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International Centre
for Theoretical Physics

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Joint ICTP-IAEA Workshop on Physics of Radiation Effect and its Simulation for Non-Metallic Condensed Matter

13 - 24 August 2012

Theory of the Ion Beam Induced Charge Technique (IBIC)

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www.dfs.unito.it/solid

Theory of the Ion Beam Induced Charge Technique (IBIC).

Bibliography

Books:

M.B.H. Breese, D.N. Jamieson, P.J.C. King, "Materials Analysis Using a Nuclear Microprobe", John Wiley and Sons, 1996

Articles:

M. B. H. Breese, E. Vittone, G. Vizkelethy, P.J. Sellin, "*A review of ion beam induced charge microscopy*", Nuclear Instruments and Methods in Physics Research B 264 (2007) 345–360.

See slides

Links:

http://www.dfs.unito.it/solid/RICERCA/IBA/IBA_index.html

Theory of the Ion Beam Induced Charge Technique (IBIC).

- From nuclear spectroscopy to material analysis
- Principles of IBIC
- From spectroscopy to microspectroscopy
- Basic equations
- Validation of the theory
- Charge sharing

IBIC for the functional characterization of semiconductor materials and devices

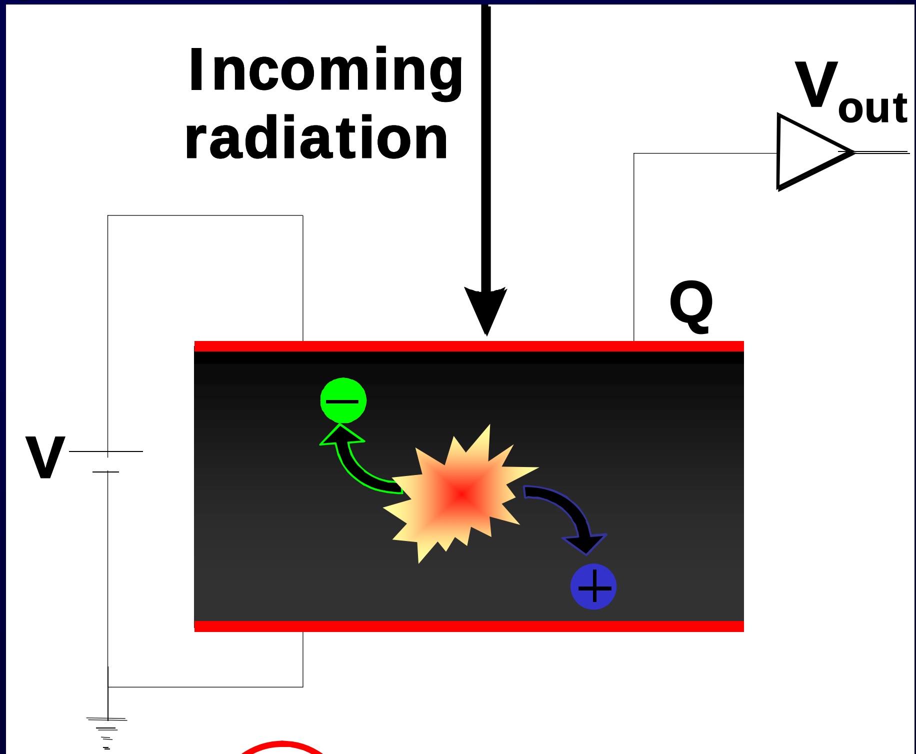
Measurement of the their electronic properties and performances

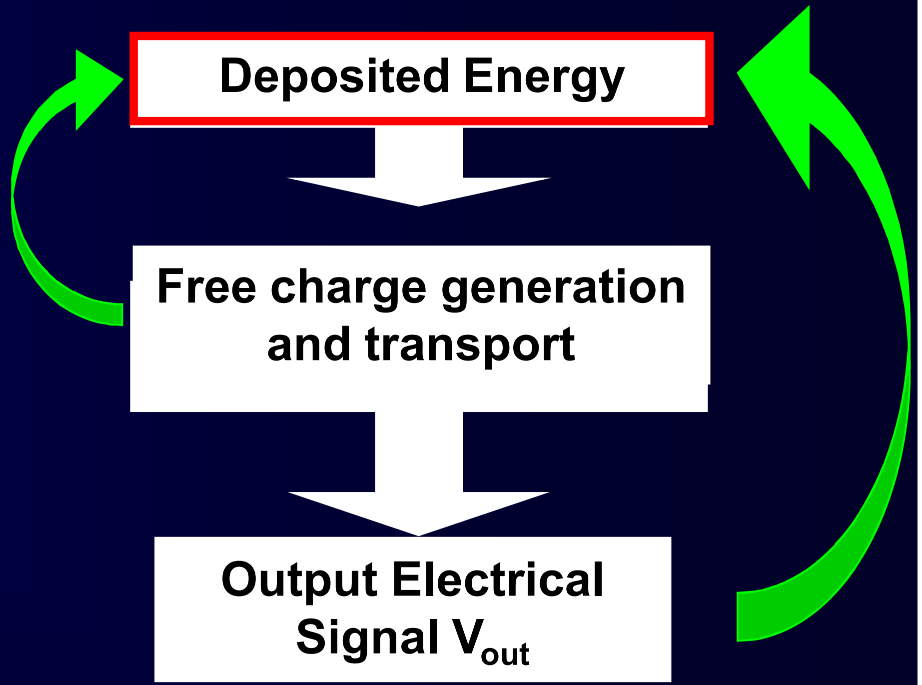
Main physical observable: current

Current = F(carrier density; carrier transport)

Carrier density	Carrier transport
Carrier generation by MeV ions Generation profile Recombination/trapping Carrier lifetime τ	Free carriers (electron/hole) transport Two mechanisms: Drift $\Rightarrow$ electric field $v=\mu\cdot E$ Diffusion $\Rightarrow$ concentration gradient

Principles of radiation detection techniques





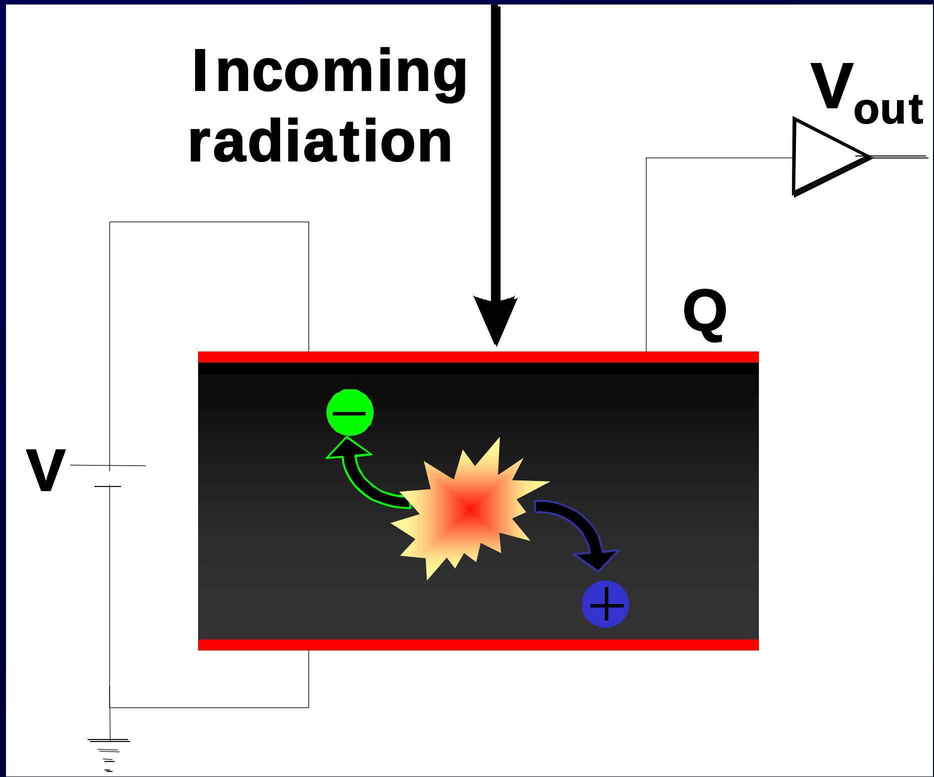
$$V_{out} = F(\text{Deposited Energy}, \text{Free Carrier Transport})$$

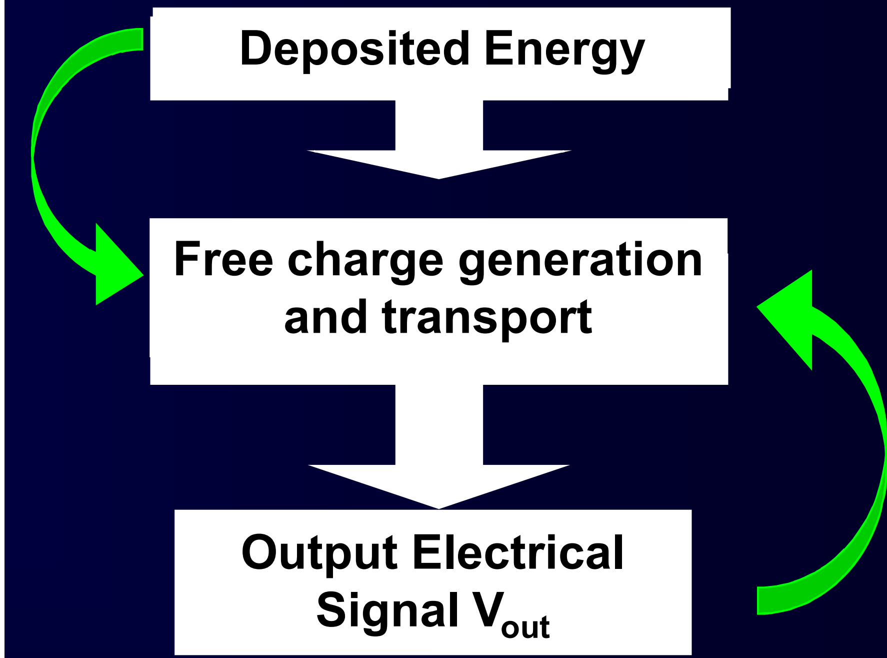
Measured

Nuclear spectroscopy

Well known

IBIC principles





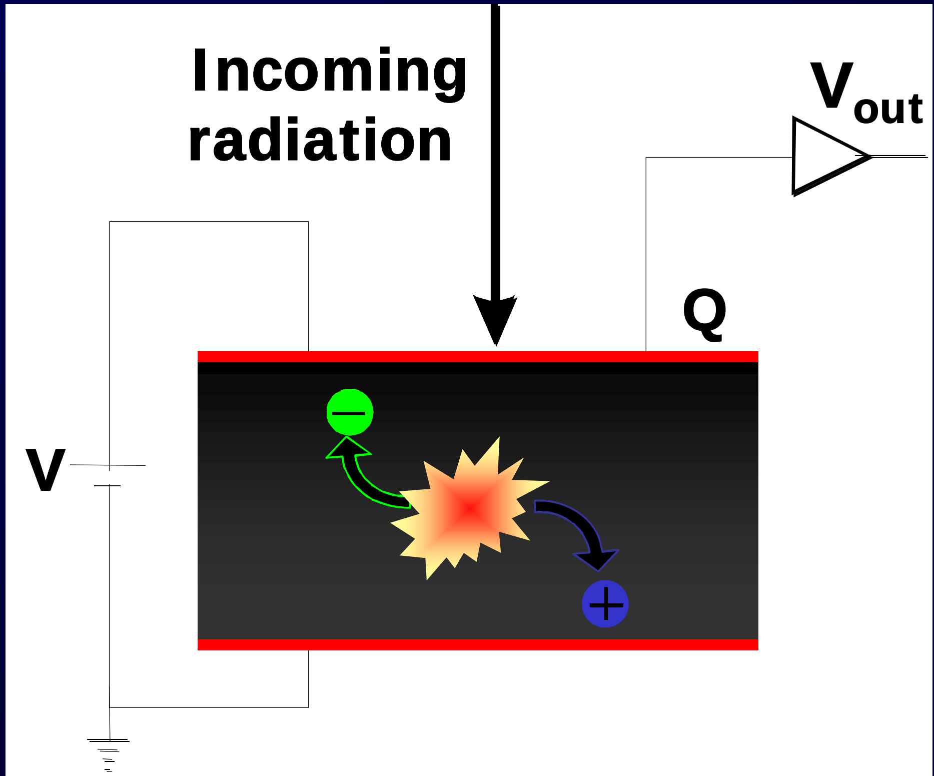
$$V_{out} = F(\text{Deposited Energy}, \text{Free Carrier Transport})$$

Measured (V_{out})

Well known (Deposited Energy)

Material Characterization (Free Carrier Transport)

IBIC principles



MeV ion energy deposition

↓

Electron/hole pair generation

↓

Charge carrier transport

↓

Induced Charge at the sensing electrode

↓

Output Signal Vout

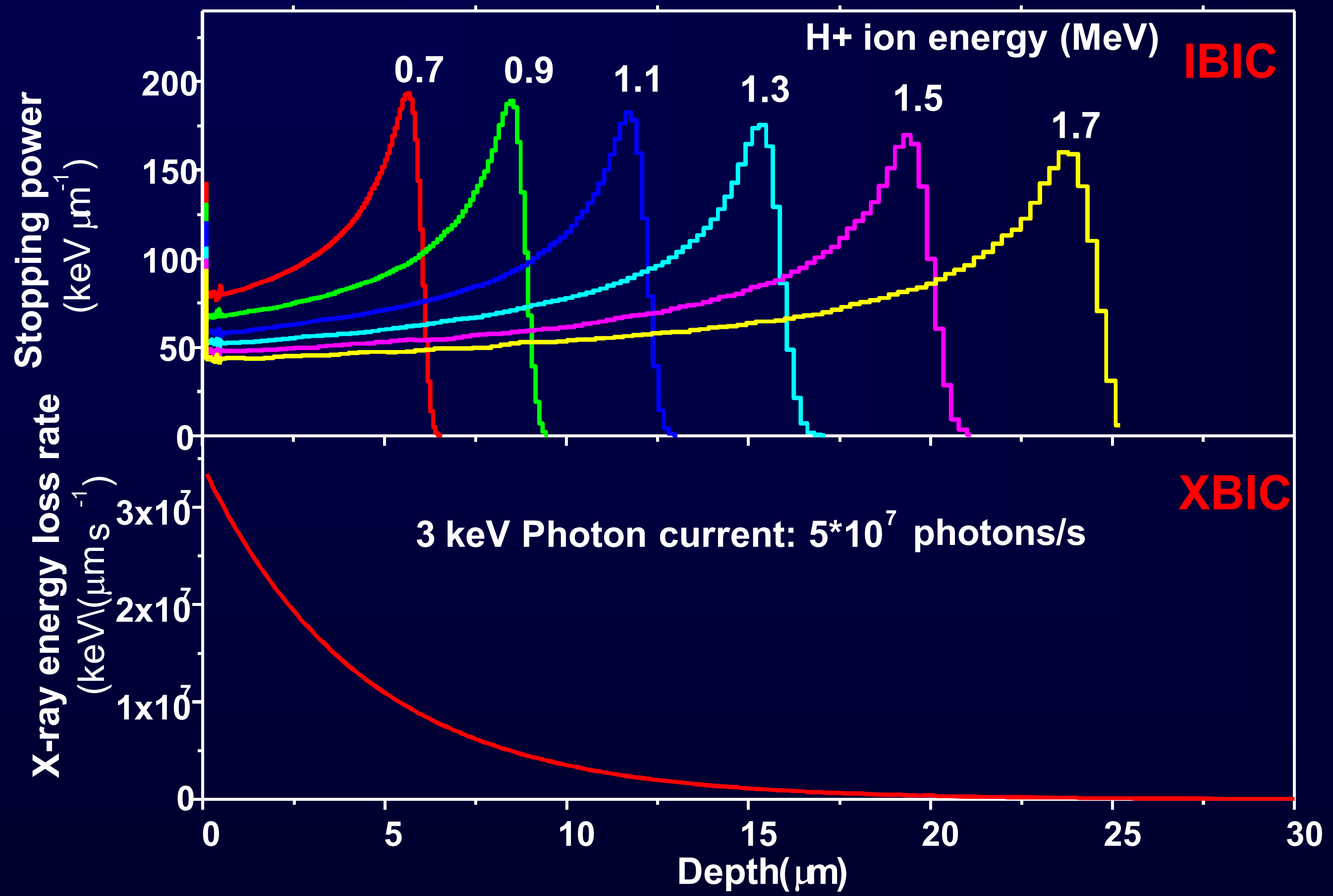
$$V_{out} = F(\text{Deposited Energy}, \text{Free Carrier Transport})$$

Measured (V_{out})

Well known (Deposited Energy)

Material Characterization (Free Carrier Transport)

Using MeV ions to probe the electronic features of semiconductors



SRIM (Stopping and Range of Ion in Matter)

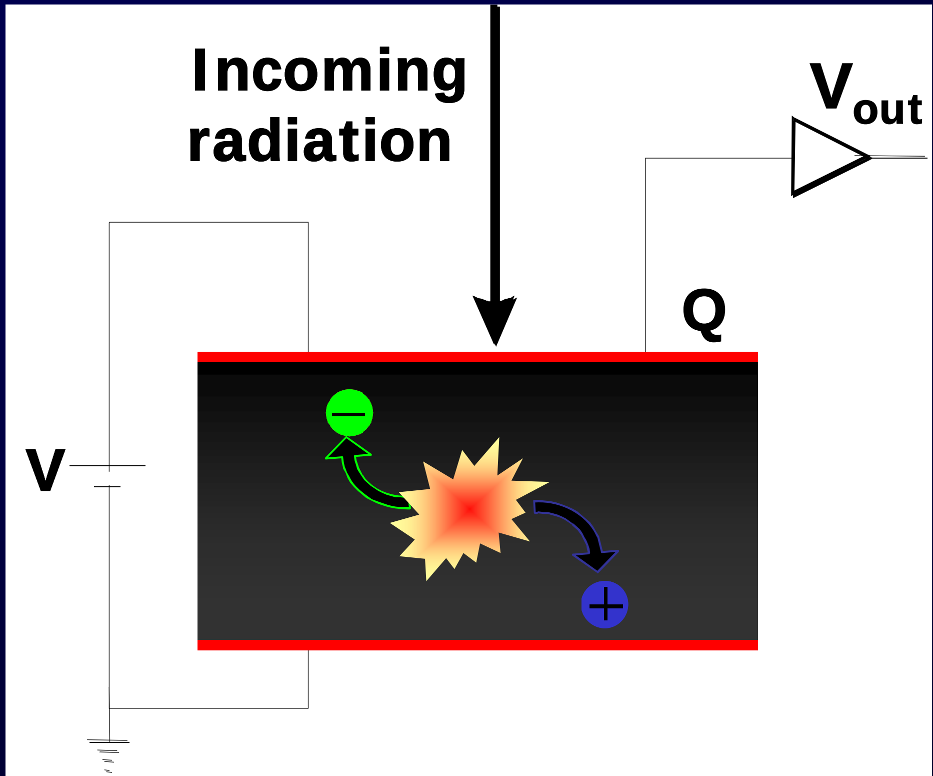
Electrode energy loss very small (≅ 1%)

- ➢long range
- ➢low lateral scattering
- ➢a wide choice of ion ranges and electronic energy losses

↓

- ✓analysis through thick surface layers
- ✓charge pulses height spectra almost independent on topography .
- ✓profiling

