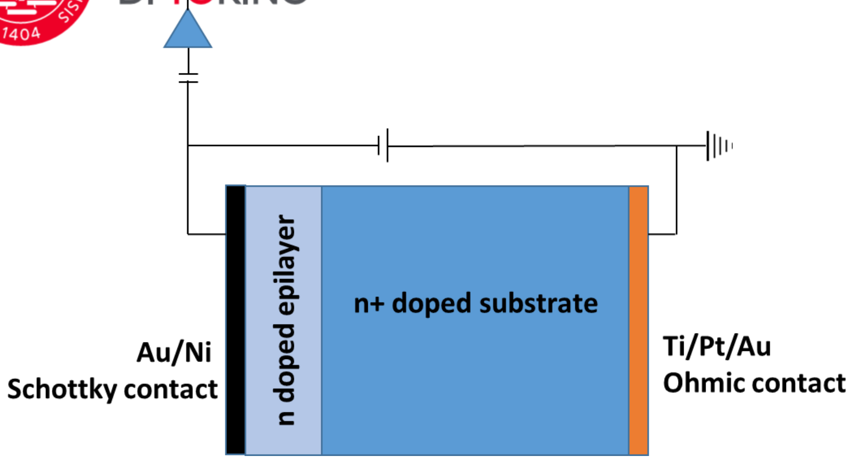




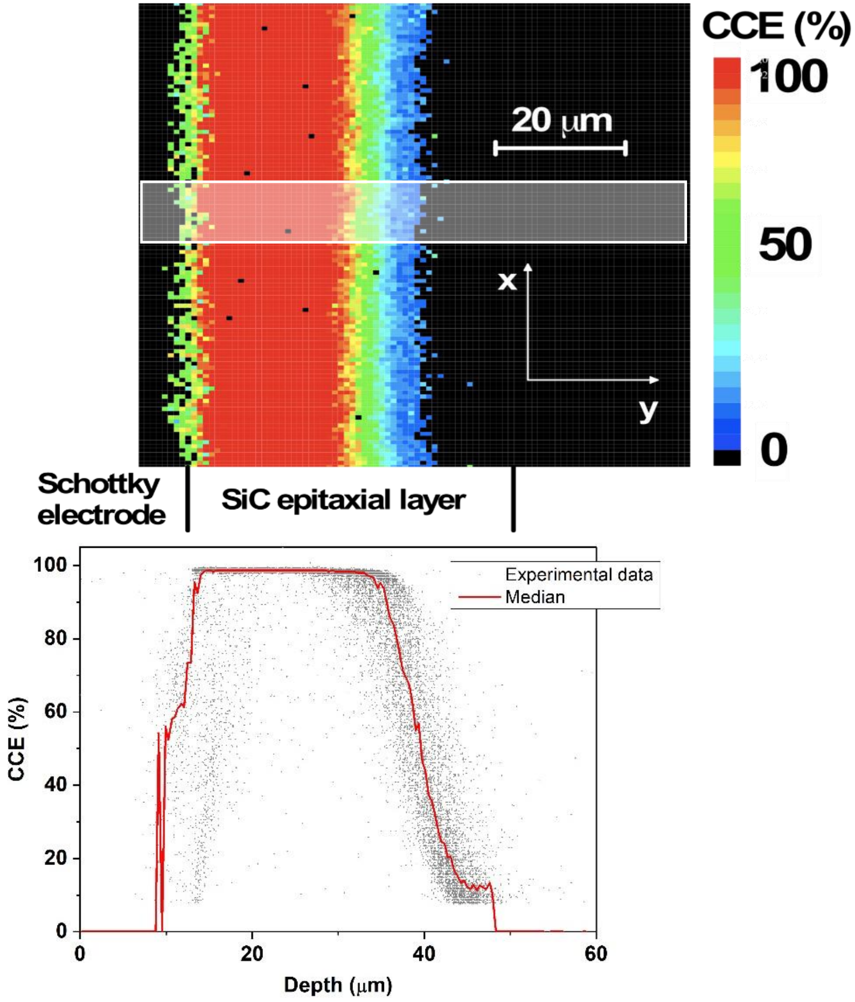
Range
Longitudinal: 100 μm
Lateral: 2.6 μm


n doped epilayer
n+ doped substrate
Au/Ni
Schottky contact
Ti/Pt/Au
Ohmic contact

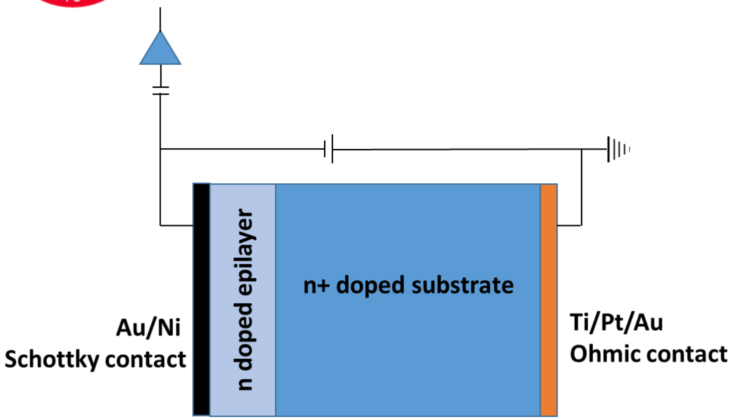

CCE (%)
100
50
0
20 μm
x
y
Schottky
electrode
SiC epitaxial layer

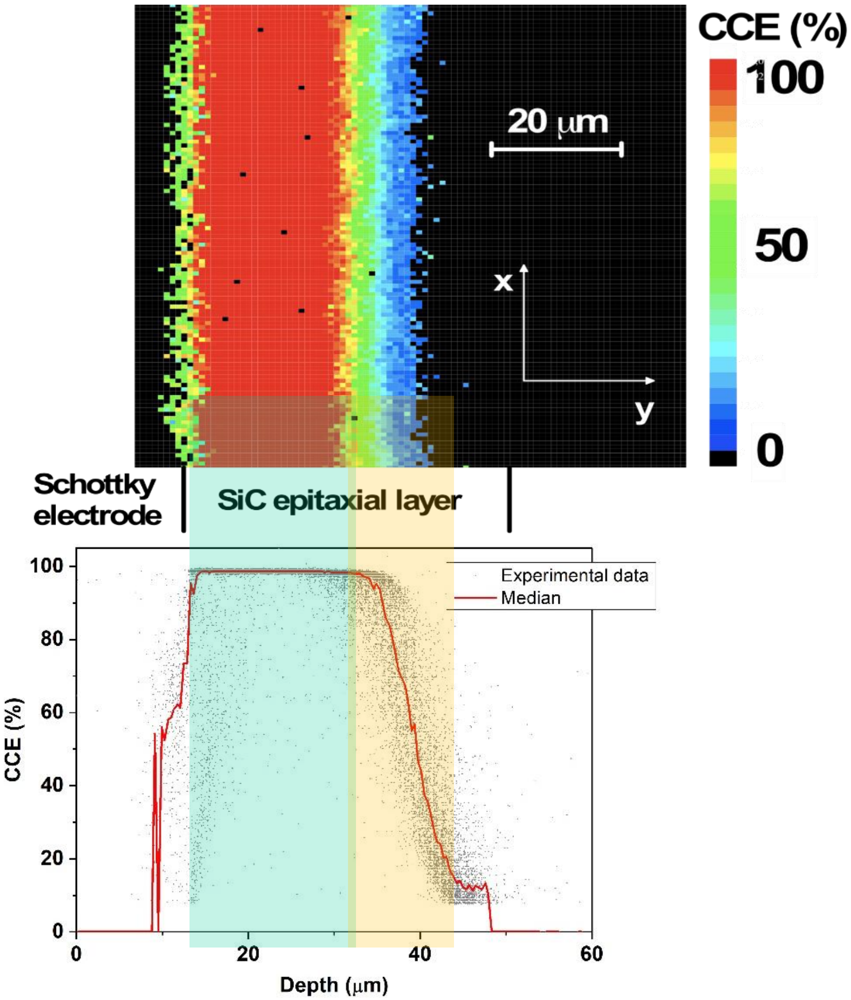


n doped epilayer
n+ doped substrate
Au/Ni
Schottky contact
Ti/Pt/Au
Ohmic contact



CCE (%)
100
50
0
20 μm
x
y
Schottky electrode
SiC epitaxial layer
Experimental data
Median
CCE (%)
Depth (μm)