IBIC principles



MeV ion energy deposition

Electron/hole pair generation

Charge carrier transport

Induced Charge at the sensing electrode

Output Signal Vout

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

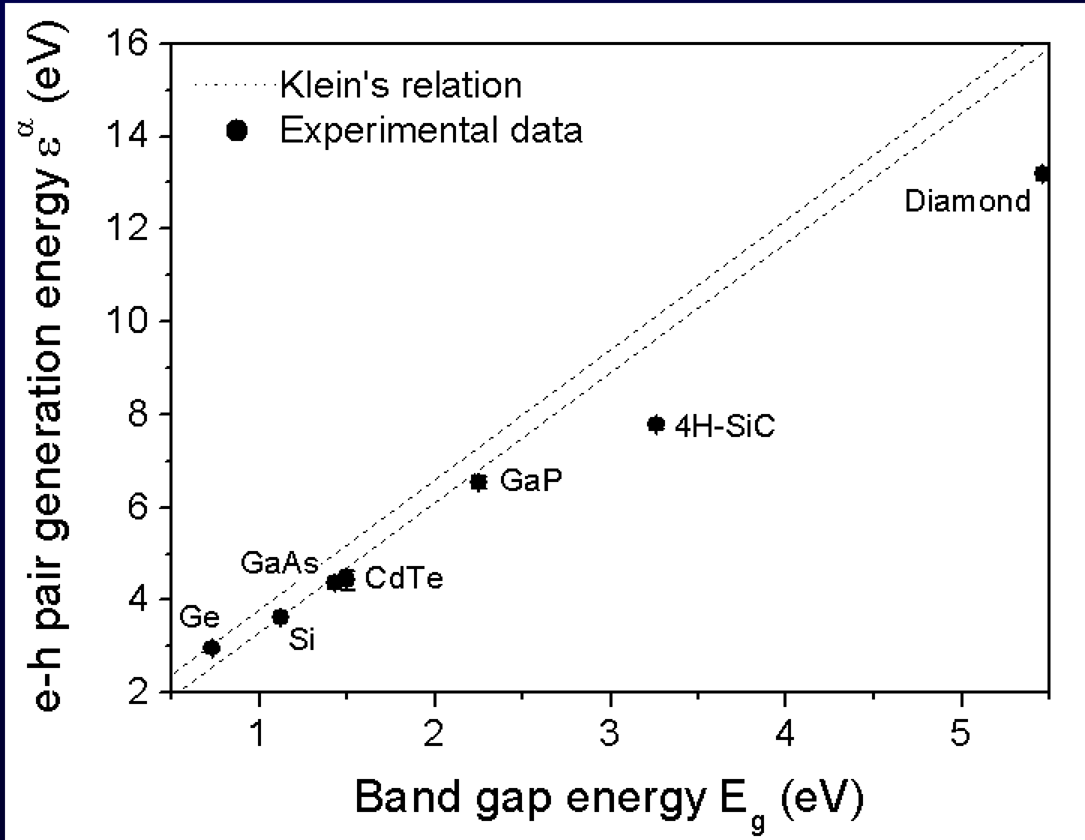
Measured

Well known

Material Characterization

Electron/Hole pair generation

$$N_{eh} = \frac{E_{ion}}{\varepsilon_{eh}}$$



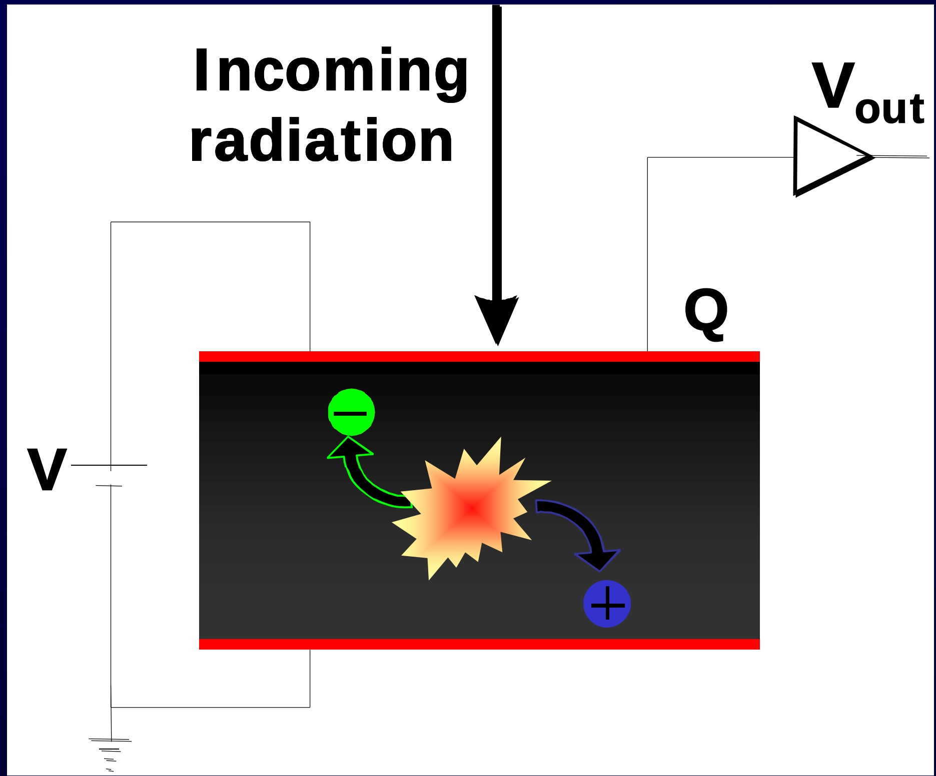
A. Lo Giudice et al. Applied Physics Letters 87, 22210 (2005)

ε_{eh}=average energy expended by the primary ion to produce one electron/hole pair

1 MeV ion in diamond generates about 77000 e/h pairs

Each high energy ion creates large numbers of charge carriers to be measured above the noise level.

IBIC principles



MeV ion energy deposition

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Electron/hole pair generation

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Charge carrier transport

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Induced Charge at the sensing electrode

↓

Output Signal Vout

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

Measured (V_{out})

Well known (Deposited Energy)

Material Characterization (Free Carrier Transport)

J.R. Haynes, W. Shockley,

“The mobility and life of injecting holes and electrons in germanium,

Phys. Rev. 81, (1951), 835-843.

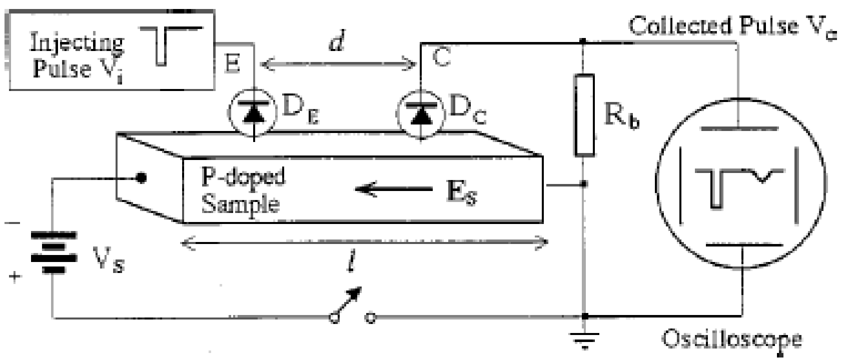


Fig. 1. Block diagram of the Haynes Shockley experiment: D_E and D_C are the emitter and collector point probes.

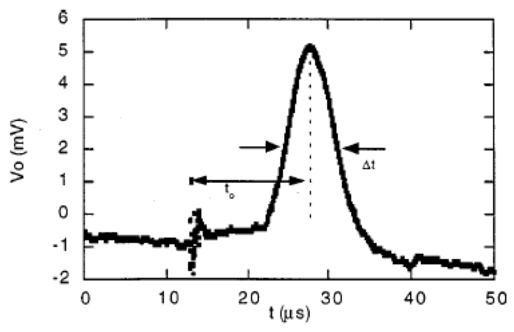


Fig. 12. Waveform observed in an N-doped Ge sample ($\rho = 1\ \Omega$ cm) with optical injection.

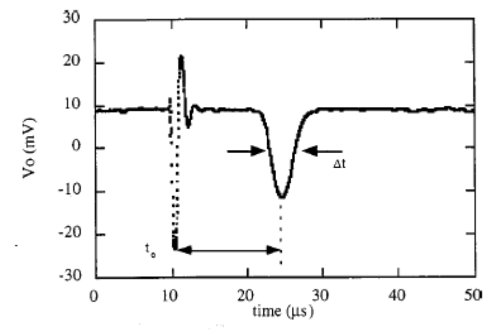
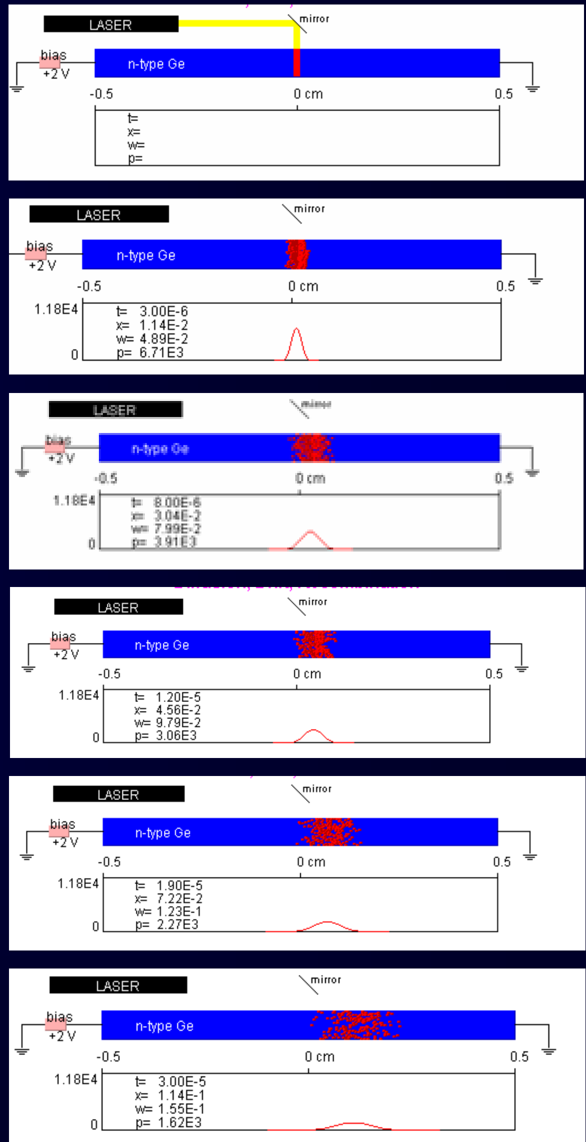


Fig. 11. Waveform observed in a P-doped Ge sample ($\rho = 15\ \Omega$ cm) with electrical injection.



J.R. Haynes, W. Shockley, Phys. Rev. 81, (1951), 835-843.

C. Canali et al., Nucl. Instr. Meth. 160 (1979) 73-77

P-doped Ge;

resistivity about 15 Ω·cm;

dielectric constant =1.4pF/cm;

Dielectric relaxation time = 21 ps.

Charge neutrality maintained

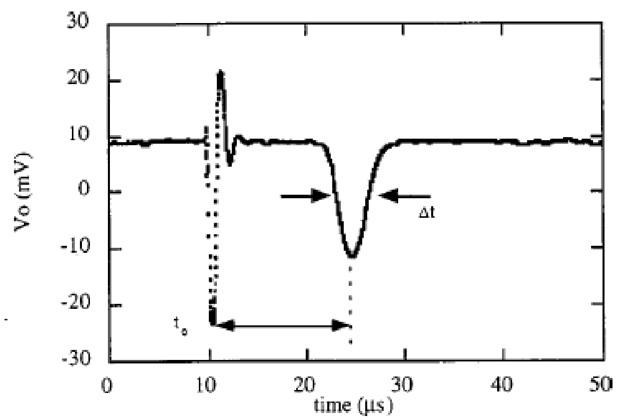


Fig. 11. Waveform observed in a P-doped Ge sample (ρ = 15 Ω cm) with electrical injection.

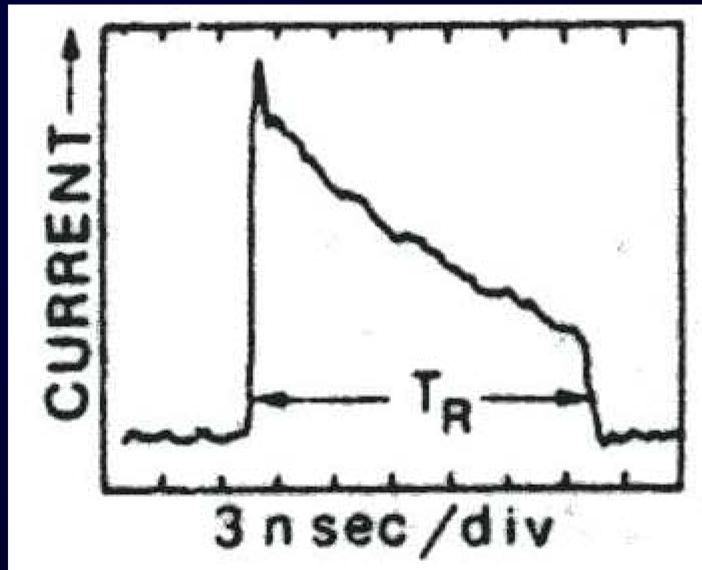
IIa diamond;

resistivity about 10^{15} Ω·cm;

dielectric constant =0.5 pF/cm;

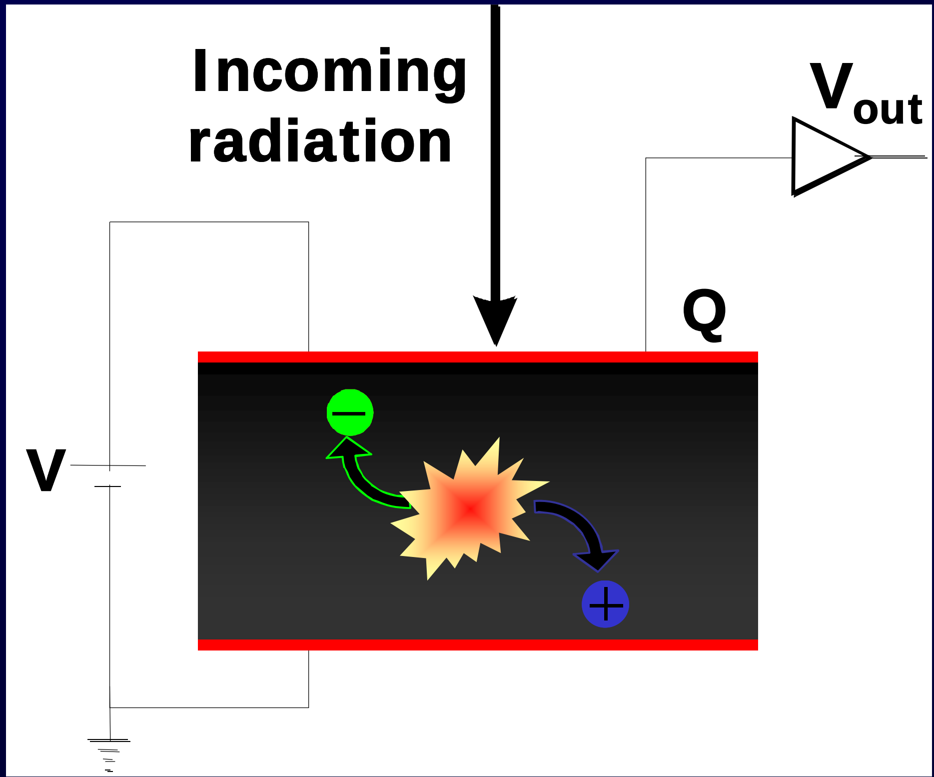
Dielectric relaxation time = 500 s.

Charge neutrality not maintained



400 μm thick natural diamond, biased at 40 V @ RT

IBIC principles



MeV ion energy deposition

↓

Electron/hole pair generation

↓

Charge carrier transport

↓

Induced Charge at the sensing electrode

↓

Output Signal Vout

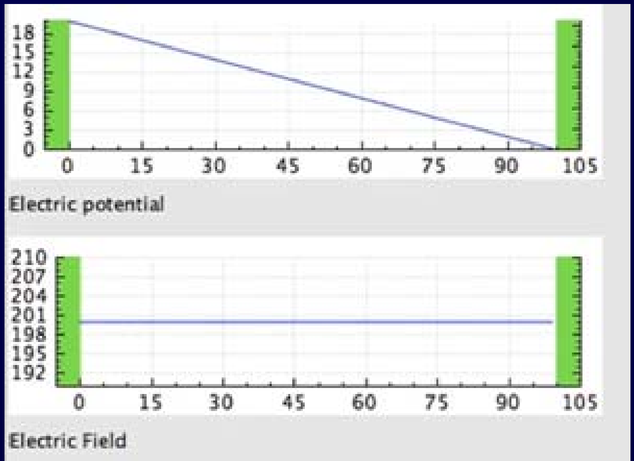
$$V_{out} = F(\text{Deposited Energy}, \text{Free Carrier Transport})$$

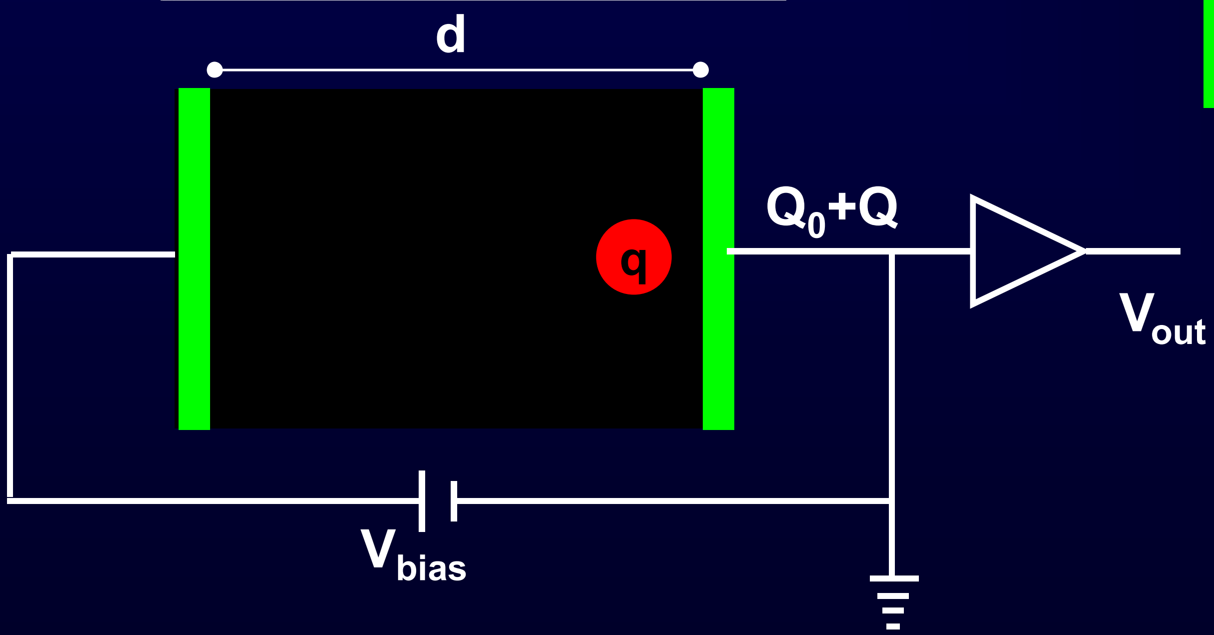
Measured (V_{out})

Well known (Deposited Energy)

Material Characterization (Free Carrier Transport)

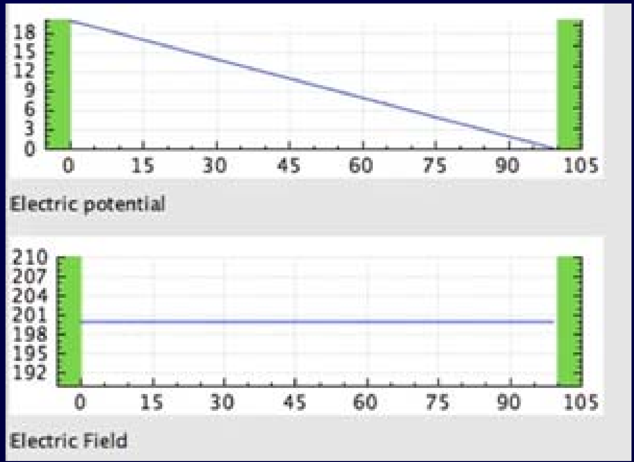
Physical Observable: Induced current/charge





$$Q = q \cdot \frac{x}{d}$$

Physical Observable: Induced current/charge



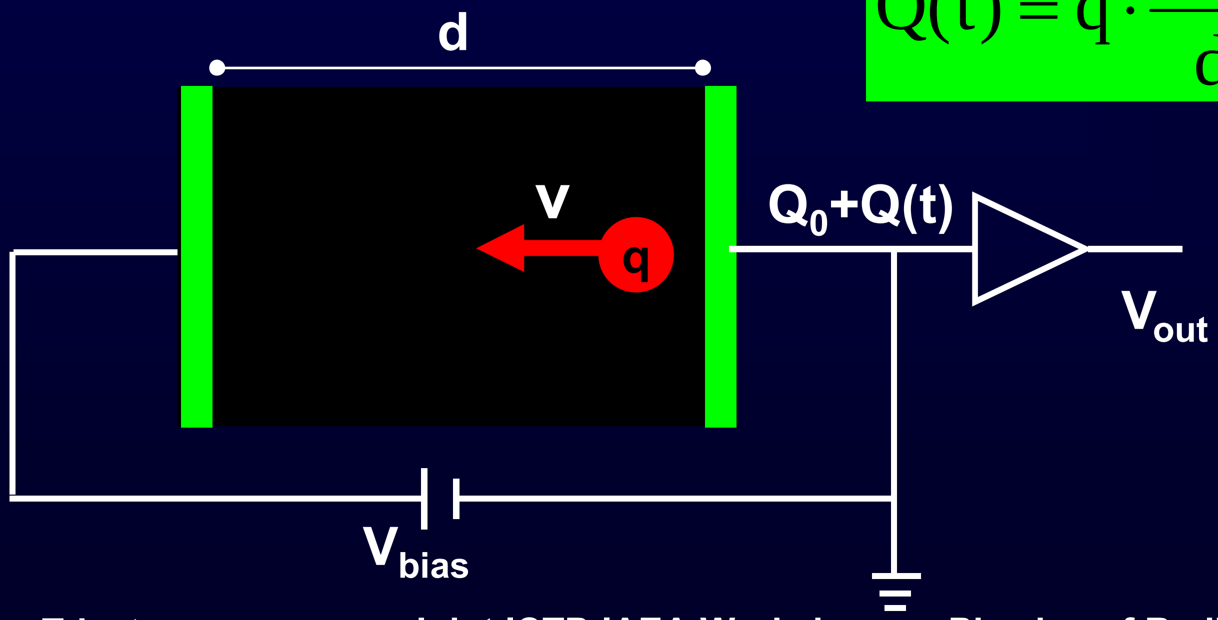
W. Shockley, J. Appl. Phys. 9 (1938) 635.

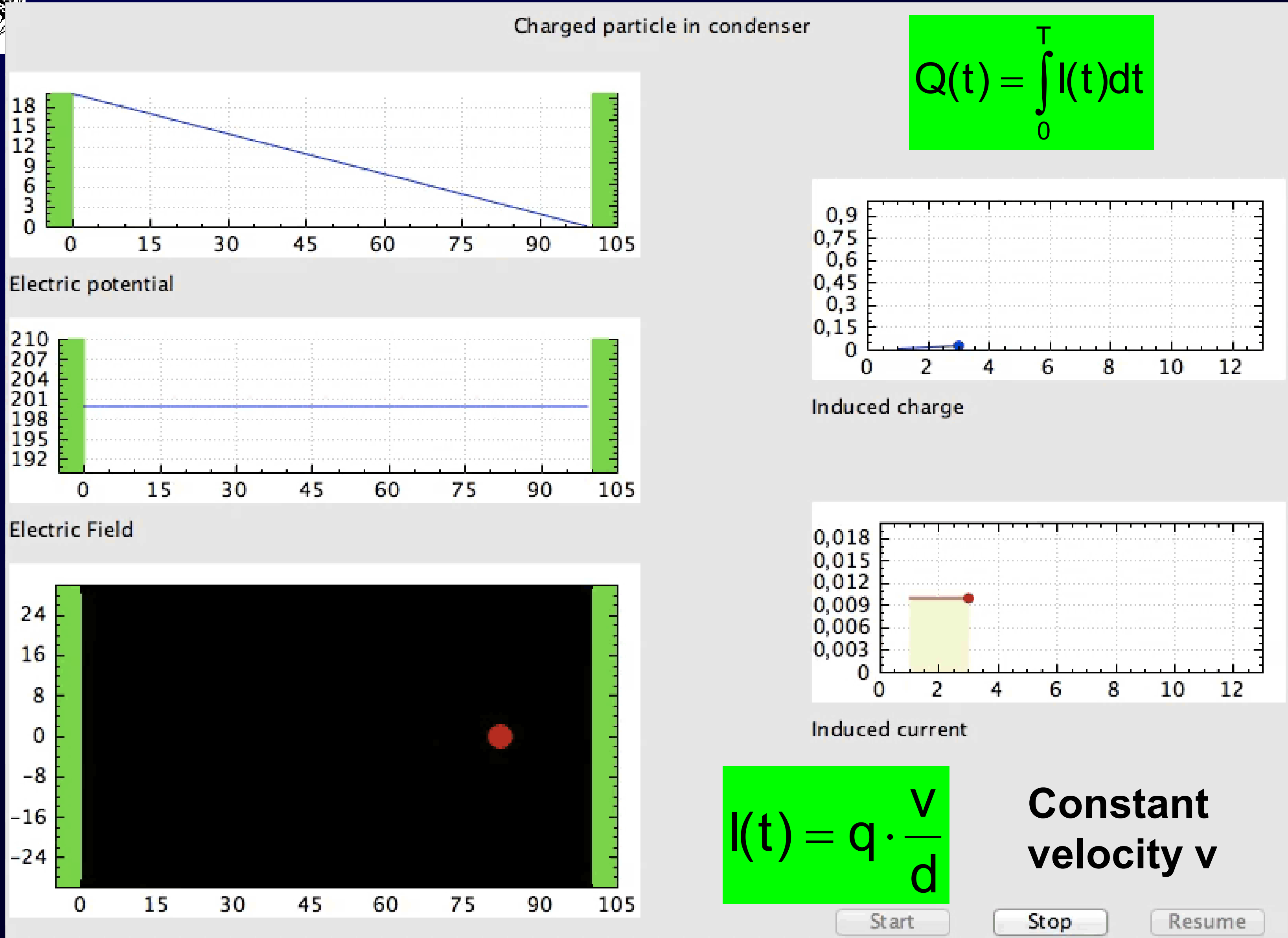
S. Ramo, Proc. I.R.E. 27 (1939) 584.

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

$$Q(t) = q \cdot \frac{x(t)}{d}$$

$$Q(t) = \int_0^T I(t)\,dt$$

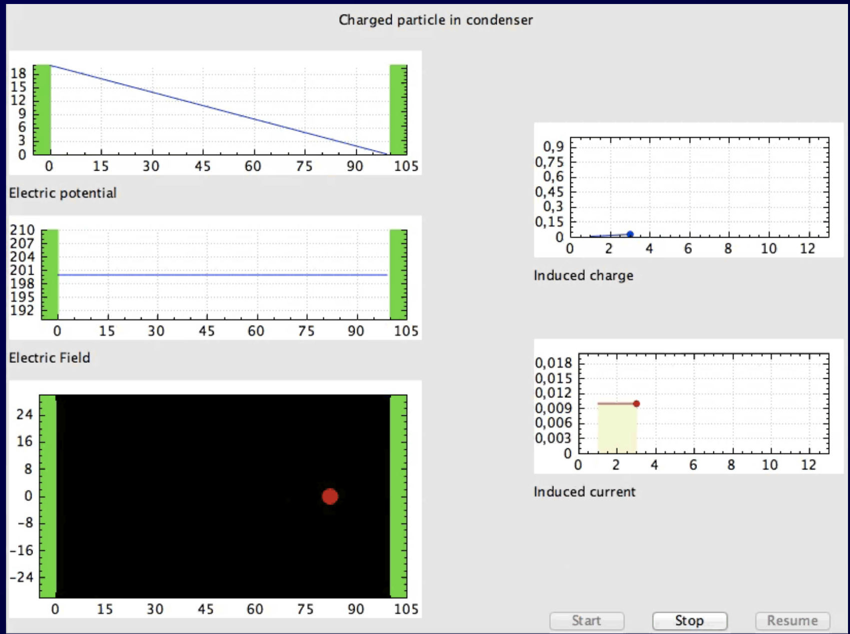




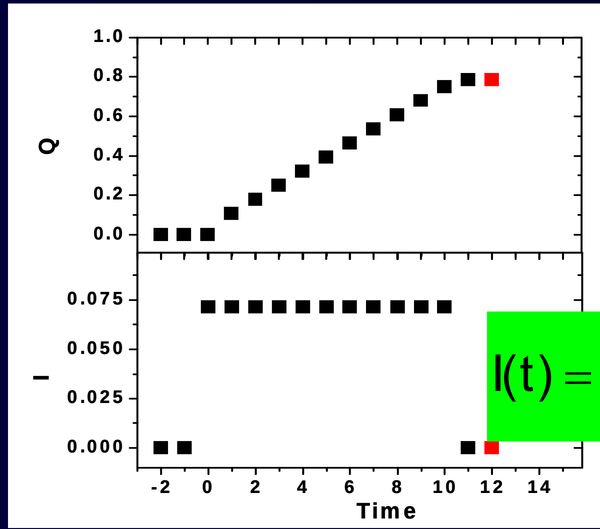
$$Q(t) = \int_0^T I(t)dt$$

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

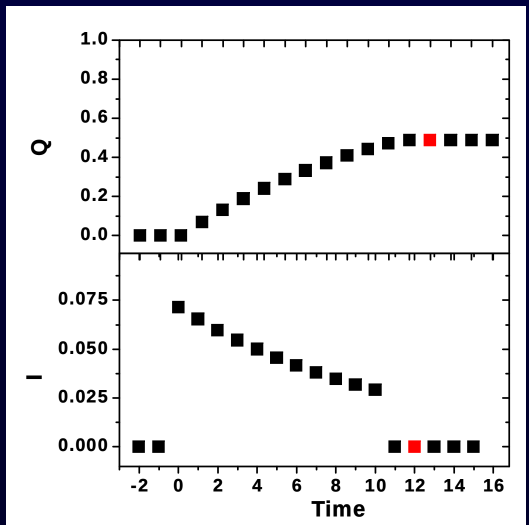
Constant velocity v



$$\tau \rightarrow \infty$$

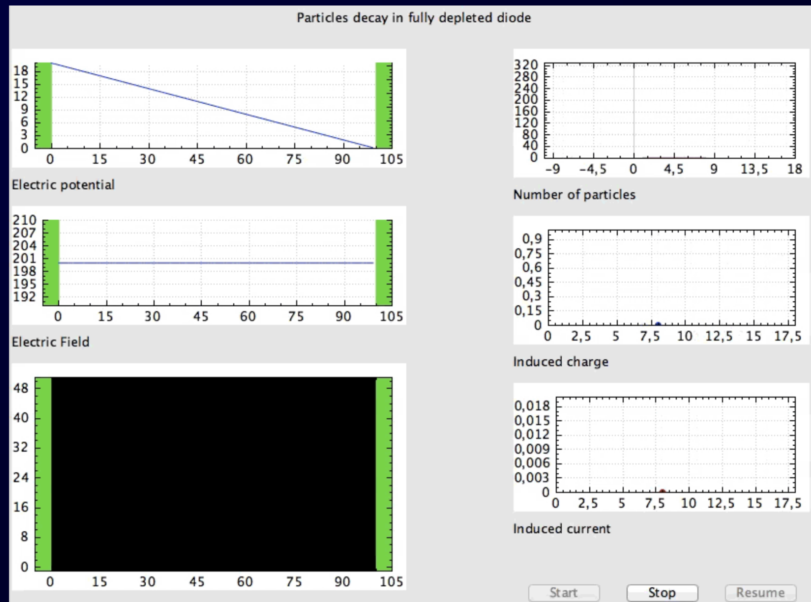


$$I(t) = q \cdot \frac{v}{d}$$



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

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

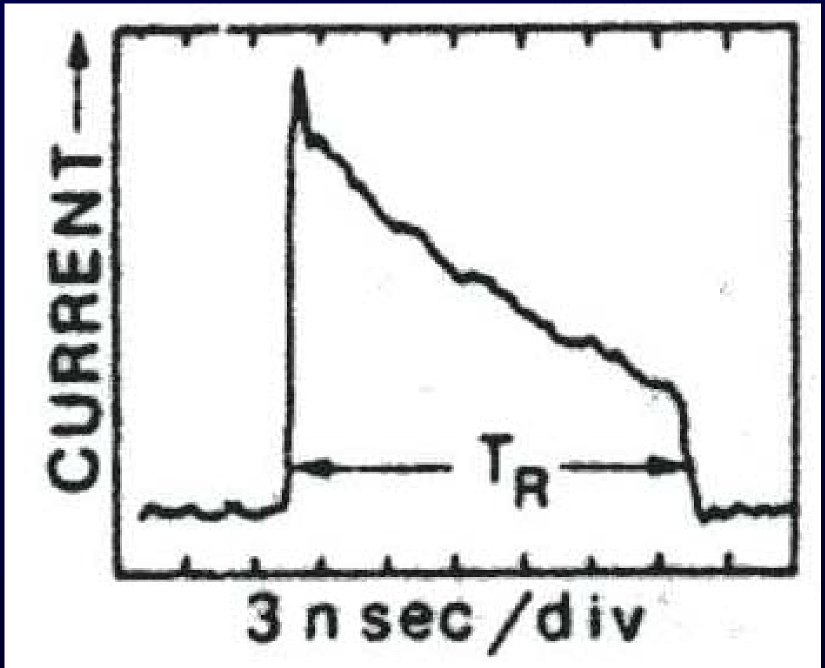


IIa diamond; resistivity about 10^{15} Ω·cm; dielectric constant =0.5 pF/cm; Dielectric relaxation time = 500 s.

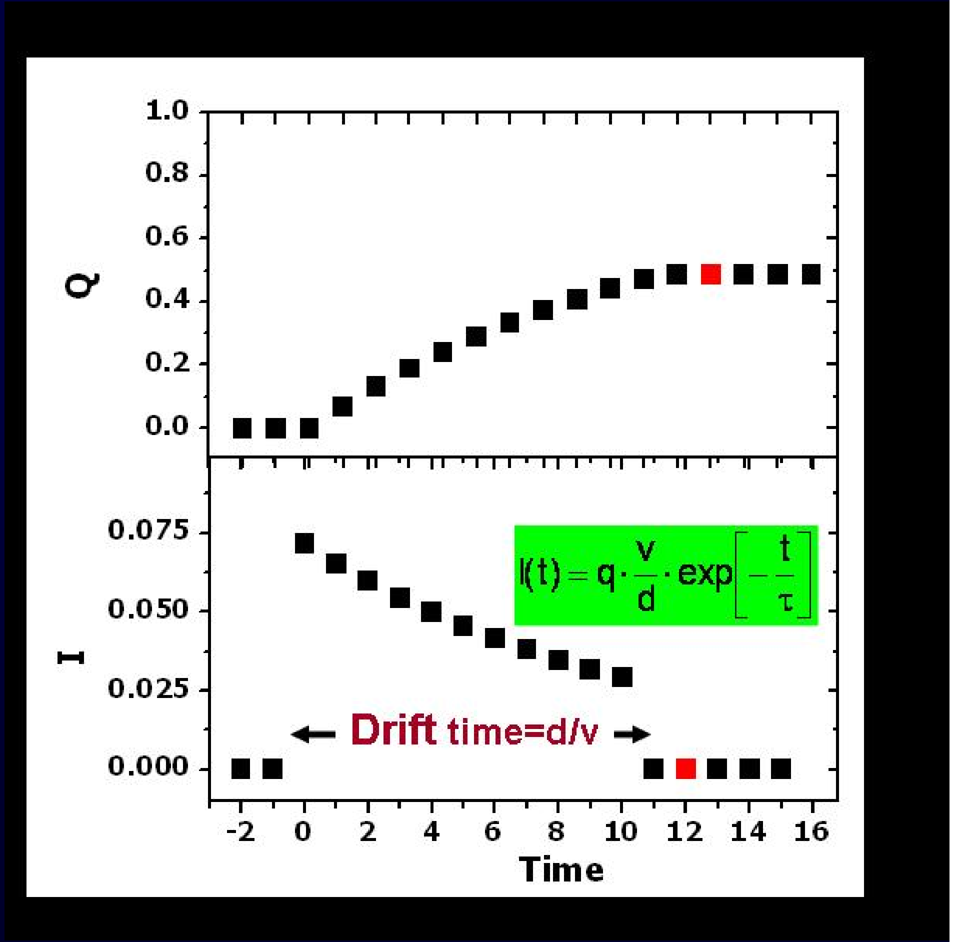
Charge neutrality not maintained

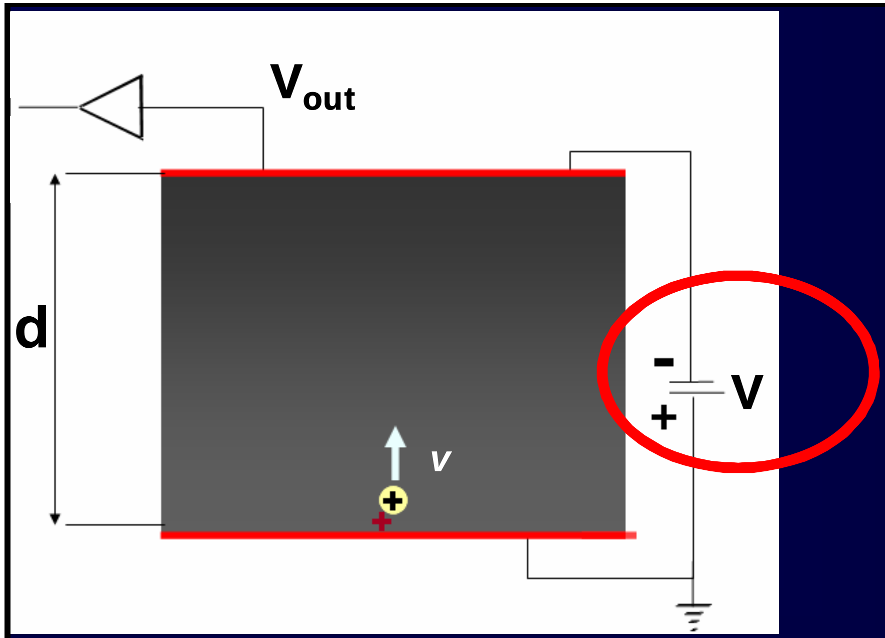
400 μm thick natural diamond,

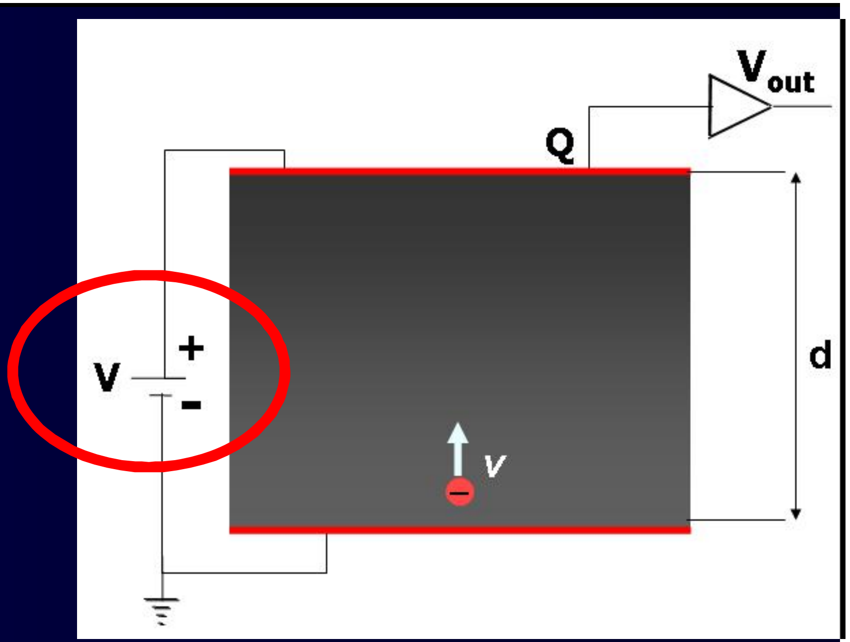
biased at 40 V @ RT



C. Canali et al., Nucl. Instr. Meth. 160 (1979) 73-77







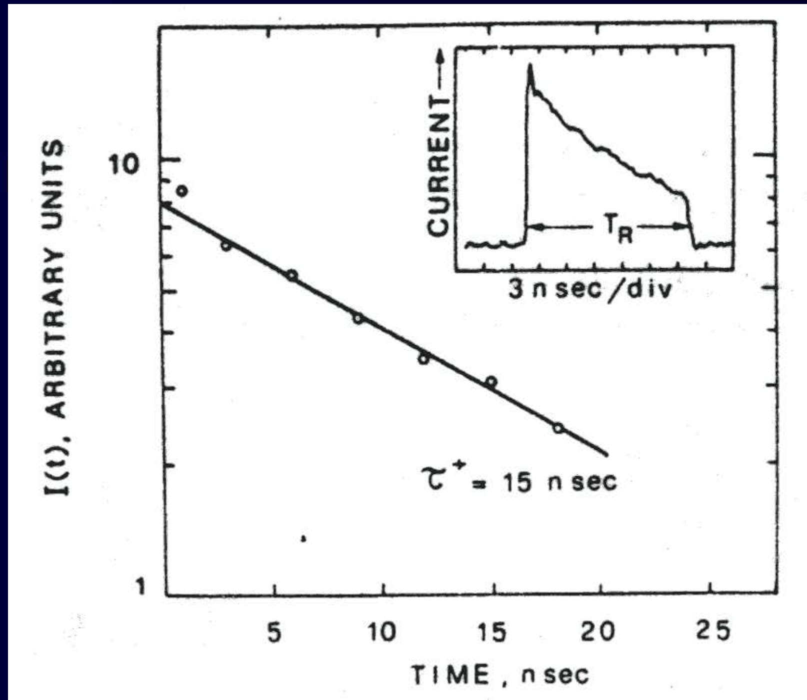
Generation at the anode
Induced signal from the Hole motion

Generation at the cathode
Induced signal from the electron motion

$$CCE \approx \frac{\mu\tau_e E}{d}\left(1-\exp\left(\frac{-d}{\mu\tau_e E}\right)\right)$$