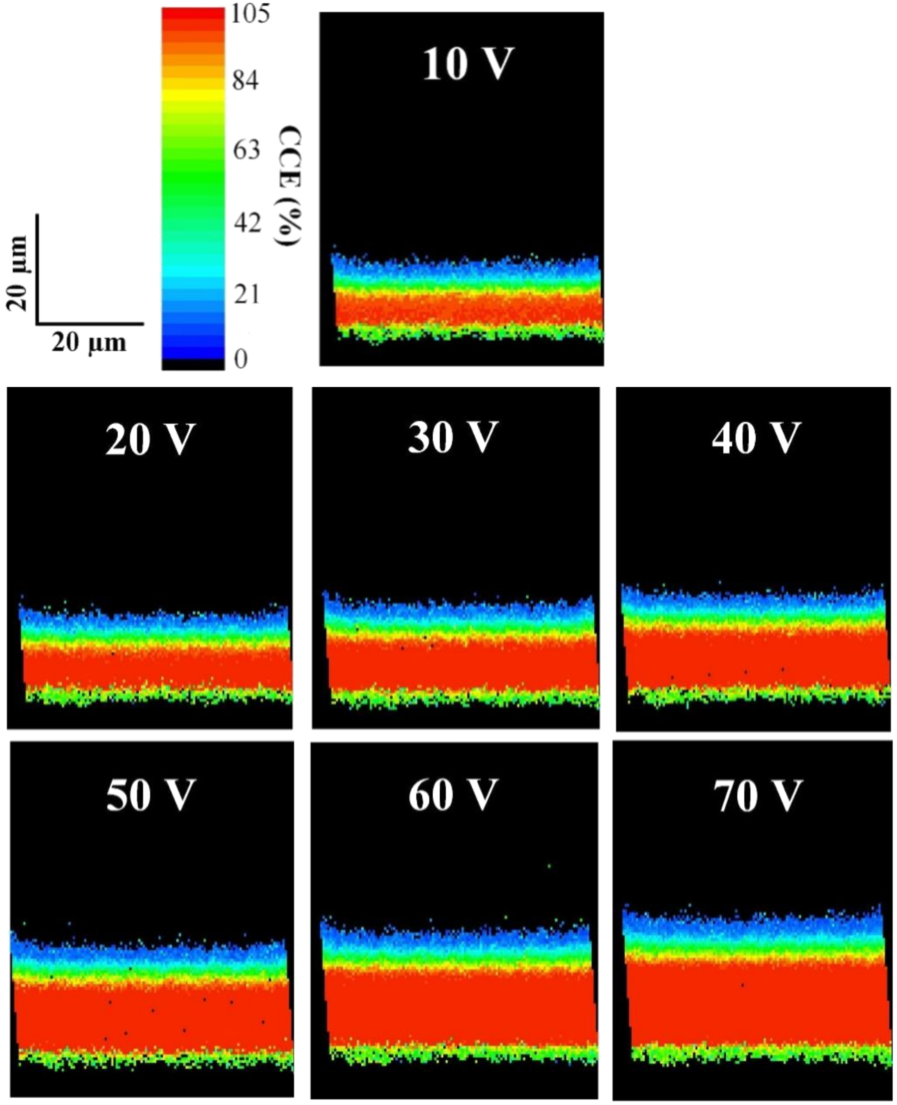


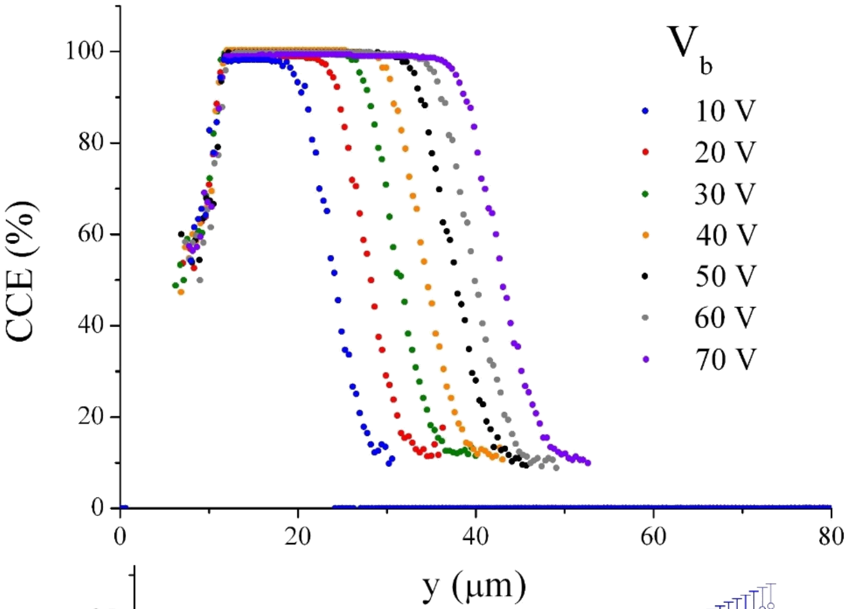


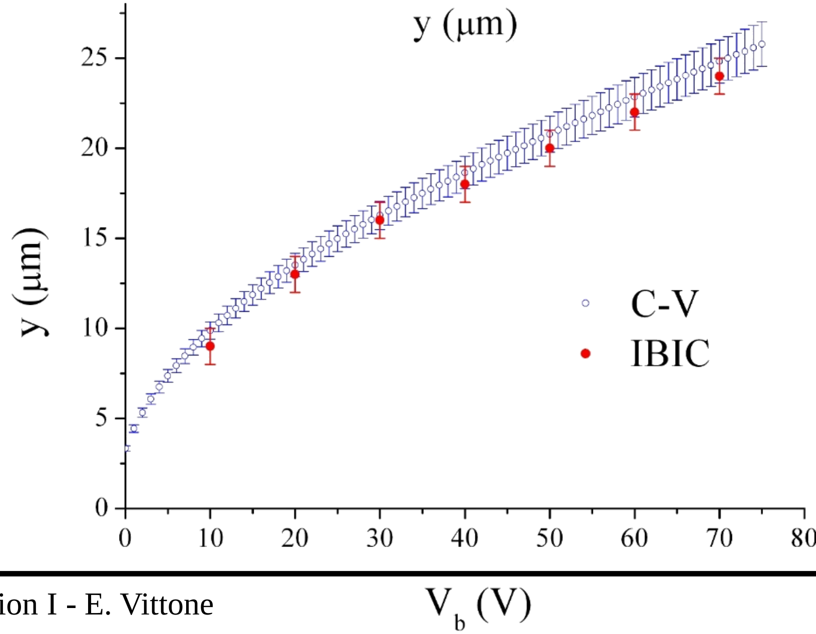
Drift-Diffusion model

Depletion layer→
→ high electric field/drift velocity →
→ Complete induced charge collection

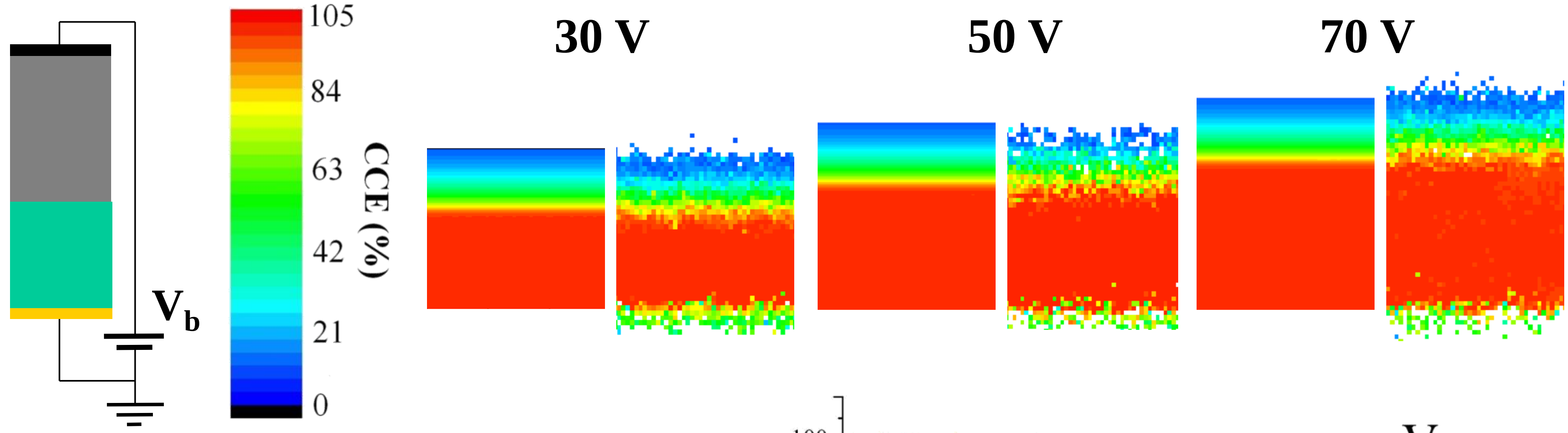
Neutral layer→
→ Minority carrier diffusion →
→ CCE exponential decay