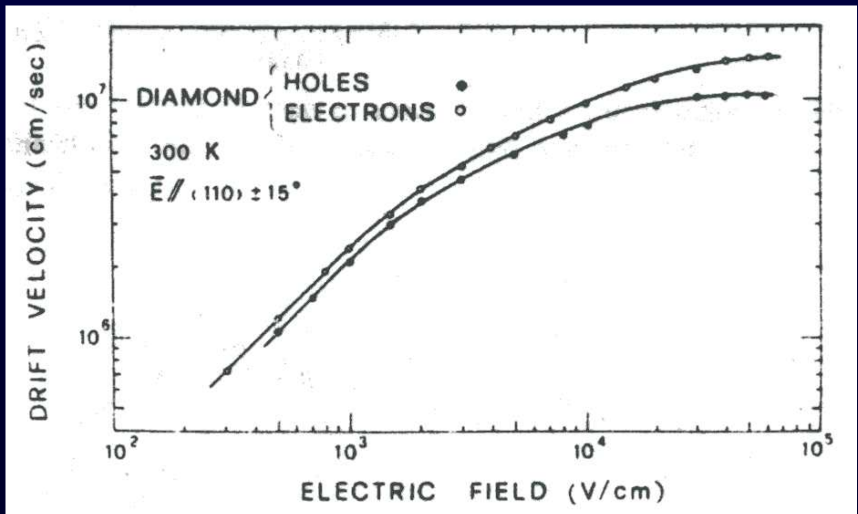
K. Hecht, Z. Physik 77, (1932) 23

Characterization of the transport properties in diamond



400 μm thick natural diamond,

biased at 40 V @ RT



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

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

Shockley-Ramo Theorem

$$v = \mu \cdot E$$

The current is induced by the motion of charges in presence of an electric field

Induced current

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

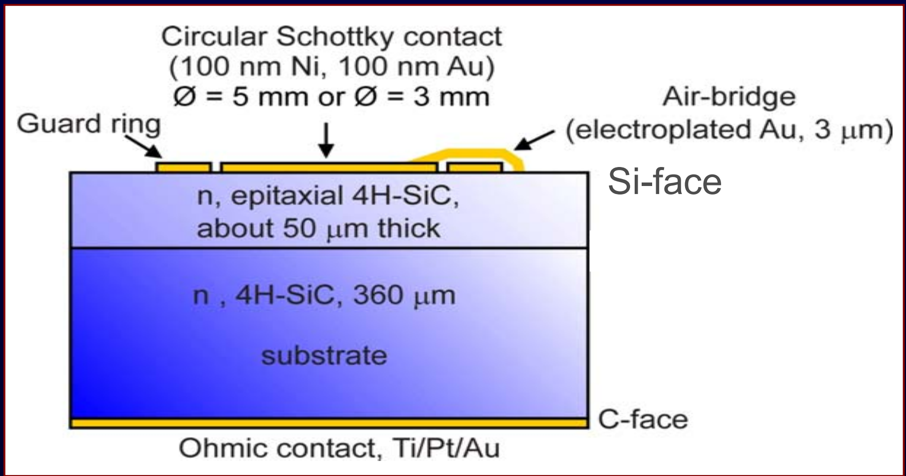
4H-SiC Schottky diode

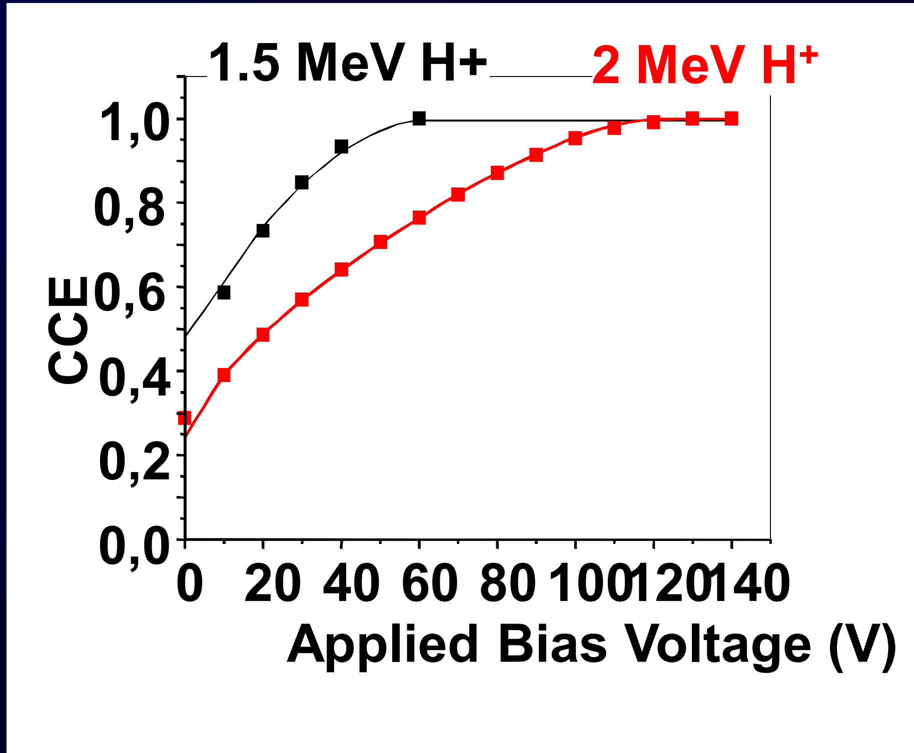
Starting Material: 360 μm n-type 4H-SiC by CREE (USA)
Epitaxial layer from Institute of Crystal Growth (IKZ), Berlin, Germany
Devices from Alenia Marconi System

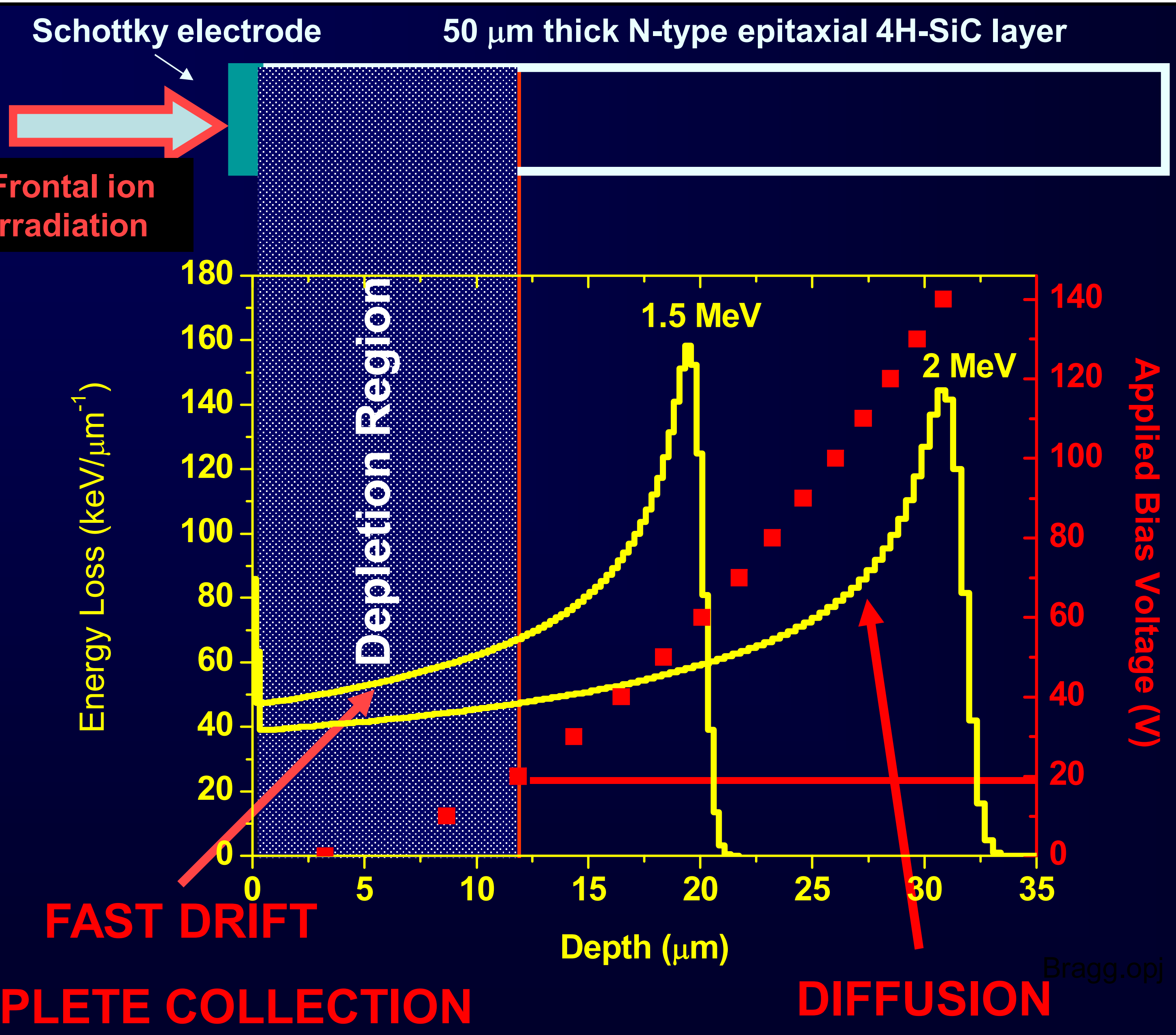
CCE=Charge Collection Efficiency
=
(Charge collected)/(Charge generated)

1.5 or 2.0

MeV H+





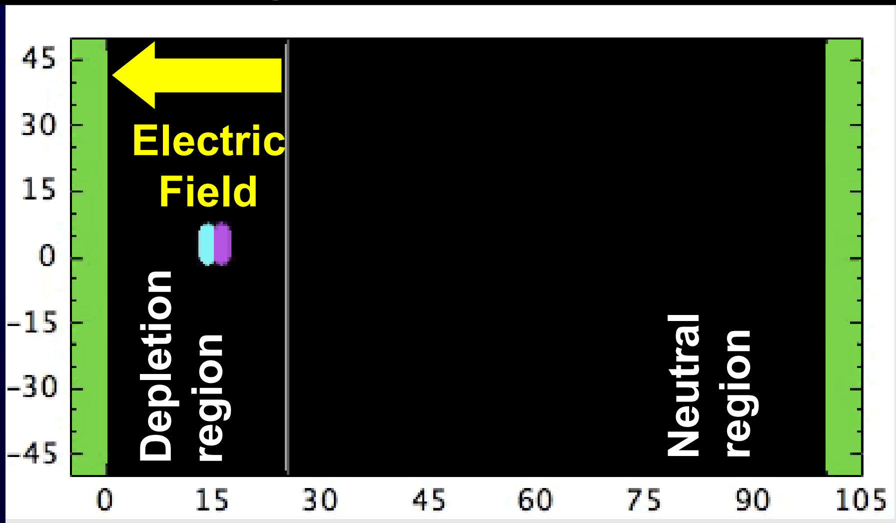

Schottky electrode
50 μm thick N-type epitaxial 4H-SiC layer
Frontal ion Irradiation
Depletion Region
1.5 MeV
2 MeV
Energy Loss (keV/μm⁻¹)
Applied Bias Voltage (V)
Depth (μm)
180
160
140
120
100
80
60
40
20
0
0
5
10
15
20
25
30
35
140
120
100
80
60
40
20
0
Bragg.opj
FAST DRIFT
COMPLETE COLLECTION
DIFFUSION