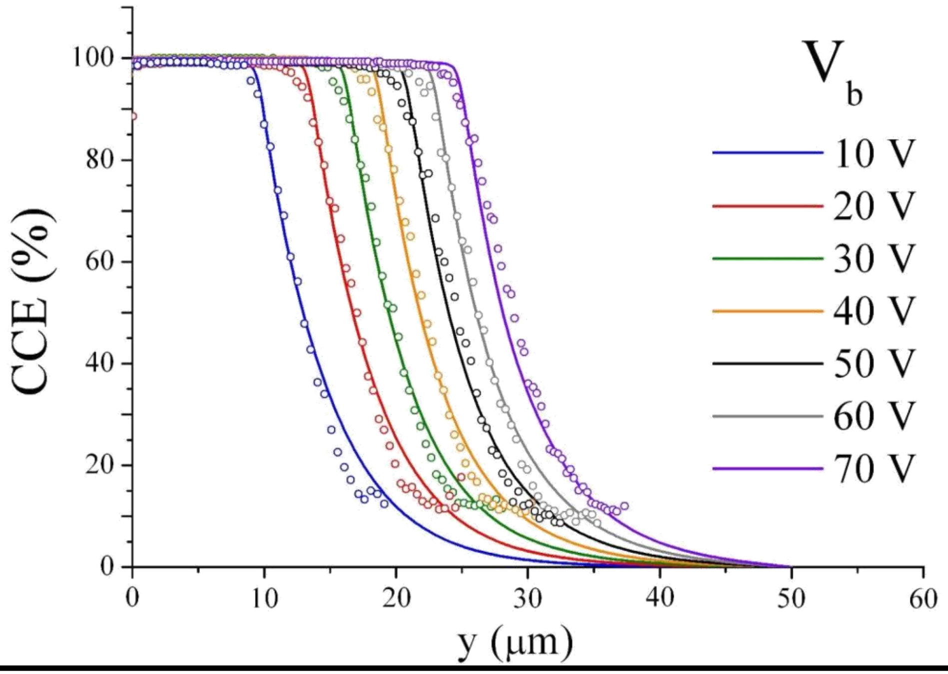

105
84
63
42
21
0
CCE (%)
20 µm
20 µm
10 V
20 V
30 V
40 V
50 V
60 V
70 V


CCE (%)
y (µm)
V_b
10 V
20 V
30 V
40 V
50 V
60 V
70 V


y (µm)
C-V
IBIC
V_b (V)

Drift-diffusion model - Simulation





$$L_p = (4{,}9 \pm 0{,}3)\,\mu m$$

$$\tau_p \approx 80\ ns$$

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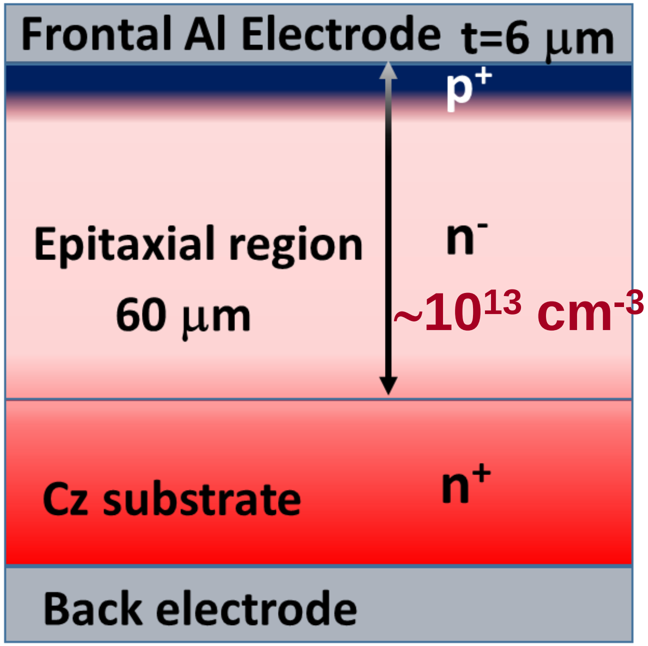
Angle Resolved Differential IBIC analysis of silicon power diodes

Objective:

- **Electronic characterization of power diodes**



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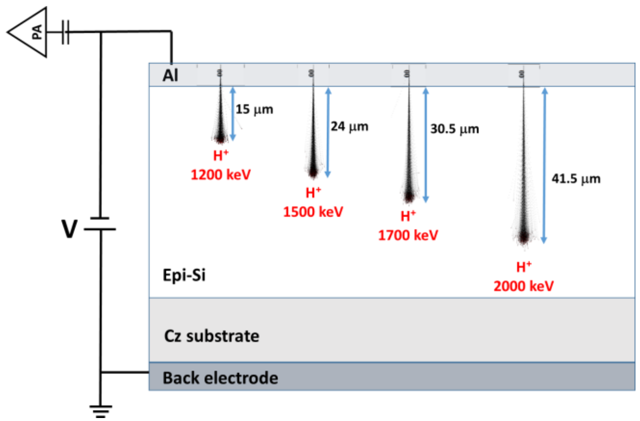
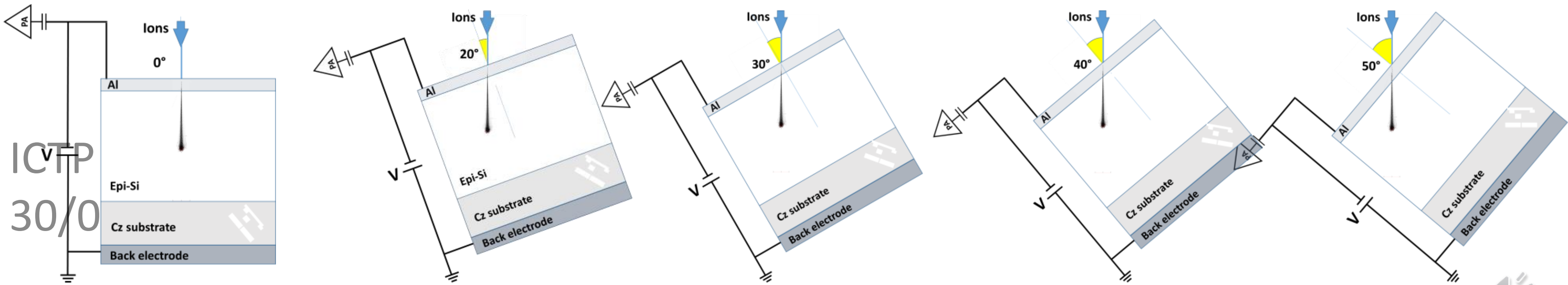
How: Polychromatic angle resolved IBIC analysis



Modulation of the probing depth by

Using different proton energies

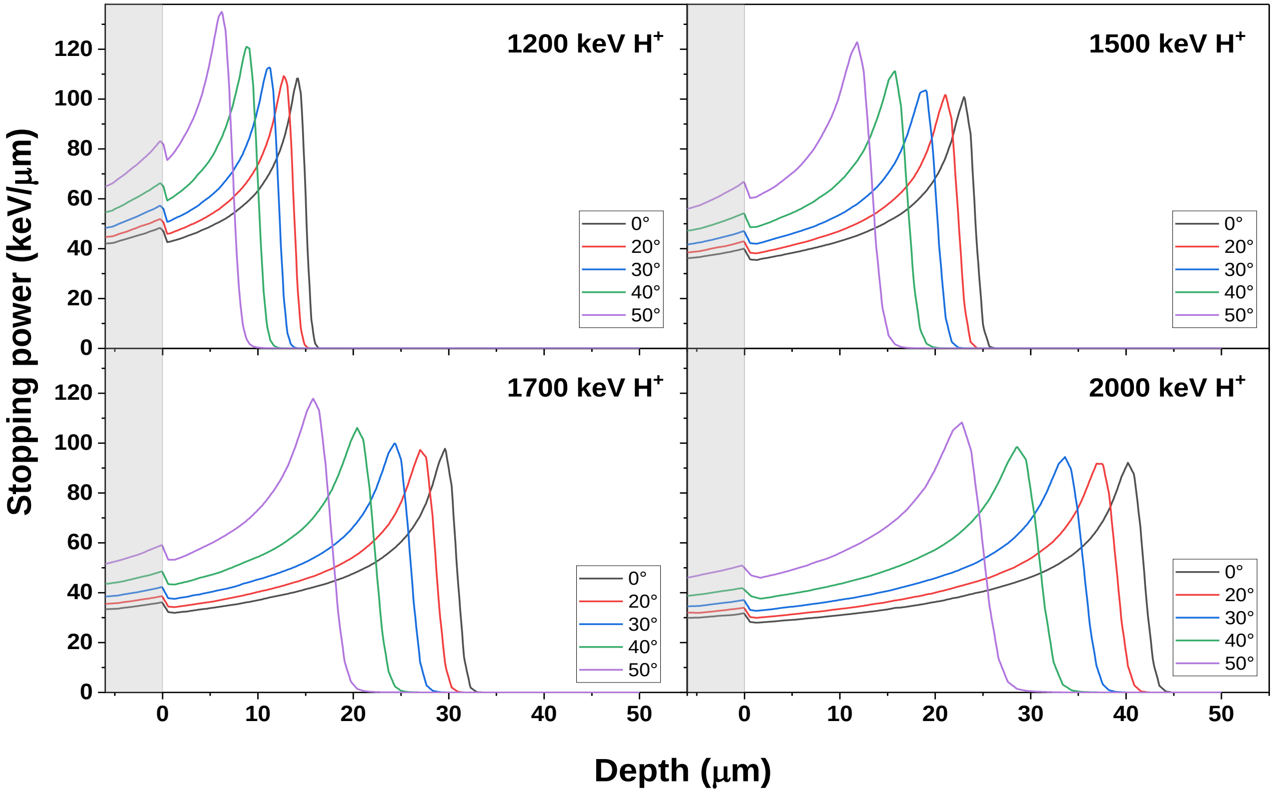
Tilting the sample with respect to the proton beam axis at different angles