Generation of electrons and holes in the

Depletion Region

Electrons

Holes

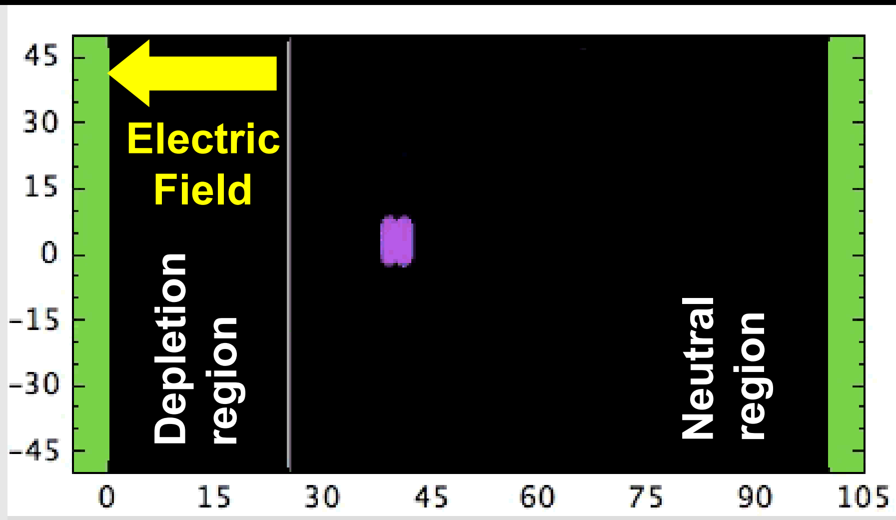


Complete charge collection

Neutral Region

Electrons

Holes

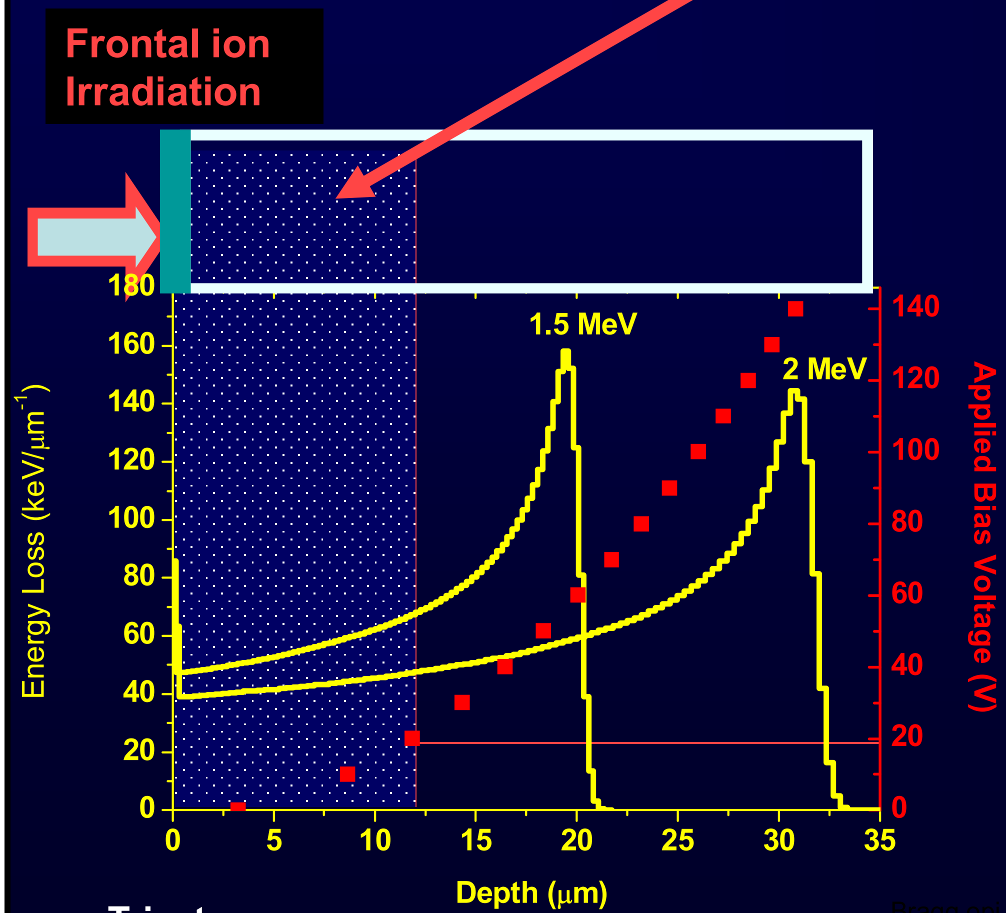


Only holes injected in the depletion region by diffusion induce a charge

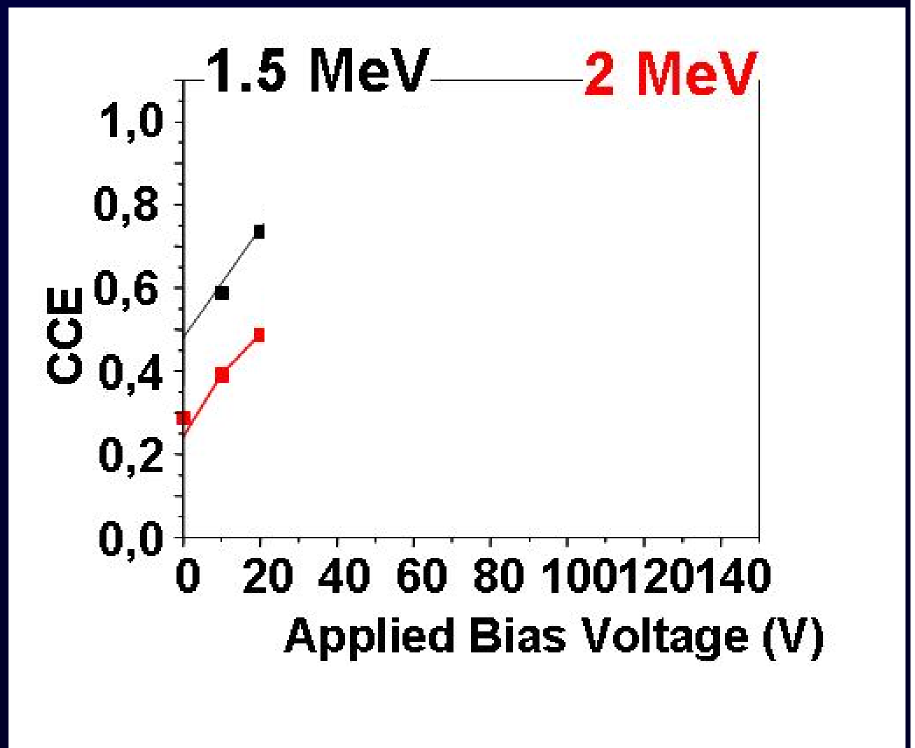
Contribution from the neutral region

Contribution from the depletion layer

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



4H-SiC Schottky diode

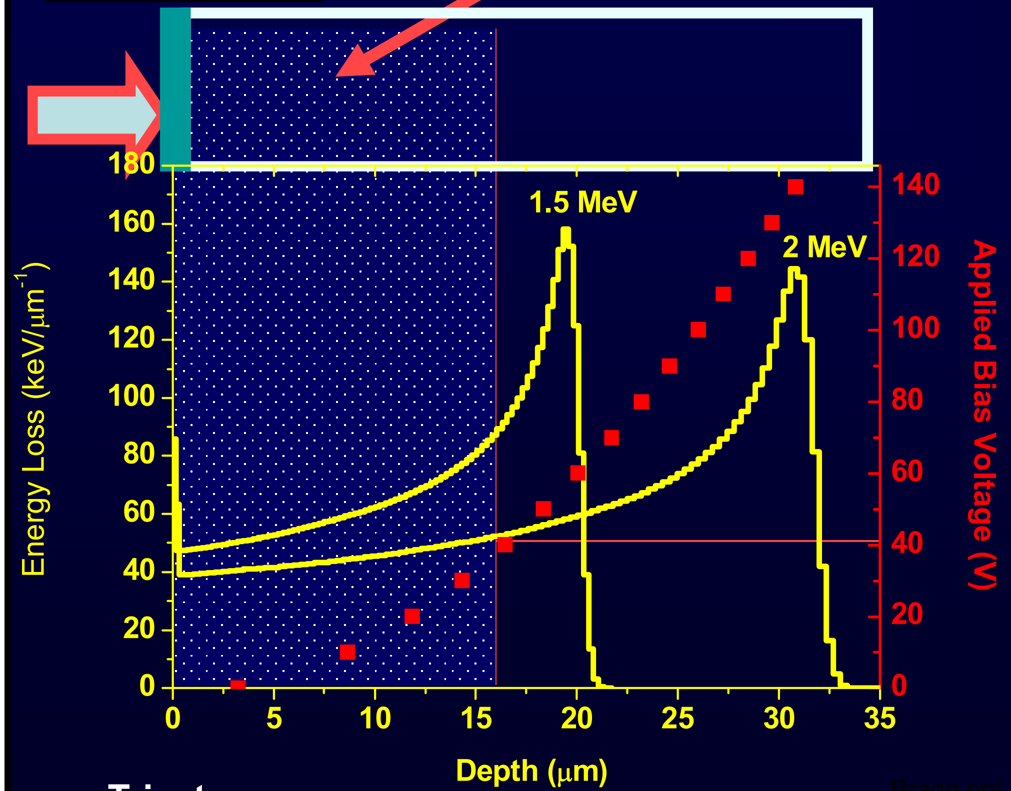


Contribution from the neutral region

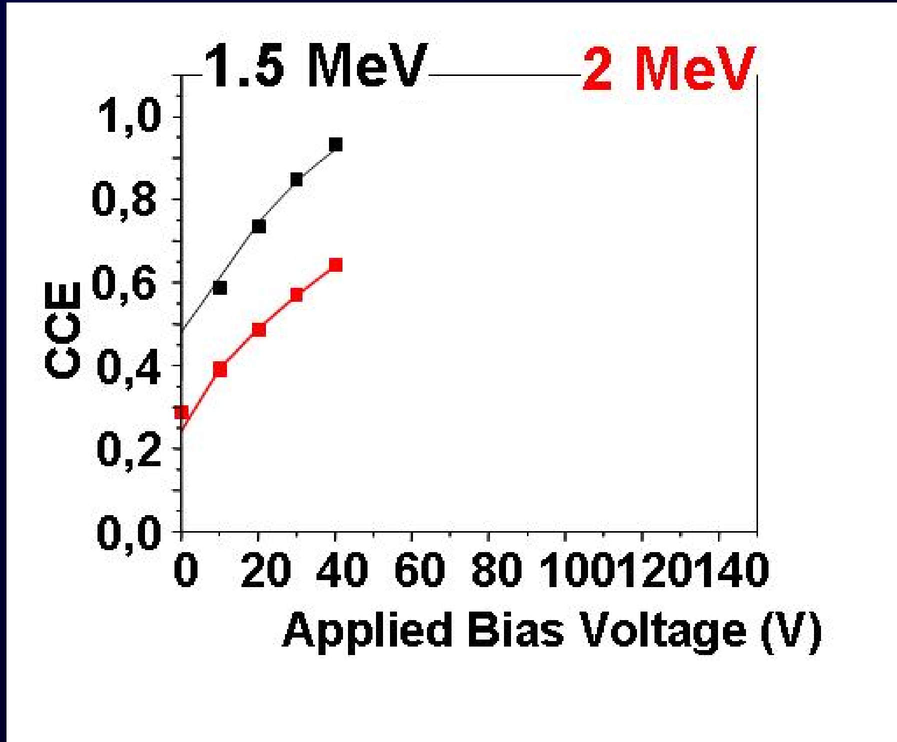
Contribution from the depletion layer

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

Frontal ion Irradiation



4H-SiC Schottky diode



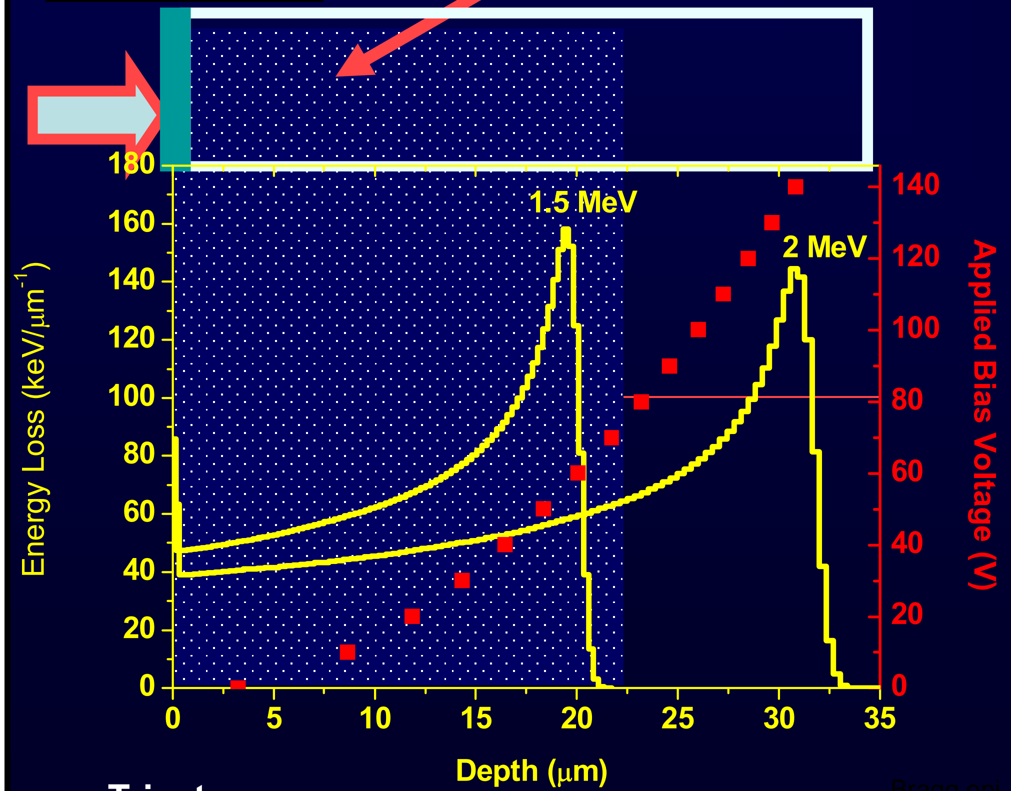
Trieste
14.08.2012

Contribution from the neutral region

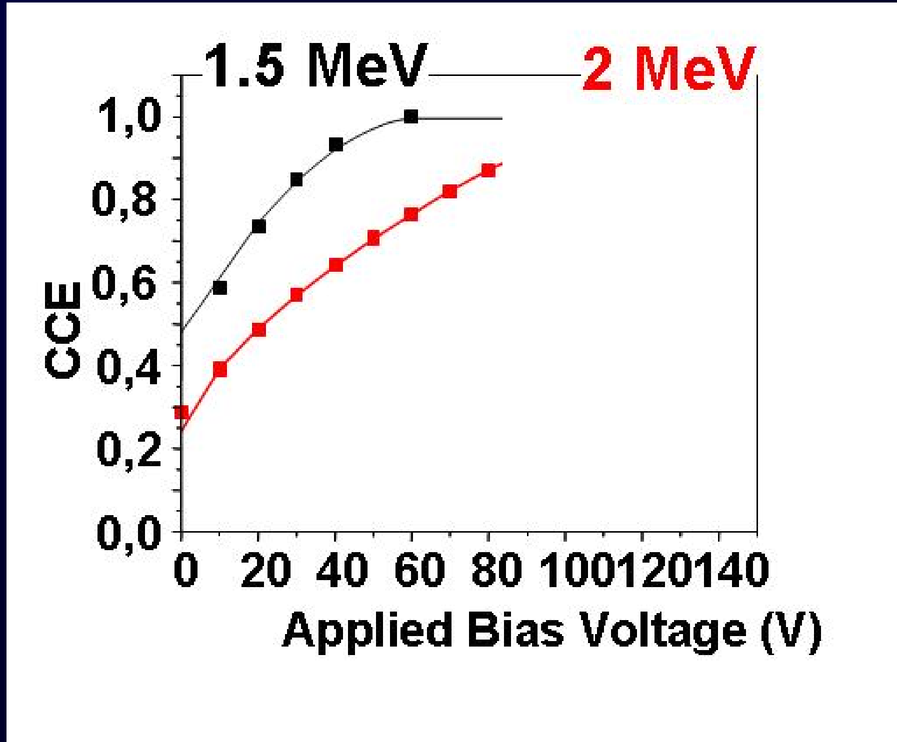
Contribution from the depletion layer

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

Frontal ion Irradiation



4H-SiC Schottky diode



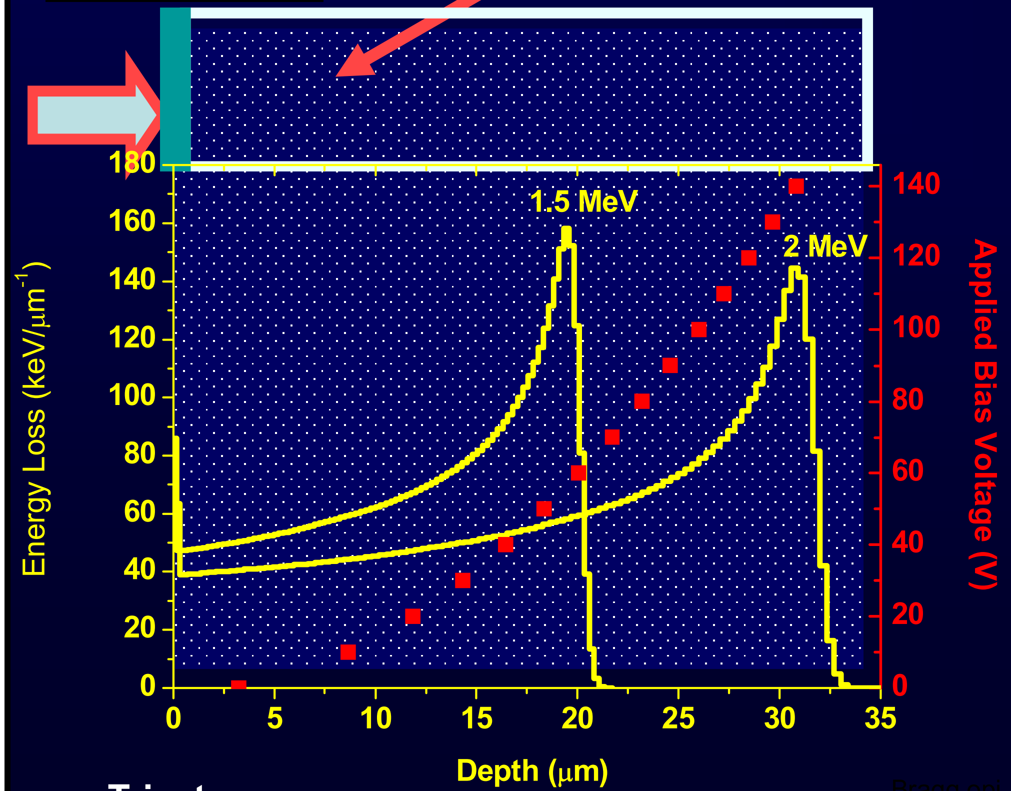
Trieste
14.08.2012

Contribution from the neutral region

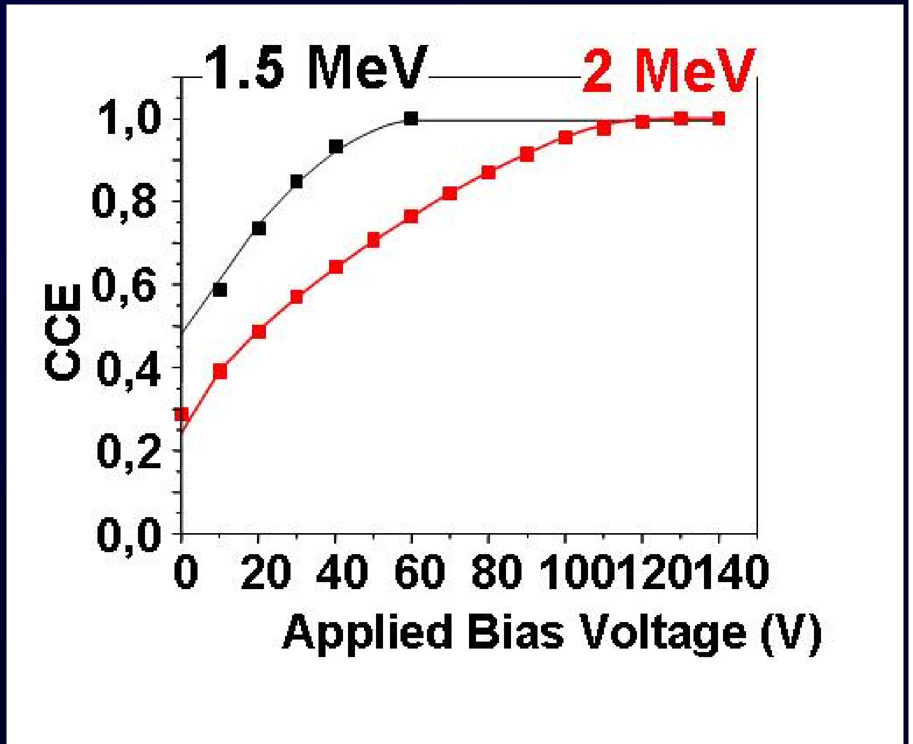
Contribution from the depletion layer

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

Frontal ion Irradiation



4H-SiC Schottky diode



Trieste
14.08.2012

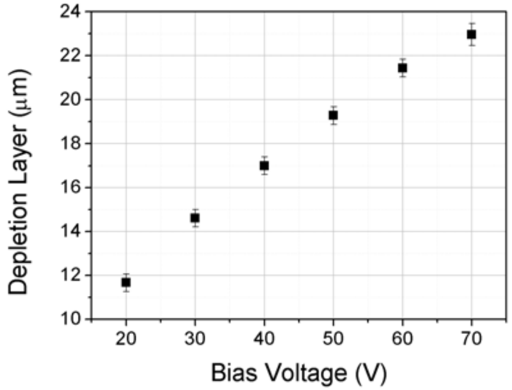
Contribution from the neutral region

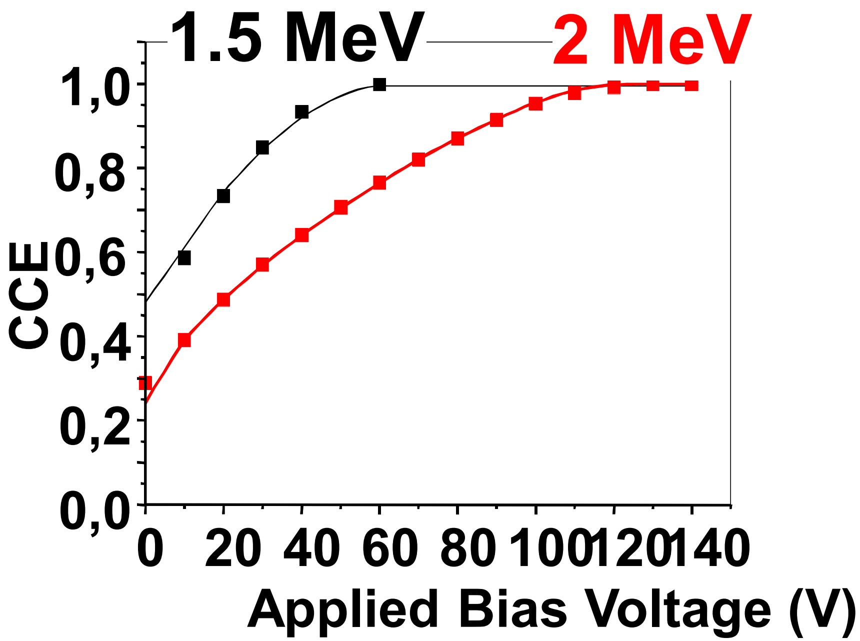
Contribution from the depletion layer

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

Active region width

minority carrier diffusion length





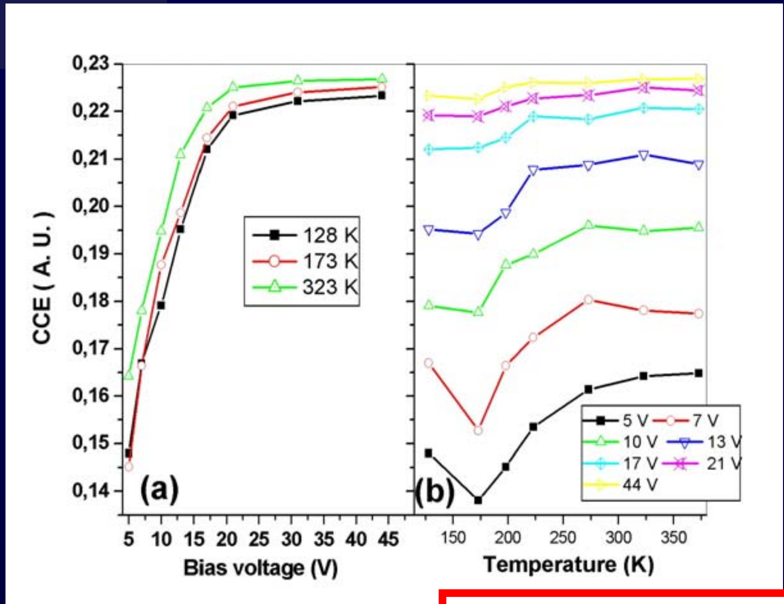
$L_p = (9.0 \pm 0.3)\ \mu m$

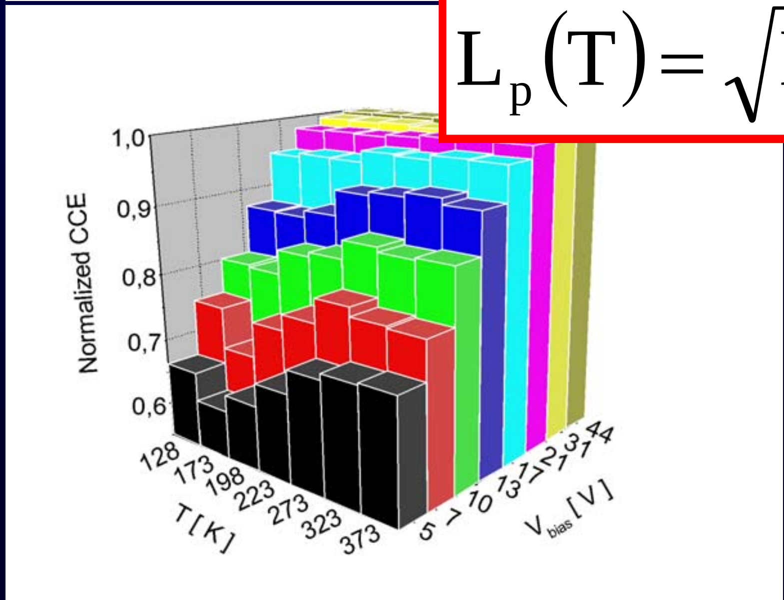
$D_p = 3\ cm^2/s$

$\tau_p = 270\ ns$

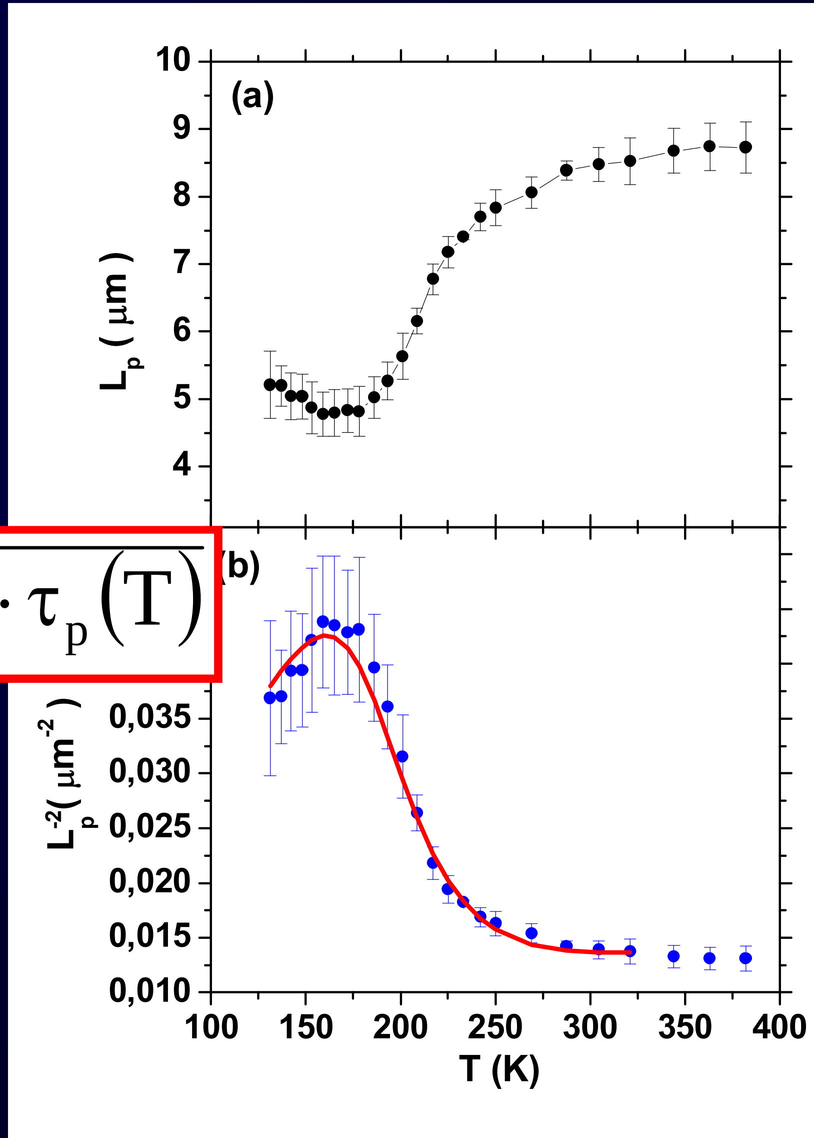
4H-SiC Schottky diode

Temperature dependent IBIC (TIBIC)