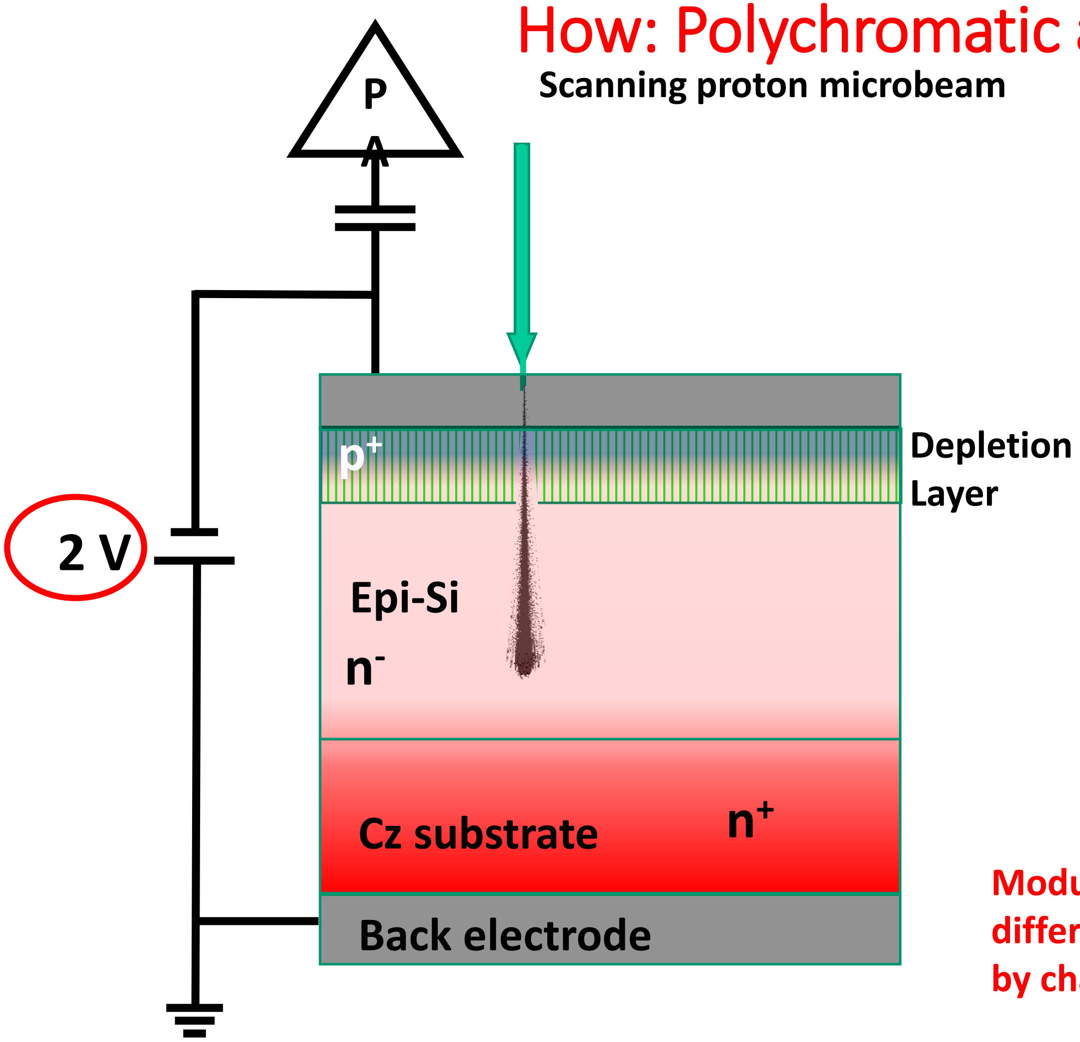
ICTP 30/0

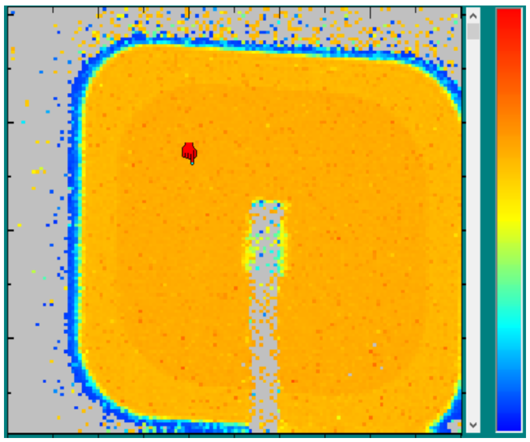
How: Polychromatic angle resolved IBIC analysis

Modulation of the carrier generation profiles by different tilting angle and different ion energies



How: Polychromatic angle resolved IBIC analysis

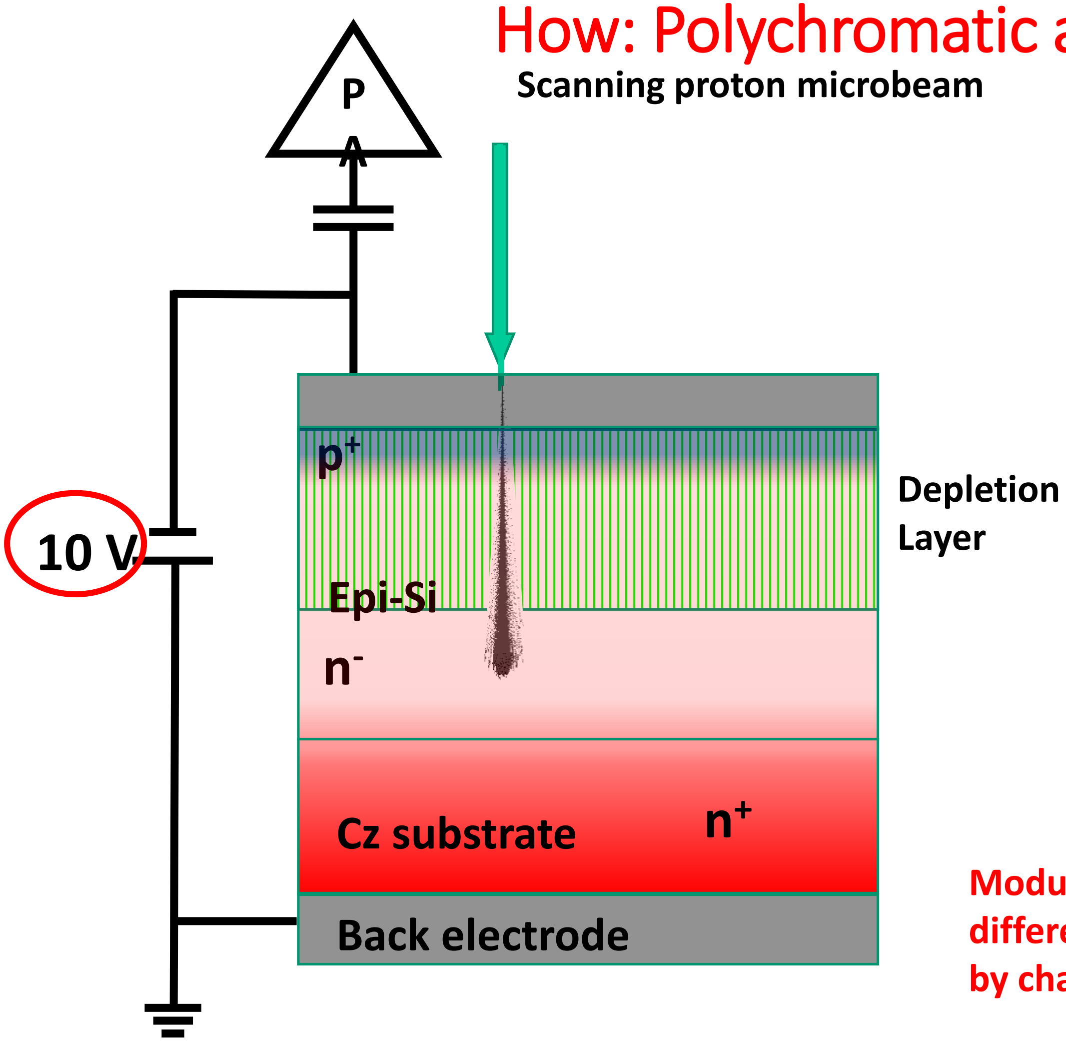




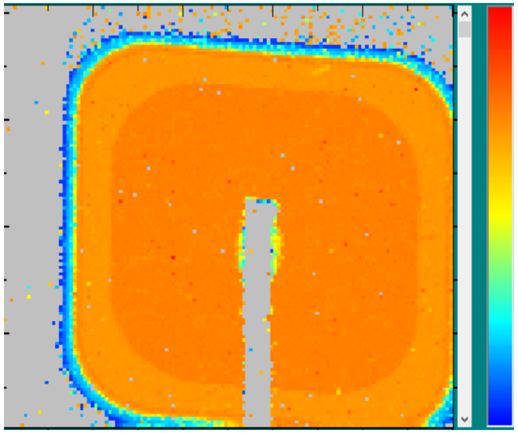
Modulation of the carrier generation profiles by different widths of the depletion region induced by changing the applied bias voltage