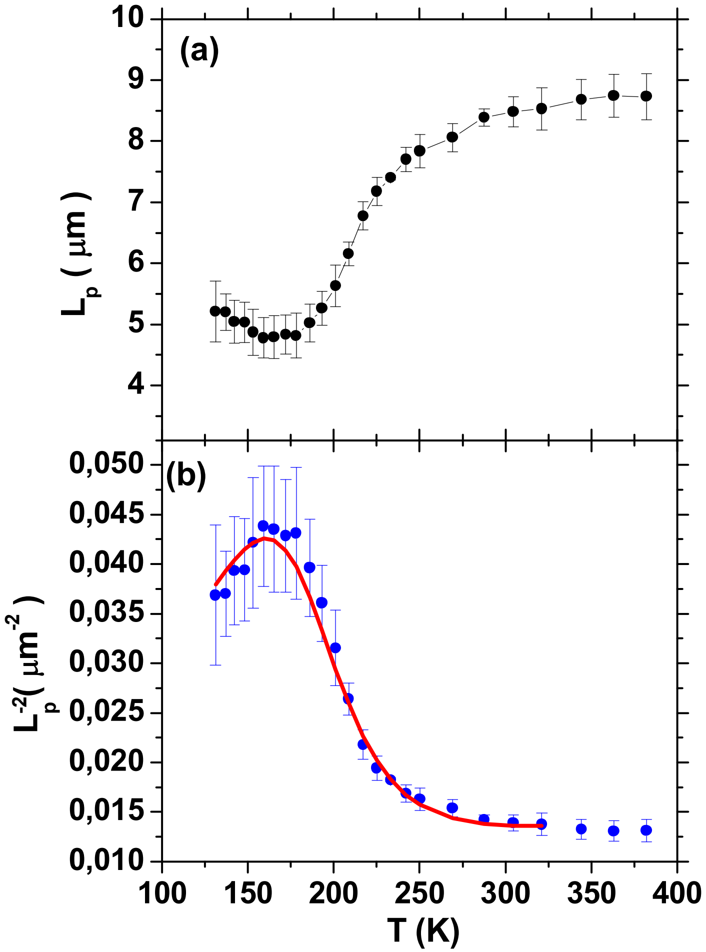




$$L_p(T) = \sqrt{D_p(T) \cdot \tau_p(T)}$$



Temperature dependent IBIC (TIBIC)



Two trapping levels

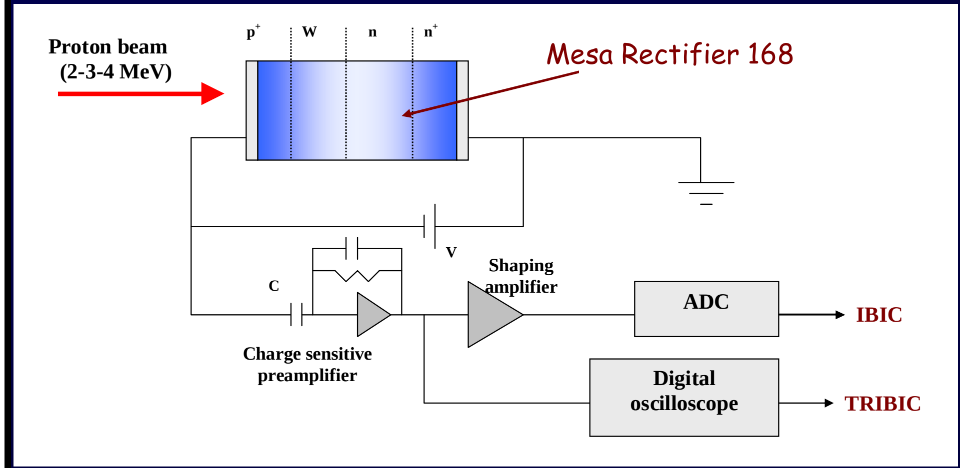
SRH recombination model

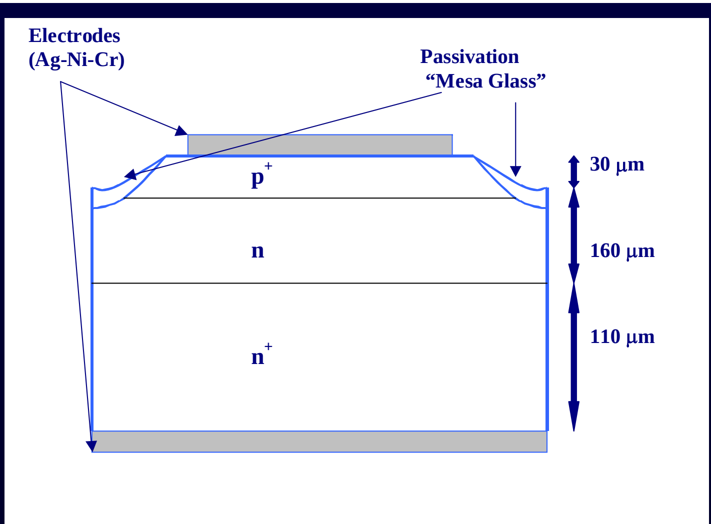
$$\frac{1}{L_p^2} = \frac{1}{D_p \cdot \tau} = \frac{1}{D_p} \cdot \left(\frac{1}{\tau(T)} + \frac{1}{\tau_B} \right) = A \cdot \frac{1}{T^{-0.5}} \cdot \left[\frac{1}{T^{-0.5} + \frac{B}{N_D} \cdot T \cdot \exp\left(-\frac{E_t}{k_B T} \right)} + \frac{1}{\tau_B} \right]$$

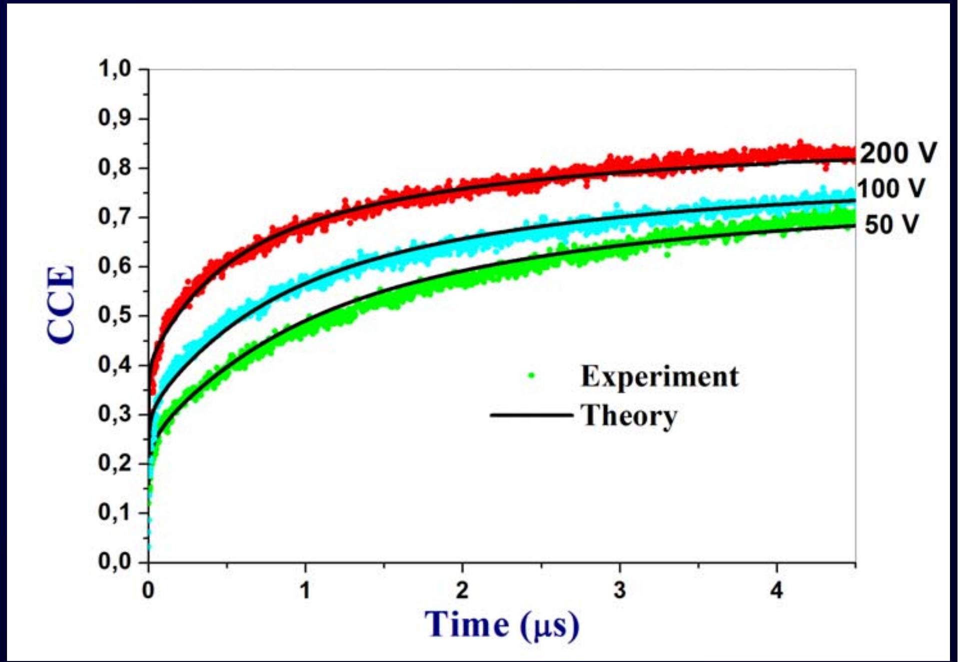
The fitting procedure provides a trapping level of about 0.163 eV which is close to the value found in similar 4H SiC Schottky diodes by DLTS technique (S1 level).

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

Time resolved IBIC (TRIBIC)
Silicon Power diode Mesa Rectifier





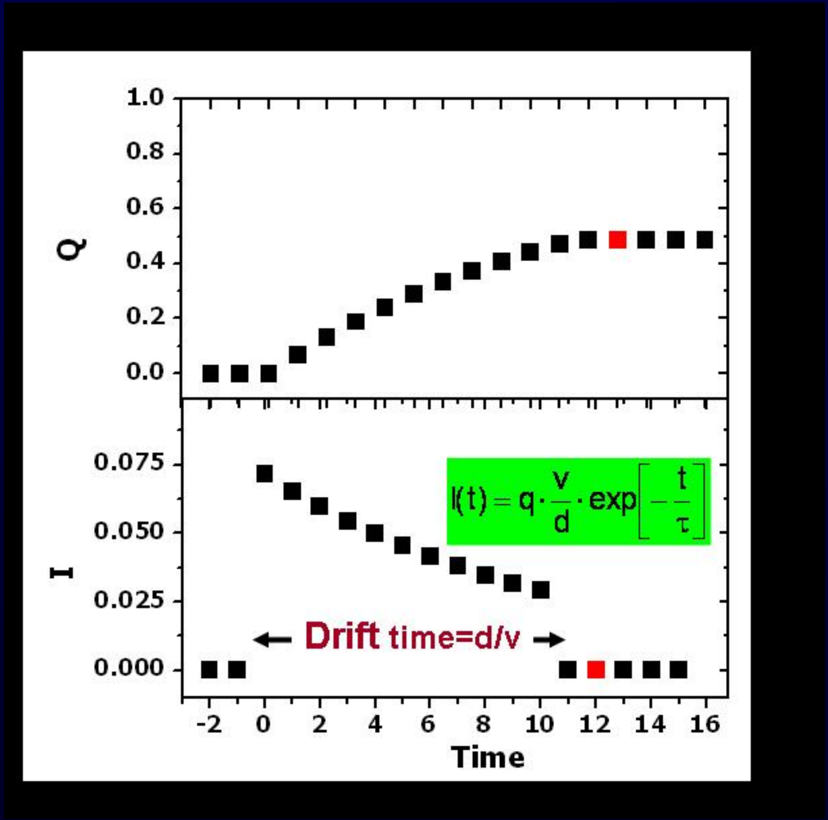


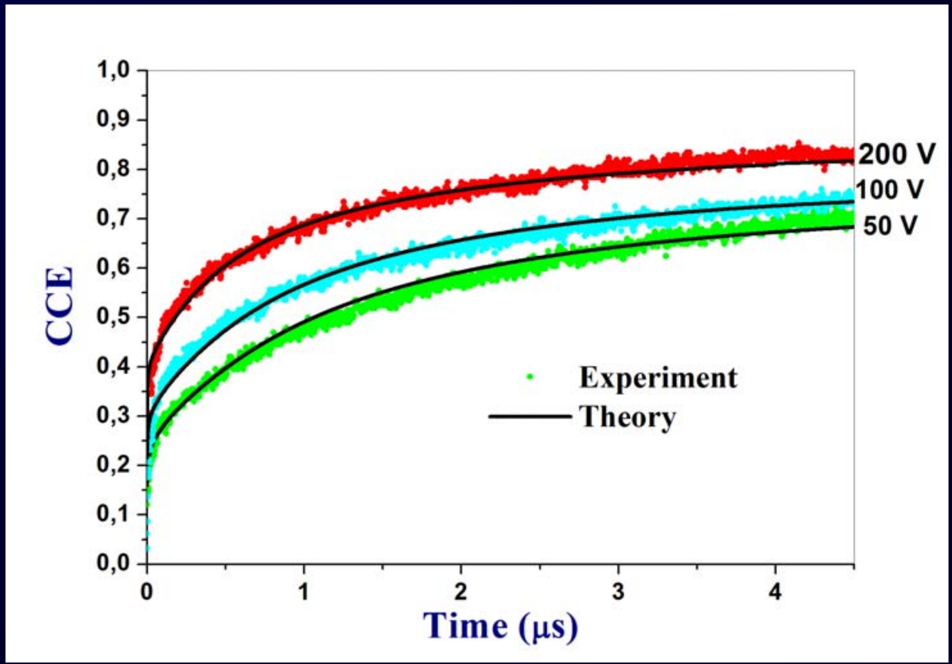
Ballistic deficit

Time resolved IBIC (TRIBIC)
Silicon Power diode Mesa Rectifier

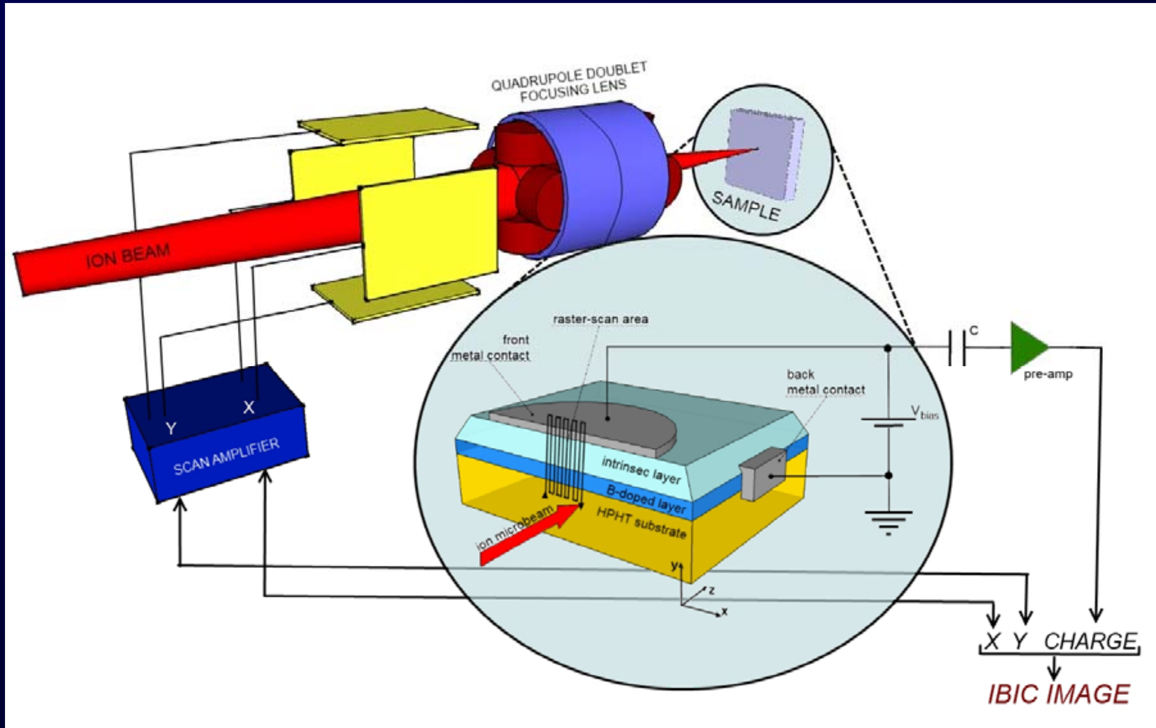
lifetime

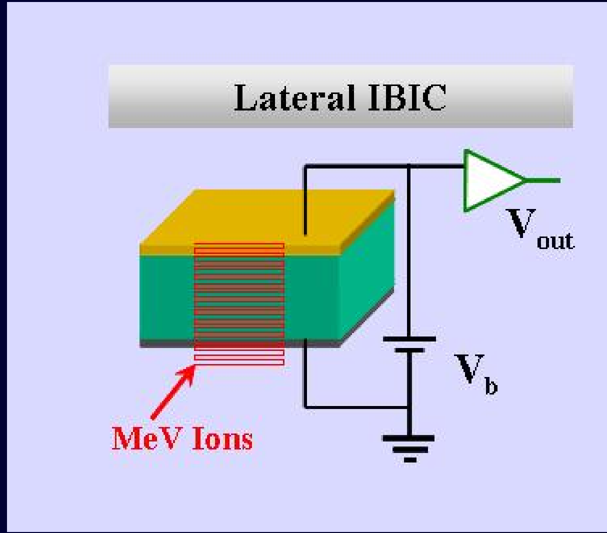
τ_0 = (5 ± 1) μs

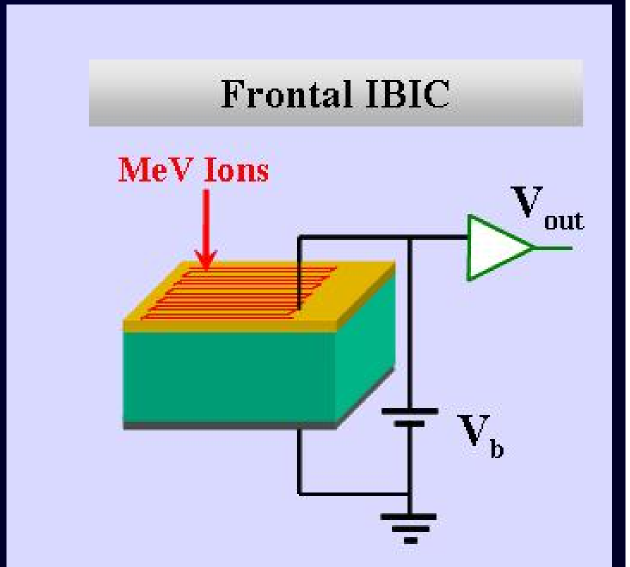




From Spectroscopy to micro-spectroscopy



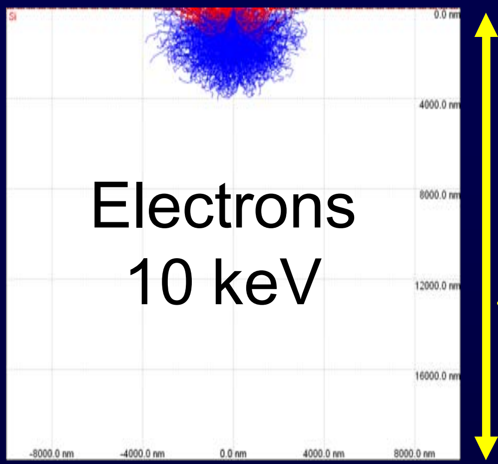


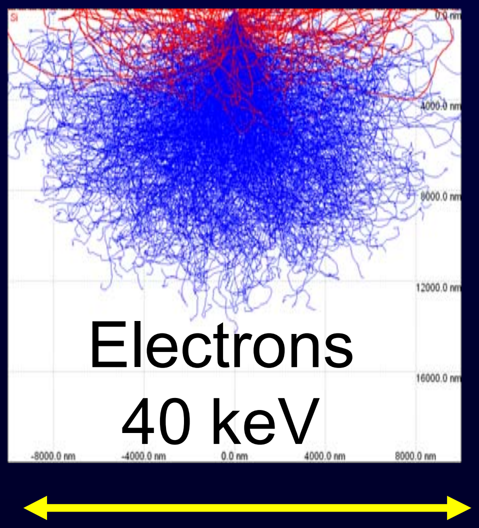


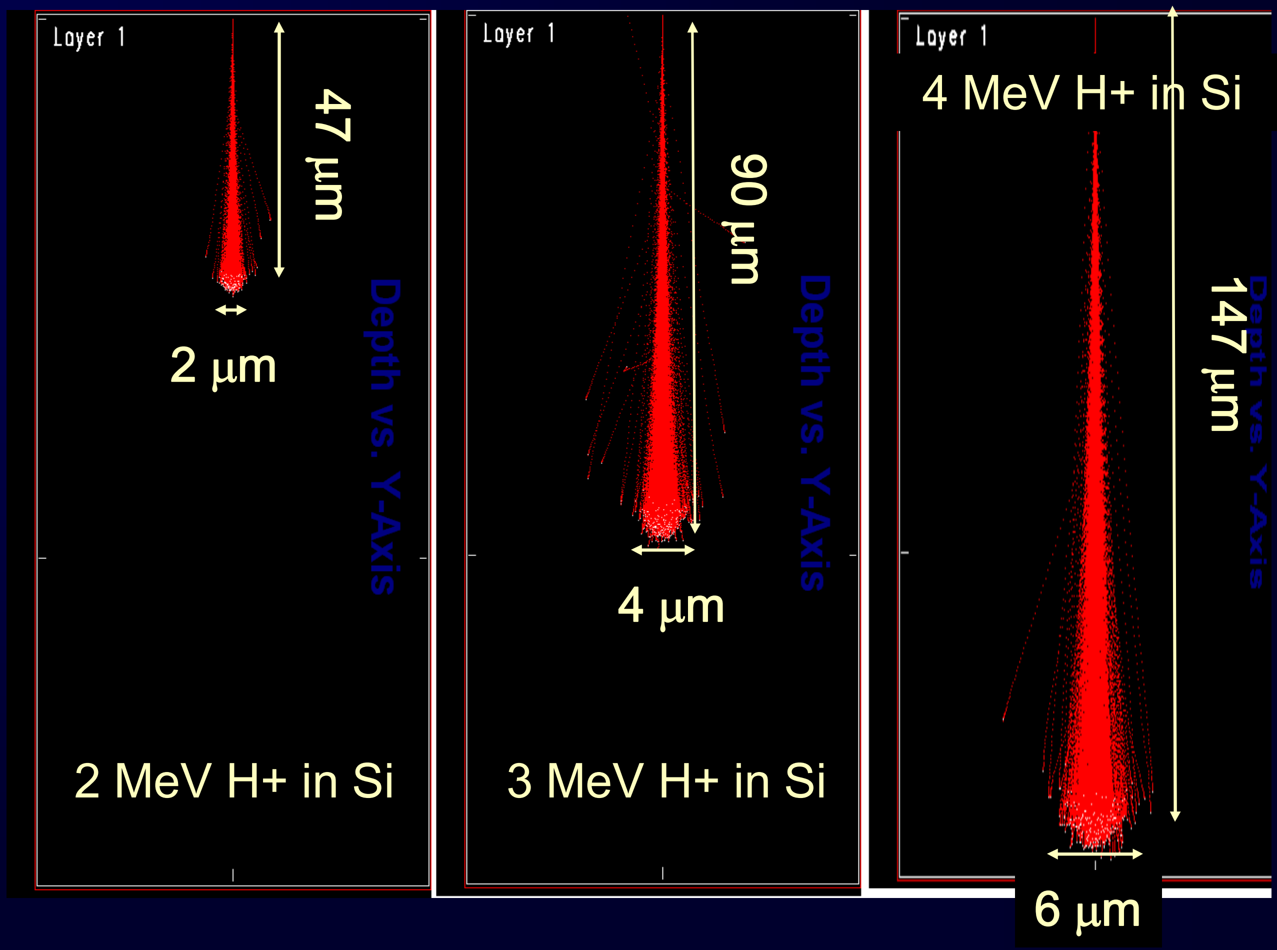
Use of focused ion beams

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.





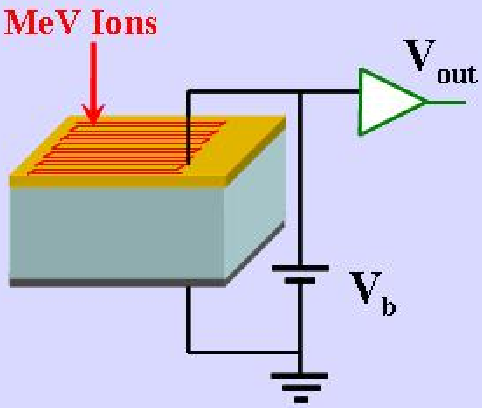


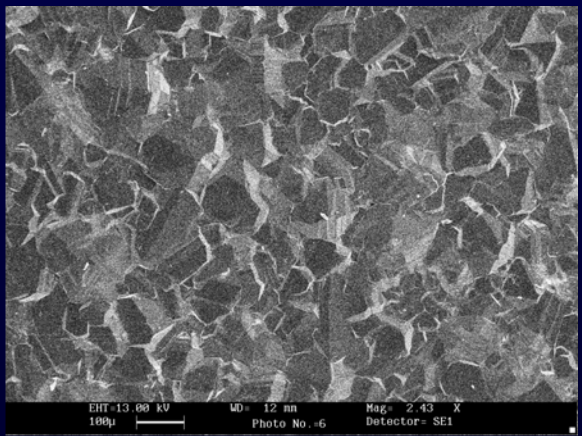
Nuclear Instruments and Methods in Physics Research B 100 (1995) 133–140

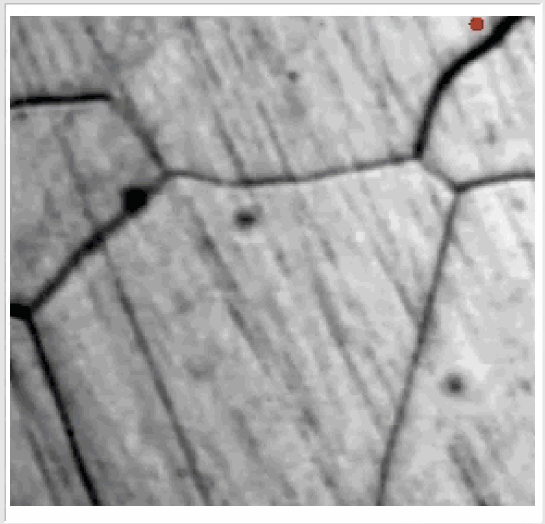
IBIC investigations on CVD diamond

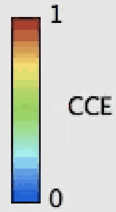
C. Manfredotti [a,b,*], F. Fizzotti [a,b], E. Vittone [a,b], M. Boero [a,b], P. Polesello [a,b],
S. Galassini [c,d], M. Jaksic [e], S. Fazinic [e], I. Bogdanovic [e]

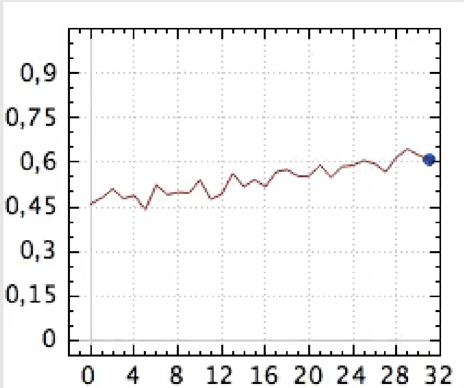
Frontal IBIC











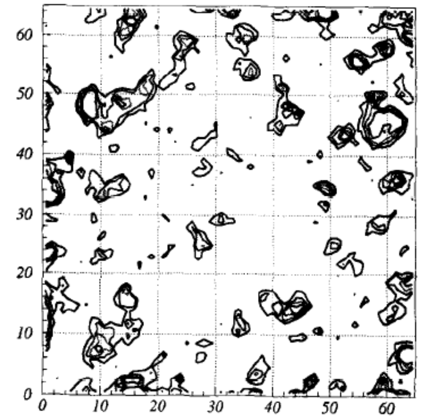


Fig. 2. Contour plot of the spectrum reported in Fig. 1. Iso-counting contours are displayed. The region contains 128×128 pixels, but it has been visualized in a 64×64 representation.

Trieste
14.08.2012

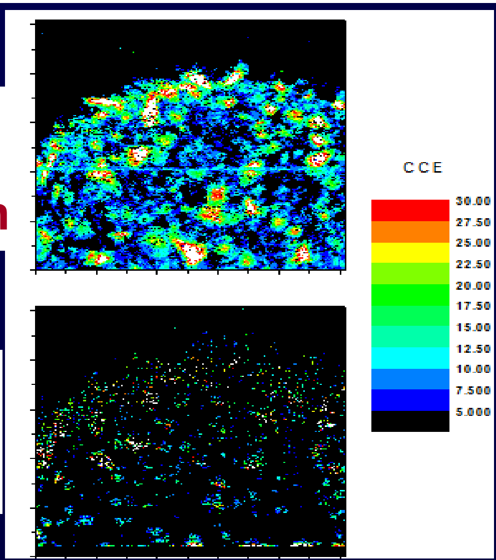
Diamond and Related Materials 11 (2002) 446–450

Effects of light on the 'primed' state of CVD diamond nuclear detectors

C. Manfredotti[a,b,*], E. Vittone[a,b], F. Fizzotti[a,b], A. Lo Giudice[a,b], C. Paolini[a,b]

Under illumination

Dark conditions



Polycrystalline CVD diamond Frontal IBIC

APPLIED PHYSICS LETTERS VOLUME 84, NUMBER 22 31 MAY 2004

Temperature-dependent emptying of grain-boundary charge traps in chemical vapor deposited diamond

S. M. Hearne, D. N. Jamieson,[a] E. Trajkov, and S. Prawer
School of Physics, University of Melbourne, Victoria, 3010, Australia

J. E. Butler

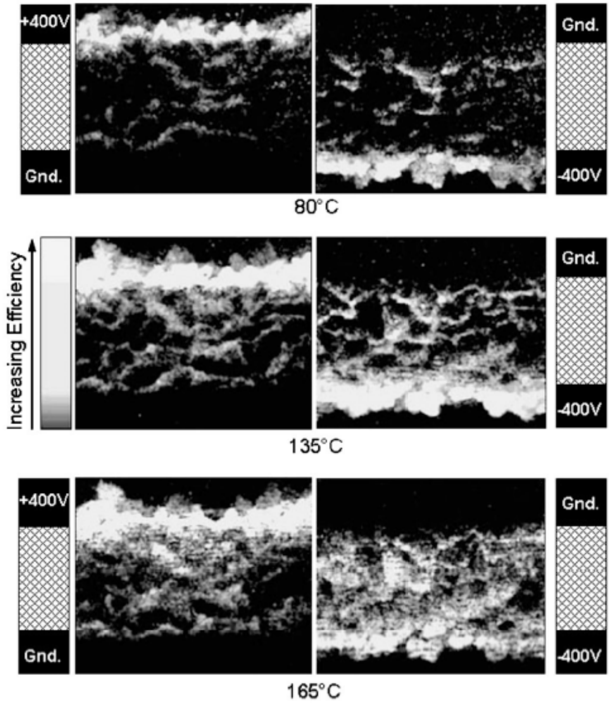
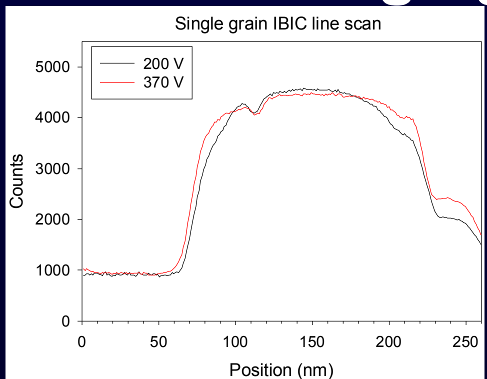
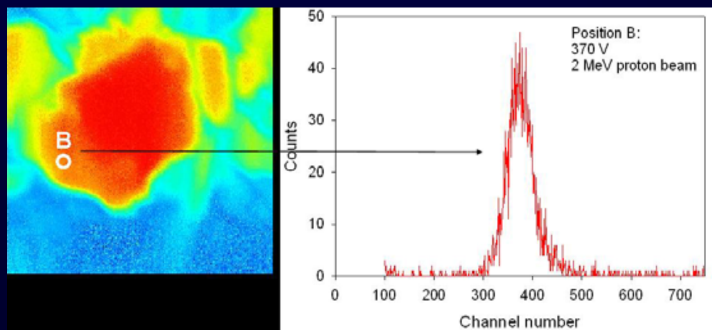
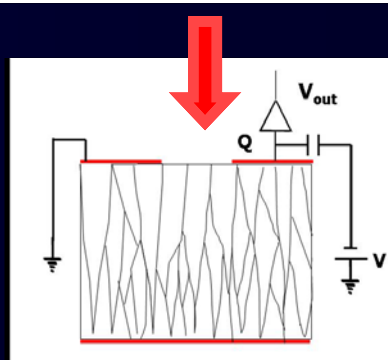


FIG. 1. Ion beam induced charge (IBIC) maps using a scanned 2 MeV He$^+$ microprobe of the charge collection in CVD diamond at various temperatures. The location of the electrodes is shown. Note that the charge collection efficiency is always highest near to the anode.

IBIC imaging with 2 MeV H+



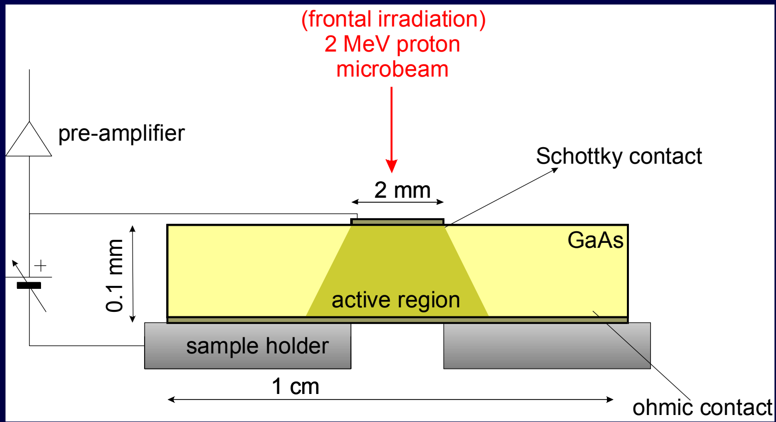


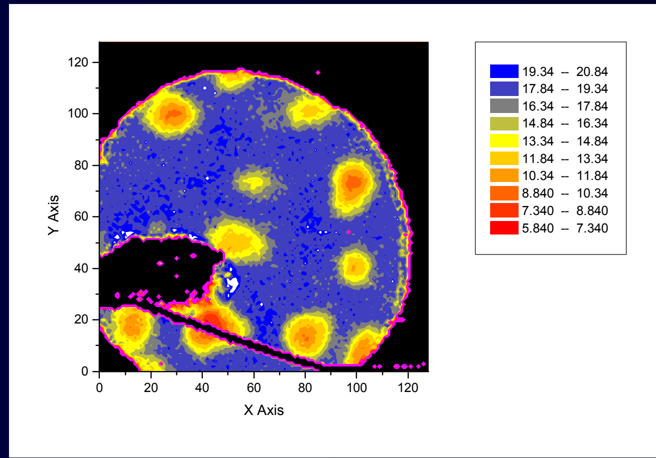


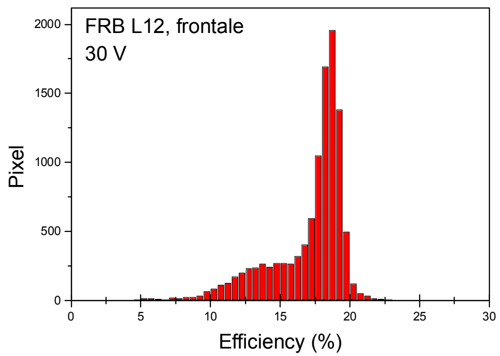
Intra-crystallite charge transport

M.B.H.Breese et al. NIM-B 181 (2001), 219-224; P.Sellin et al. NIM-B 260 (2007), 293-294

GaAs Schottky diode
Frontal IBIC



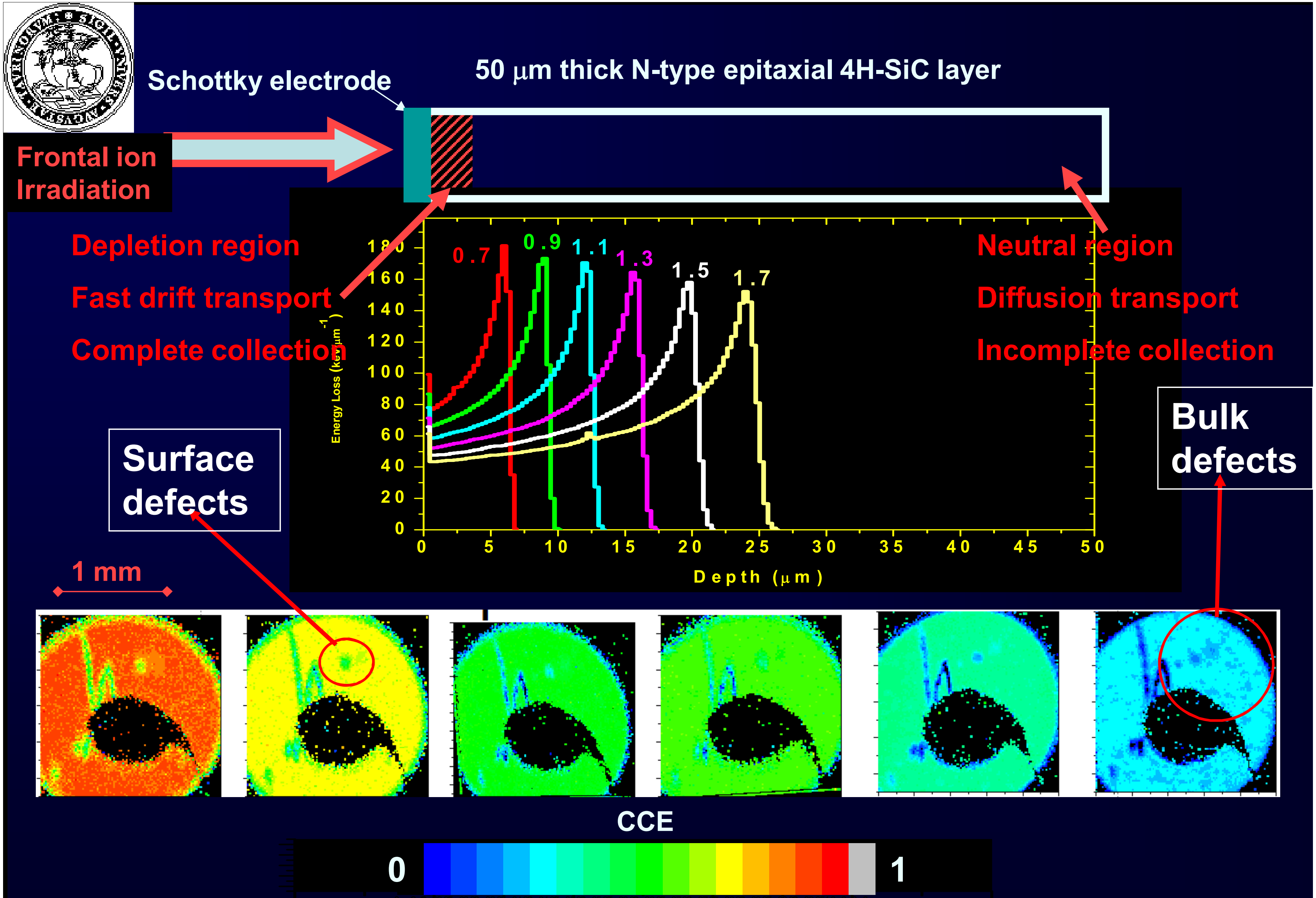




Poor spectral resolution

Effects of inhomogeneous cabon doping

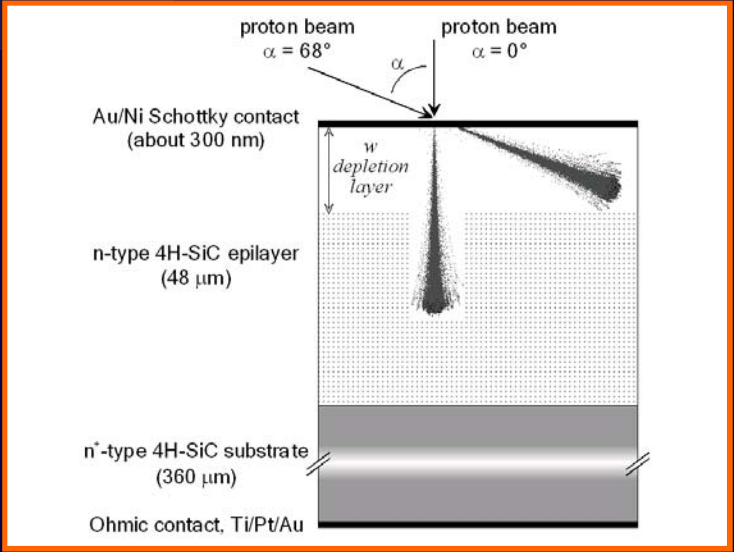
E. Vittone et al., Nuclear instruments and Methods in Physics Research B 158 (1999) 470-47

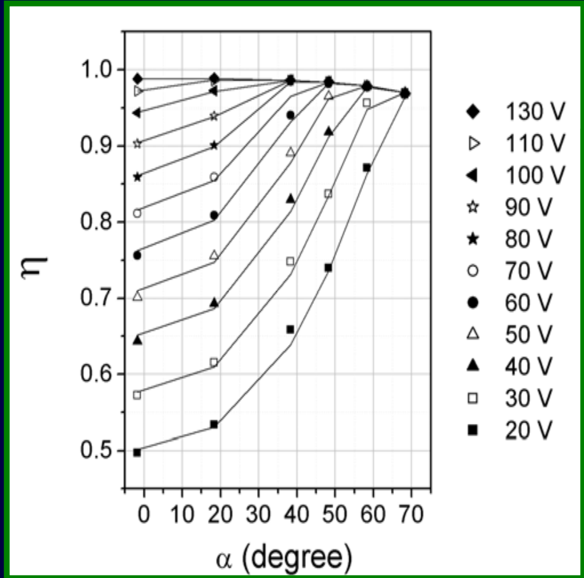


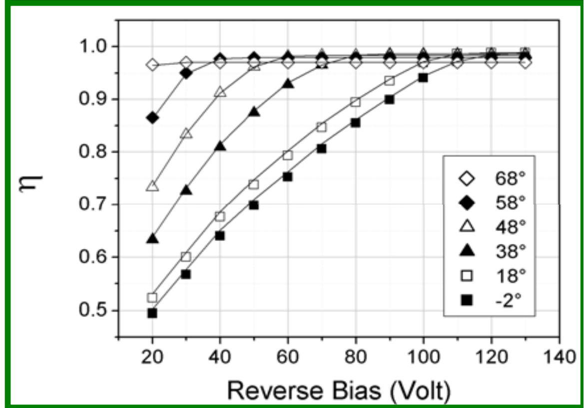
M. Jaksic et al.Nuclear Instruments and Methods in Physics Research B 188(1-4) (2002) 130-134

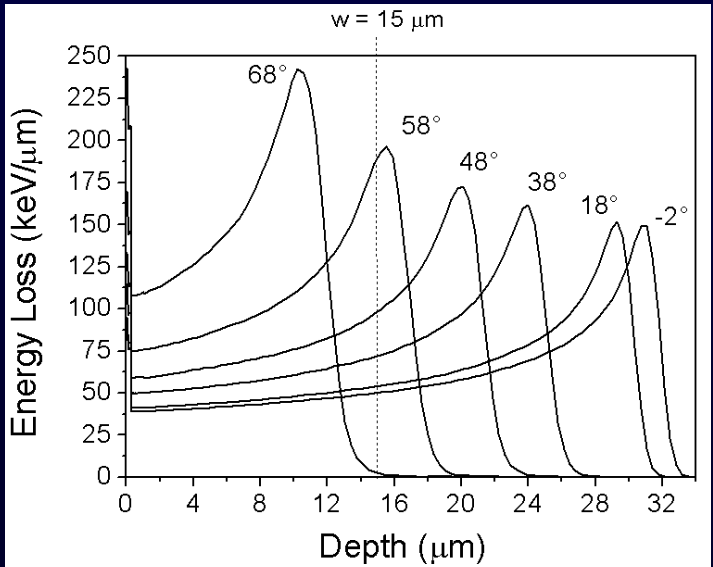
ANGLE RESOLVED IBIC (ARIBIC)

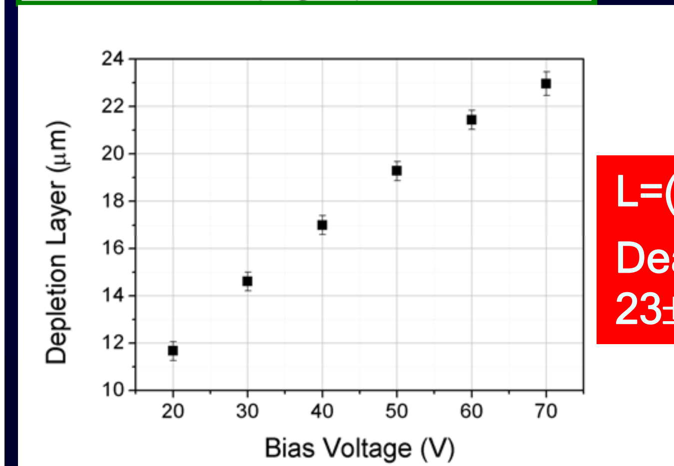
2 MeV proton beam











L=(9.9±0.8) μm

Dead layer energy loss of 23±5 keV at α=0°.