How: Polychromatic angle resolved IBIC analysis

Scanning proton microbeam

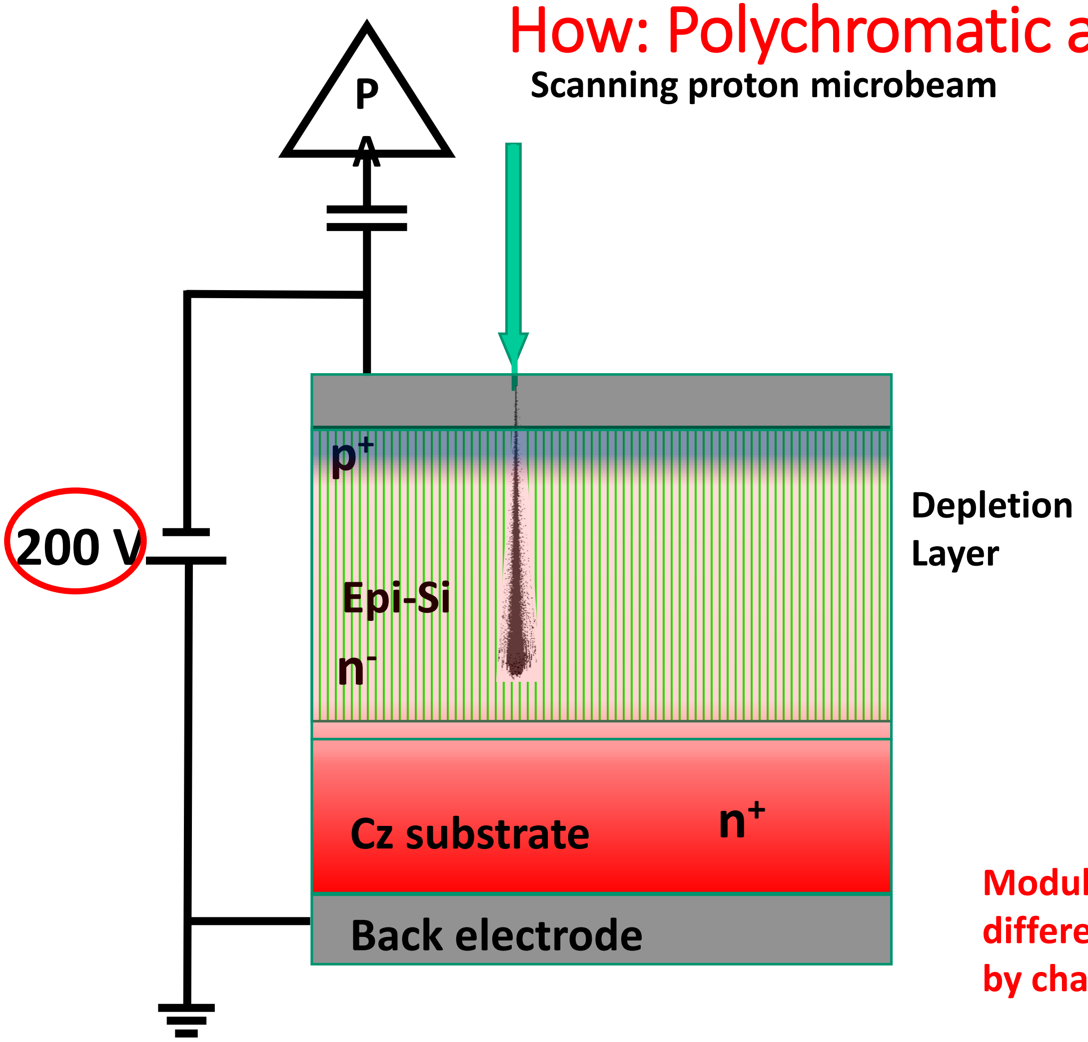


IBIC Map
1.7 MeV proton
Applied Bias = 10 V

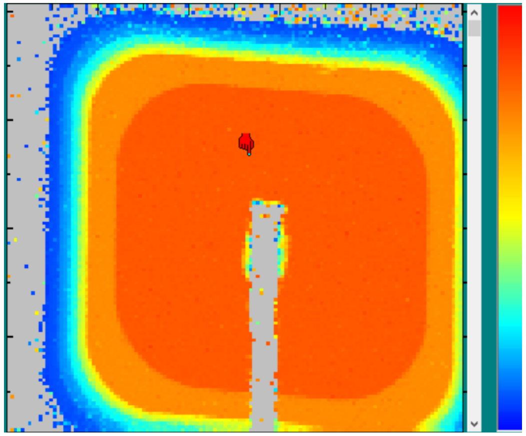


Modulation of the carrier generation profiles by different widths of the depletion region induced by changing the applied bias voltage

How: Polychromatic angle resolved IBIC analysis



IBIC Map
1.7 MeV proton
Applied Bias = 200 V

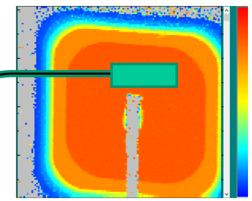


Modulation of the carrier generation profiles by different widths of the depletion region induced by changing the applied bias voltage

Parameter space: (E,θ,V)

For each (E)

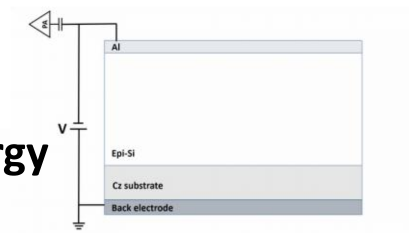
IBIC Map



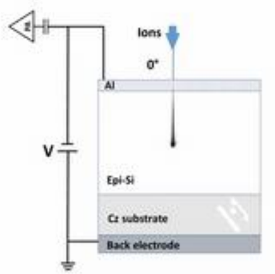
Selecting a region

IBIC SPECTRA

E
ion energy

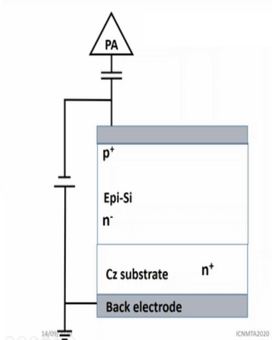


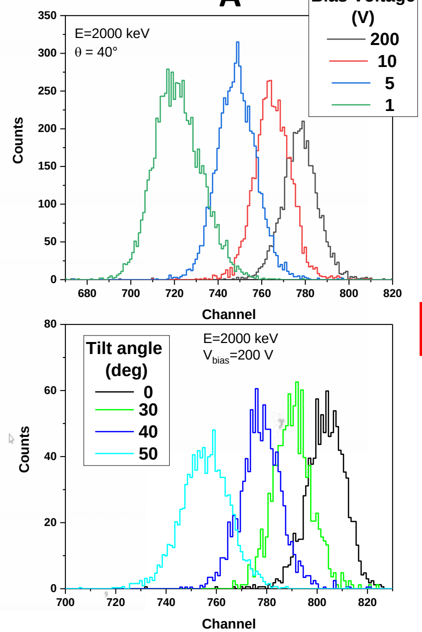
θ
Tilting angle

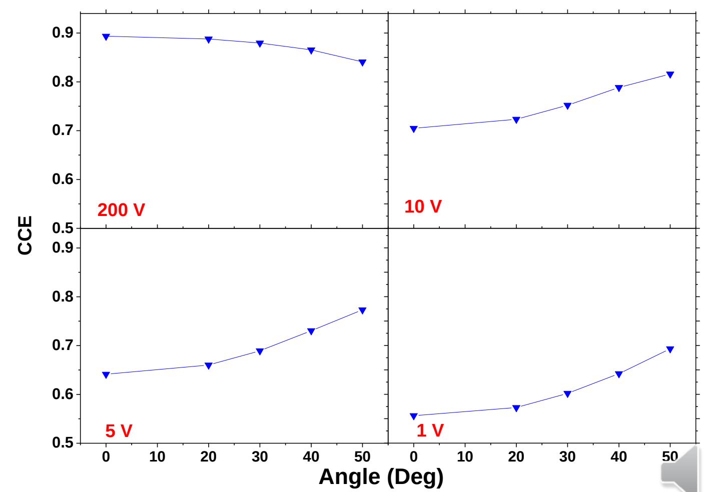


14/09/2020

V
Bias voltage

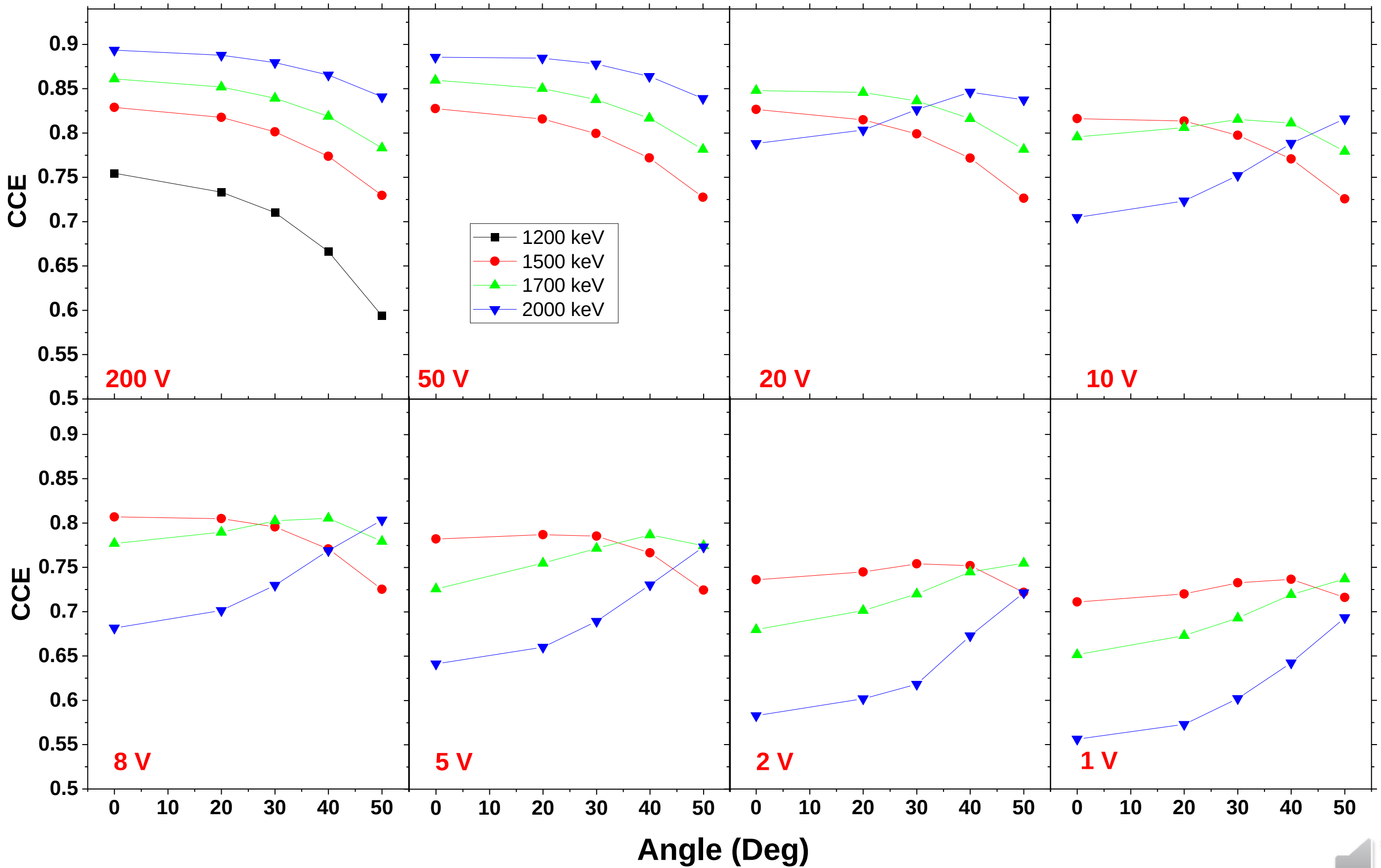






Experimental Results: Charge Collection Efficiency (CCE)

Experimental CCE as function of Tilting angle θ @ different V Parametrized by E



Lines are interpolating segments as a guide for the eyes

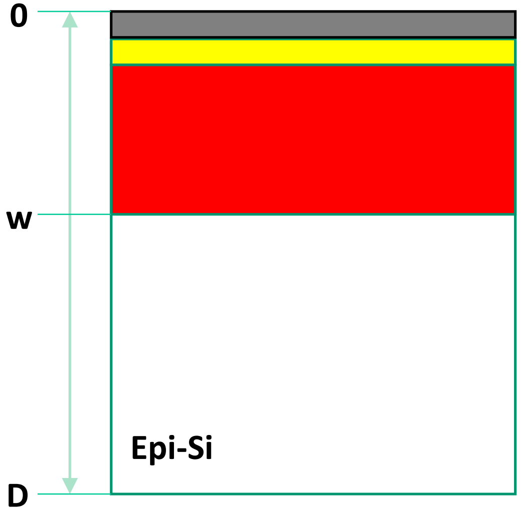
Model based on simplified IBIC theory

$$\mathbf{CCE_{model}(\theta, E_{Ion}, V) = \int_0^D \eta(x) \cdot \left[\frac{dE}{dx}\right]_{\theta, E_{Ion}} dx}$$

CCE profile

Generation profile
Electron stopping power

Best fit with two free parameters:
W(V): depletion layer width as function ov V
Lh: minority carrier diffusion length



Al Electrode+Si Dead layer: η(x)=0

Depletion region: η(x)=1

Neutral region: $\eta(x)=\frac{\cosh(D-x)}{\cosh(D-w)}$ **Solution of** $\frac{d^2\eta(x)}{dx^2} = \frac{\eta(x)}{{L_h}^2}$

With bounday conditions:

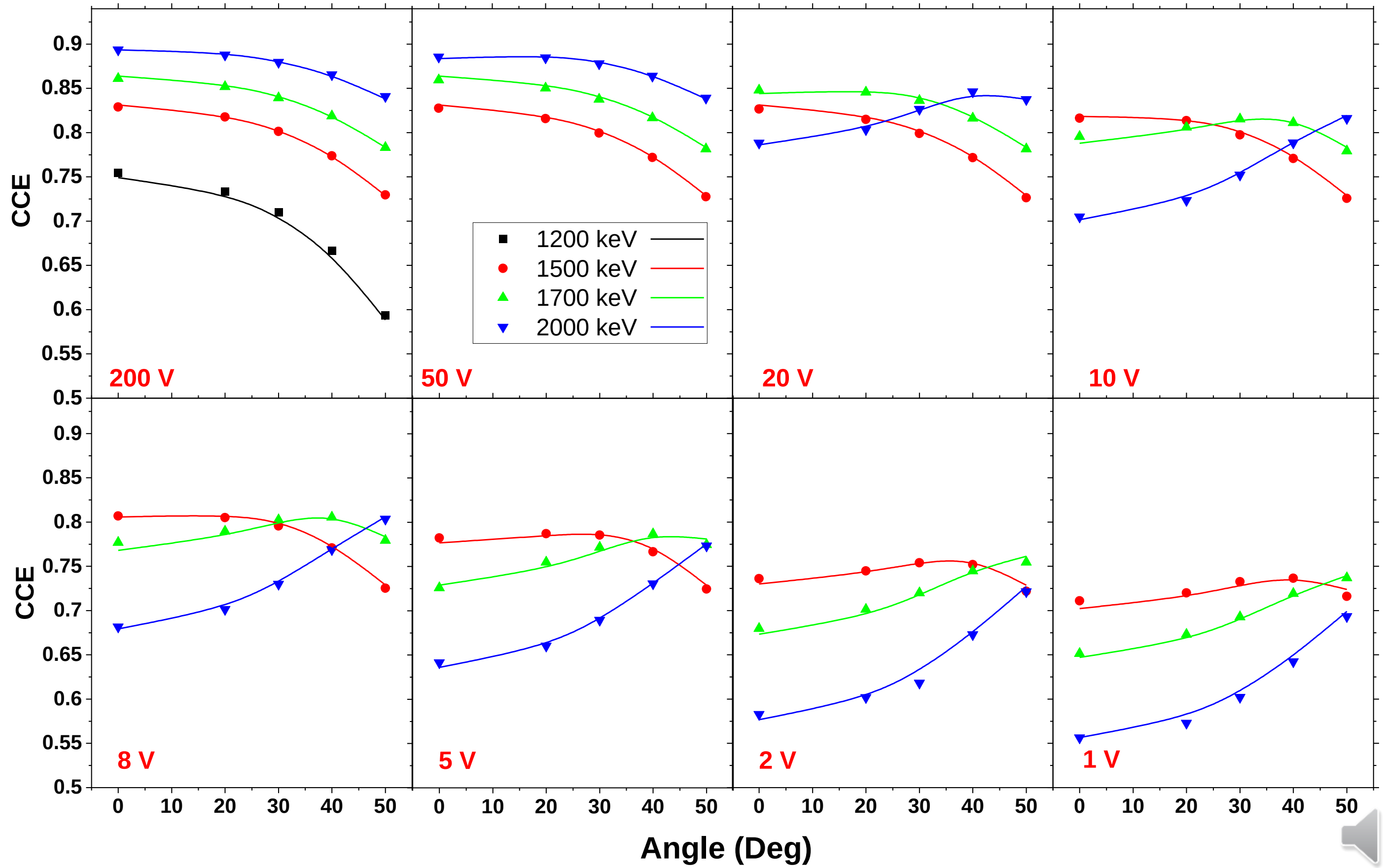
$$\begin{cases} \eta(x = w(V)) = 1 \\ \left.\frac{d\eta}{dx}\right|_{x=D} = 0 \end{cases}$$

Effect of the back surface field at the n-/n+ boundaries

Results: Model

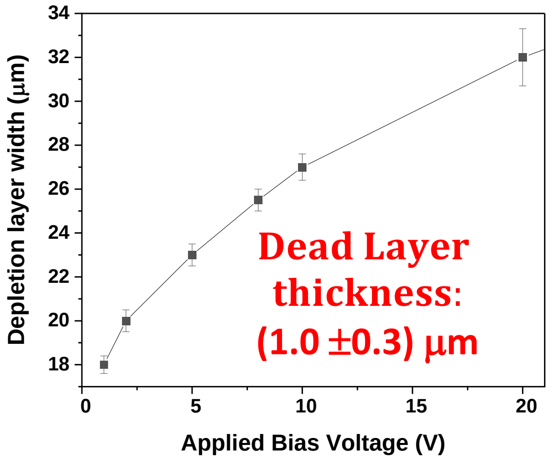
Solid lines are fitting curves

Experimental and fitting CCE as function of Tilting angle θ @ different V Parametrized by E

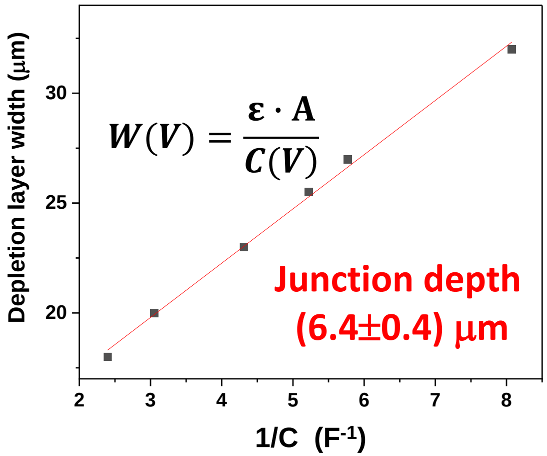


Results

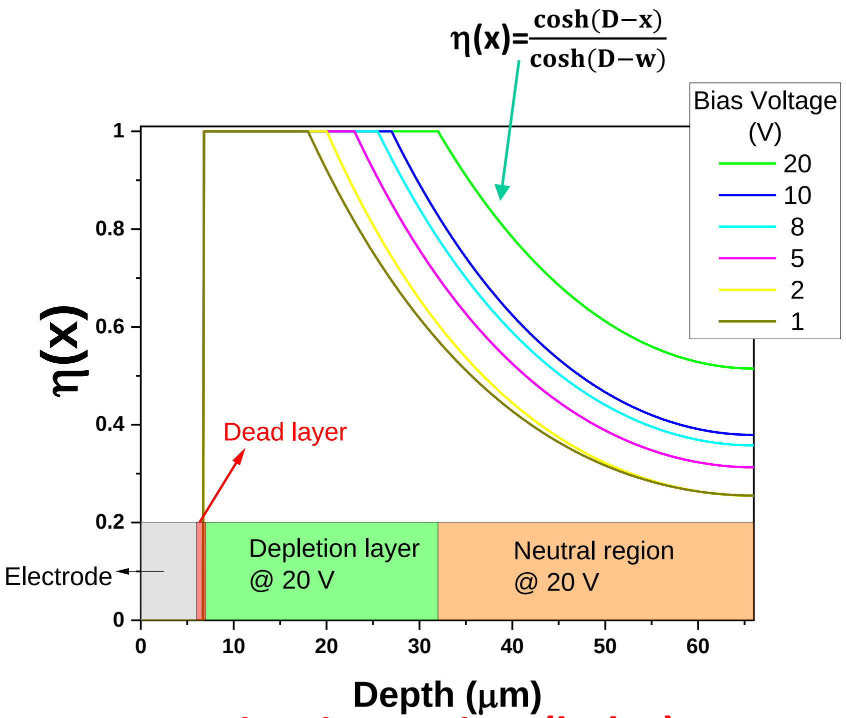
Behavior of the depletion layer width as function of the applied bias voltage



Linear relationship between inverse of capacitance and the depletion layer width



Charge collection efficiency profiles at different bias voltages



Minority carriers (holes) diffusion length:
L_h = (24.0±1.3) µm

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In this 1st lecture

- ✓ **Single ion detection based on the ion-semiconductor interaction**
- ✓ **The ion energy loss in the material generates charge carriers, which can be detected by measuring the induced charge at the sensing electrode**
- ✓ **The induced charge signal depends upon the device electrostatics, transport and recombination properties.**
- ✓ **The Gunn's theorem provides an adequate interpretation of the pulse signal formation and is at the base of powerful models to simulate electronic device performances**
- ✓ **The analytical potential of the Ion Beam Induced Charge technique stems on multiple configurations:**

  Frontal, Lateral, Depth, Angle, Temperature Resolved

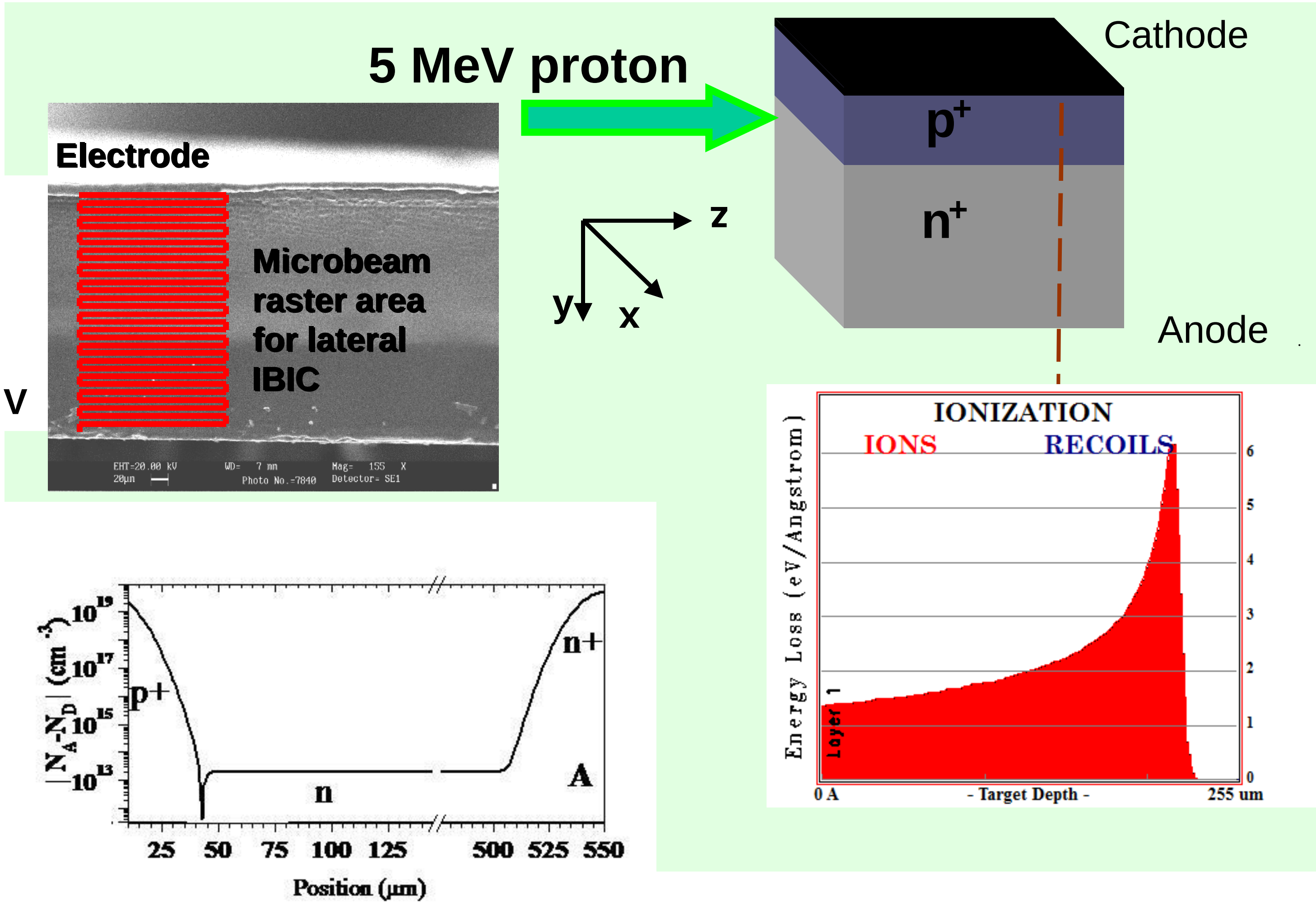
Thanks for your kind attention

Lateral IBIC

Si p-n diode

Polished and passivated lateral surface

Leakage current below 100 nA @ 100 V



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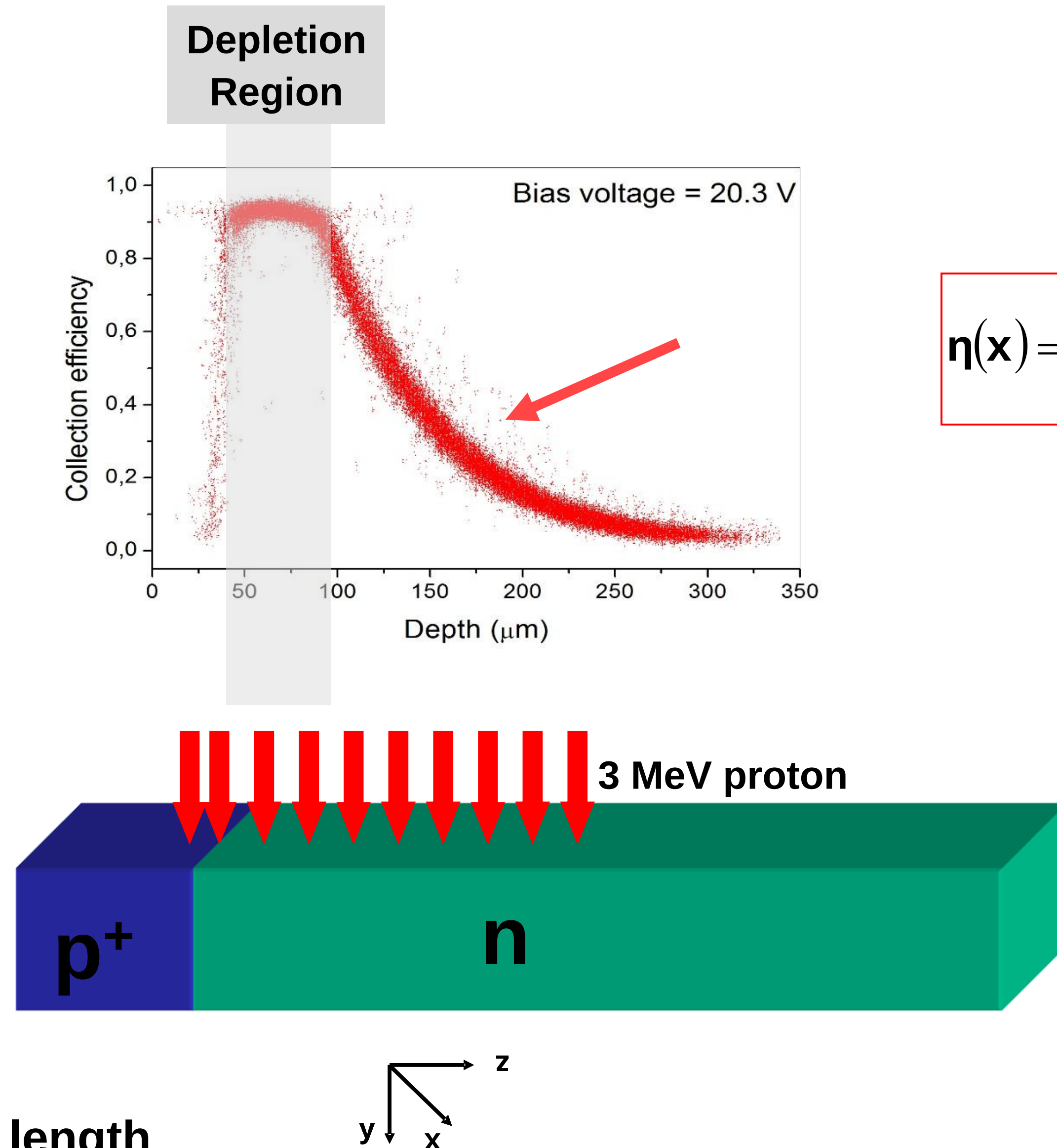
Lateral IBIC

Si p-n diode

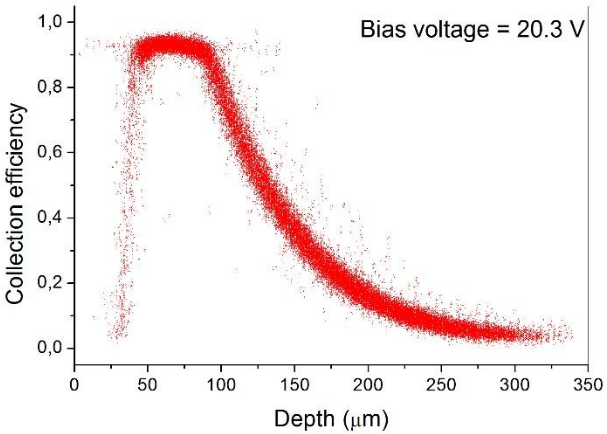


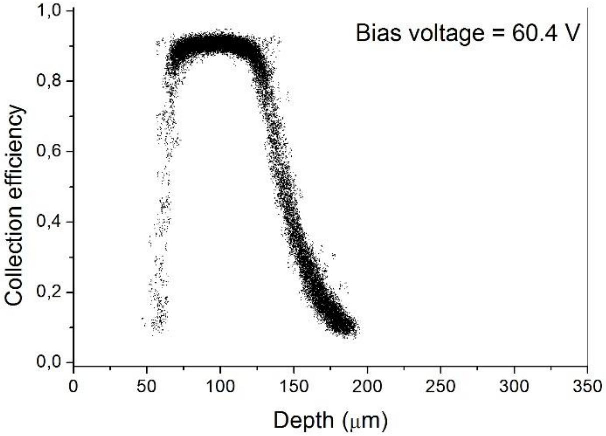
$$\eta(x) = \exp\left[-\frac{x}{L_p}\right]$$

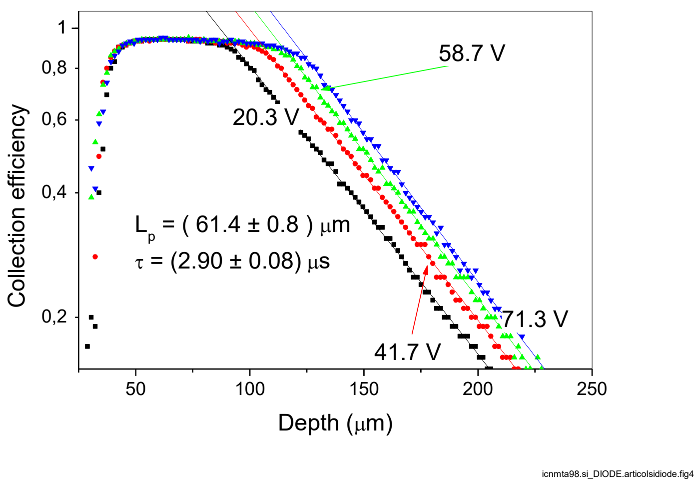
$$L_p = \sqrt{D_p \cdot \tau_p}$$

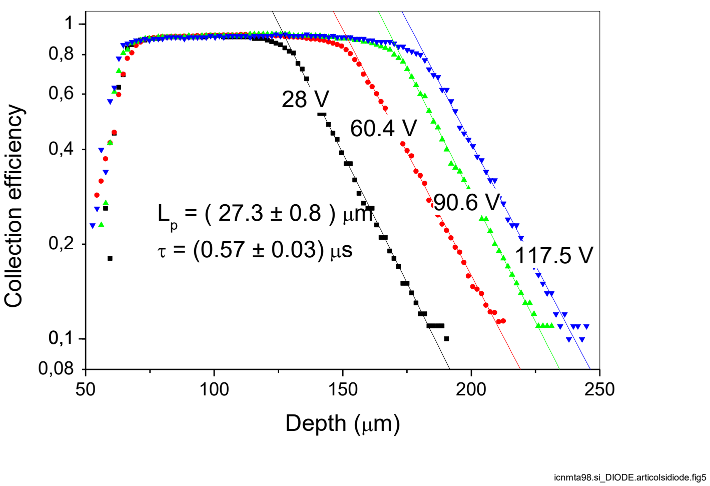
minority carrier diffusion length

C. Manfredotti et al., Nuclear instruments and Methods in Physics Research B 158 (1999) 476-480


Bias voltage = 20.3 V
Collection efficiency
Depth (μm)


Bias voltage = 60.4 V
Collection efficiency
Depth (μm)


58.7 V
20.3 V
L_p = (61.4 ± 0.8) μm
τ = (2.90 ± 0.08) μs
71.3 V
41.7 V
Collection efficiency
Depth (μm)
icnmta98.si_DIODE.articolsidiode.fig4


28 V
60.4 V
L_p = (27.3 ± 0.8) μm
τ = (0.57 ± 0.03) μs
90.6 V
117.5 V
Collection efficiency
Depth (μm)
icnmta98.si_DIODE.articolsidiode.fig5