A. Lo Giudice et al. Nuclear Instruments and Methods in Physics Research B 249 (2006) 213–216

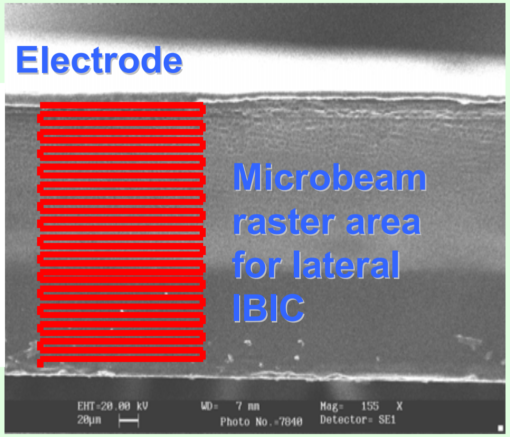
Ion Microbeam Facility of Ruder Boskovich Institute, Zagreb (HR)

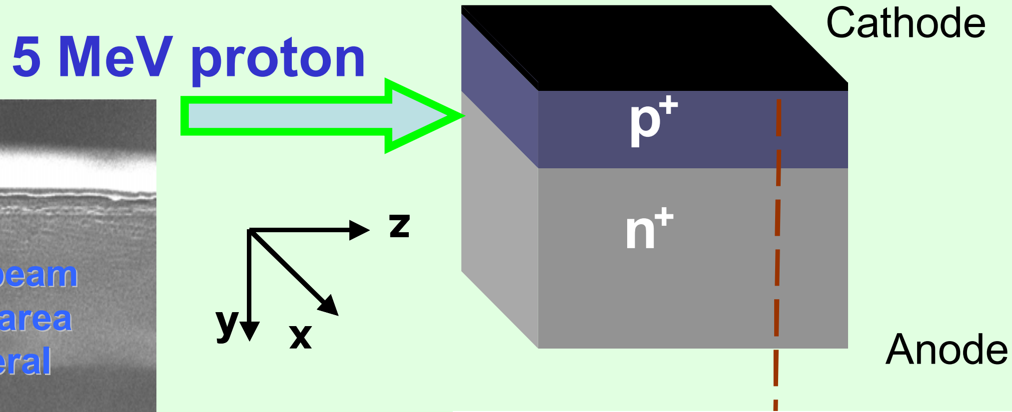
Lateral IBIC

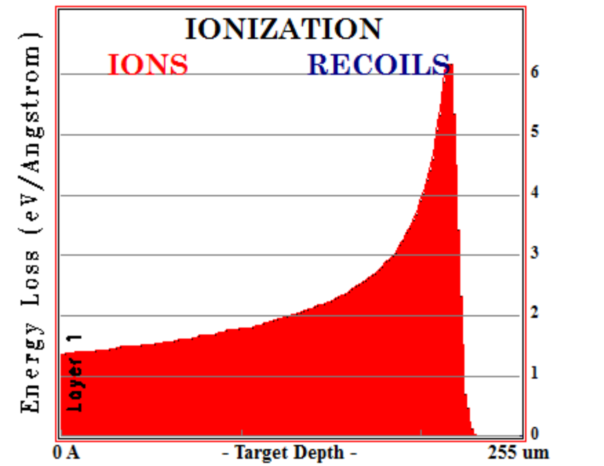
Si p-n diode

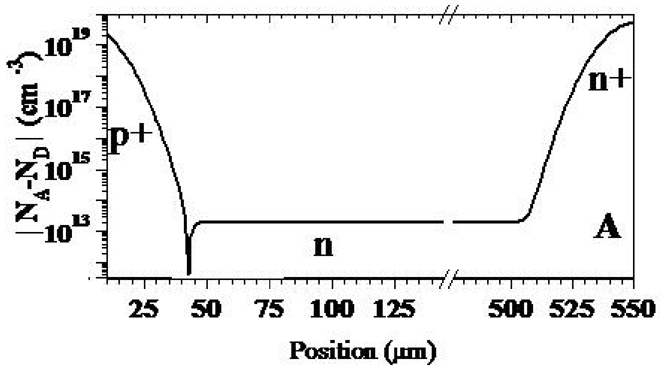
Polished and passivated lateral surface

Leakage current below 100 nA @ 100 V



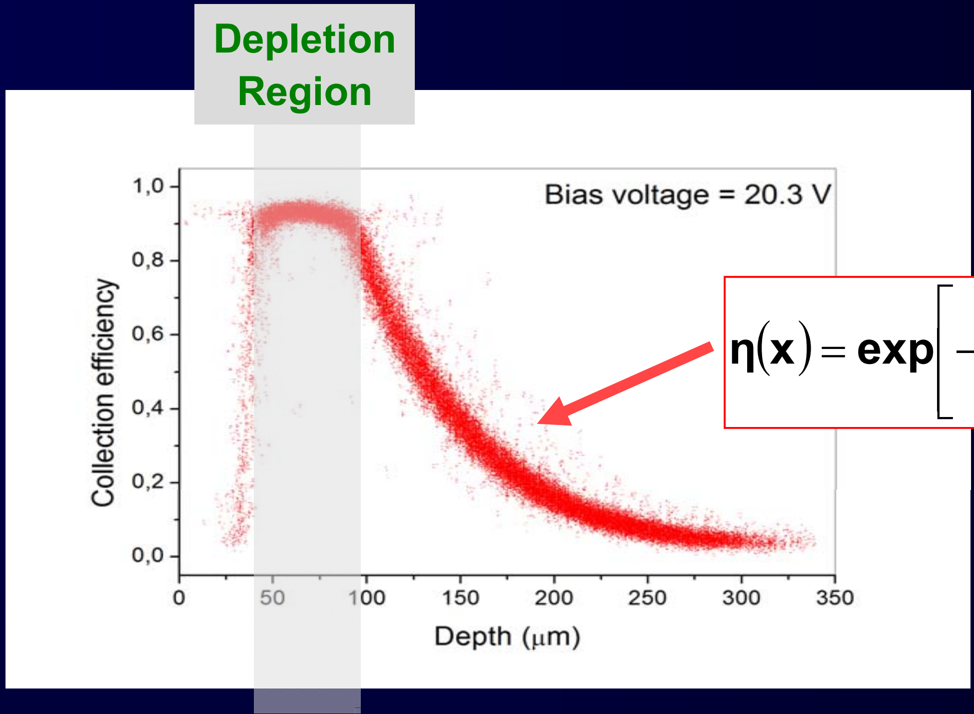




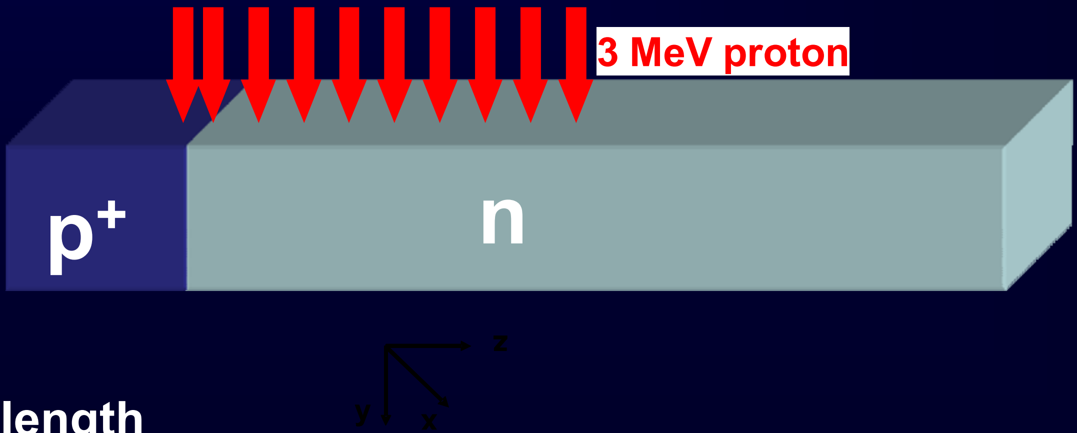


Lateral IBIC

Si p-n diode



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

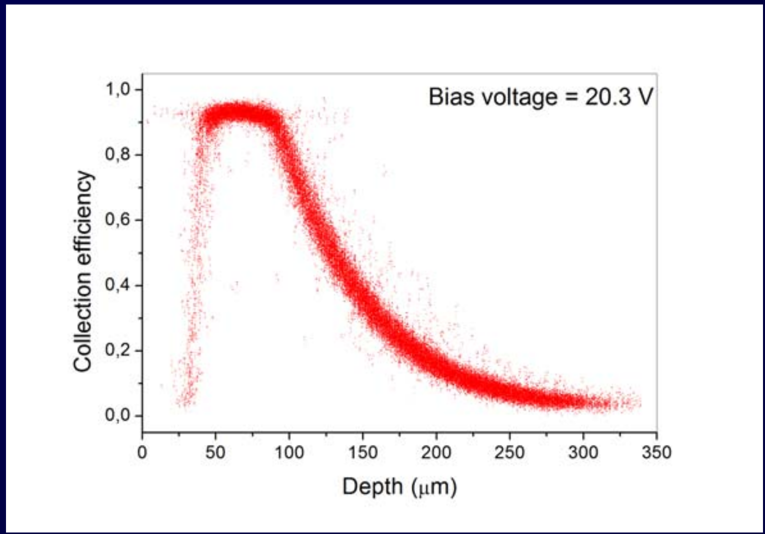


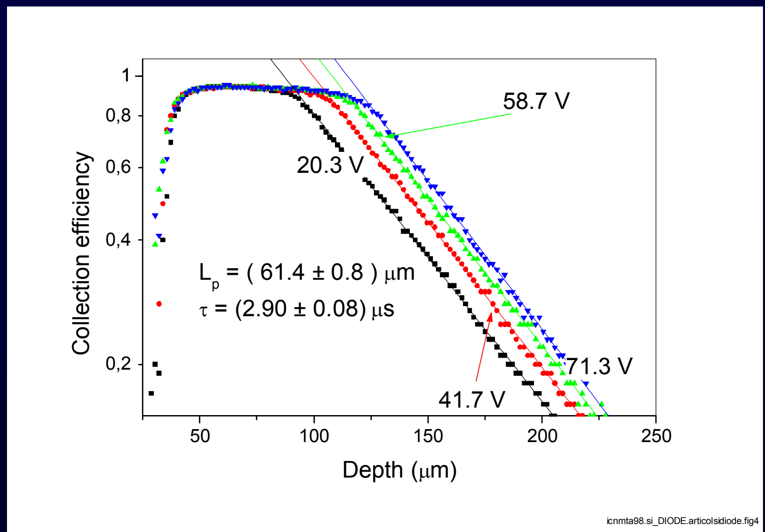
$$L_p = \sqrt{D_p \cdot \tau_p}$$

minority carrier diffusion length

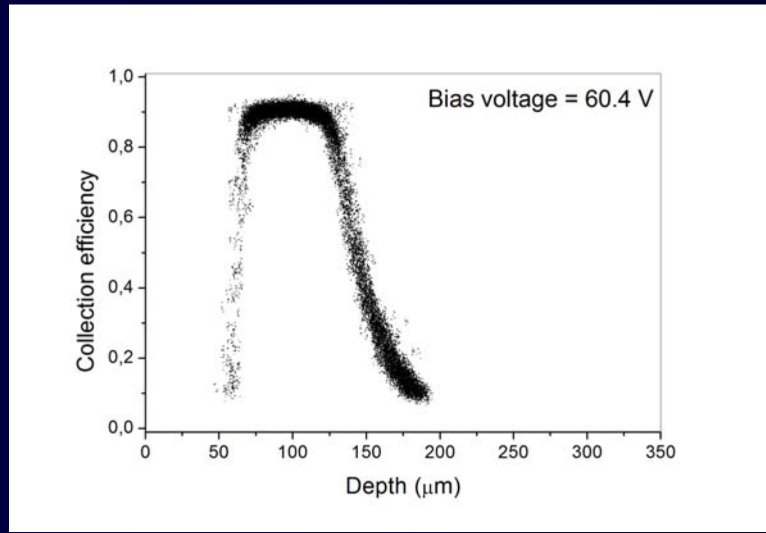
C. Manfredotti et al., Nuclear instruments and Methods in Physics Research B 158 (1999) 476-480

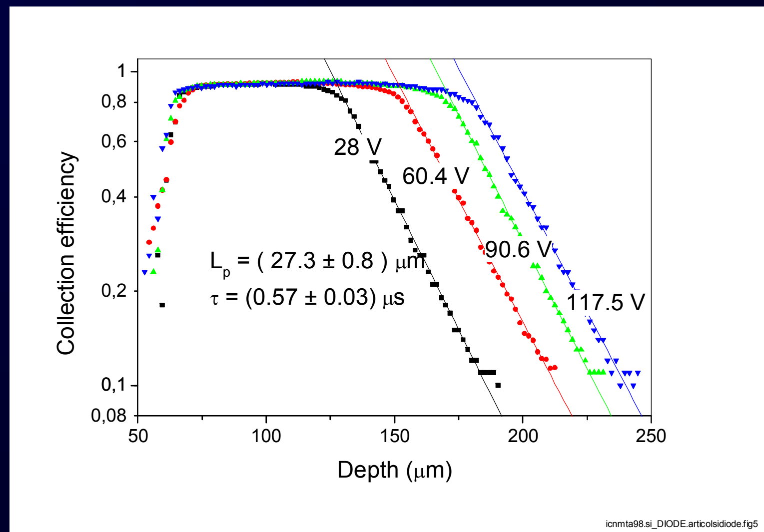
Pristine diode





Au doped diode





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

Induced current into the sensing electrode

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

Weighting field

Weighting potential:

$$\nabla \psi_w = -\mathbf{E}_w = -\nabla \frac{\partial \psi}{\partial V} \Rightarrow \psi_w = \frac{\partial \psi}{\partial V}$$

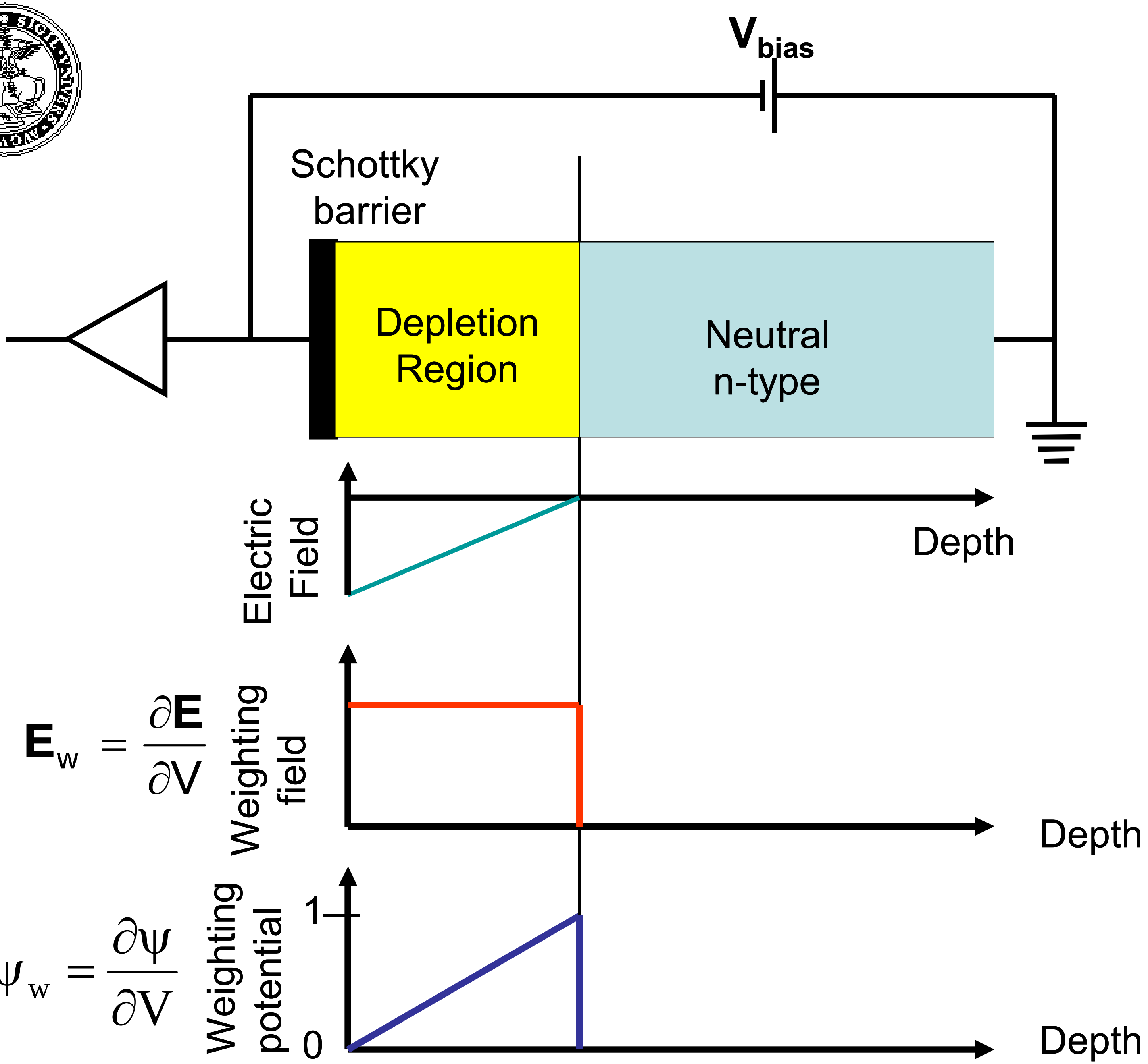
Equation of motion: $\mathbf{v} = \frac{d\mathbf{r}}{dt}$

$$Q = \int_{t_A}^{t_B} I dt = -q \int_{t_A}^{t_B} \mathbf{v} \cdot E_w dt = -q \int_{\mathbf{r}_A}^{\mathbf{r}_B} E_w d\mathbf{r} =$$

$$= q \cdot \left(\psi_w(\mathbf{r}_B) - \psi_w(\mathbf{r}_A)\right) = q \cdot \left(\left.\frac{\partial \psi}{\partial V}\right|_{\mathbf{r}_B} - \left.\frac{\partial \psi}{\partial V}\right|_{\mathbf{r}_A} \right)$$

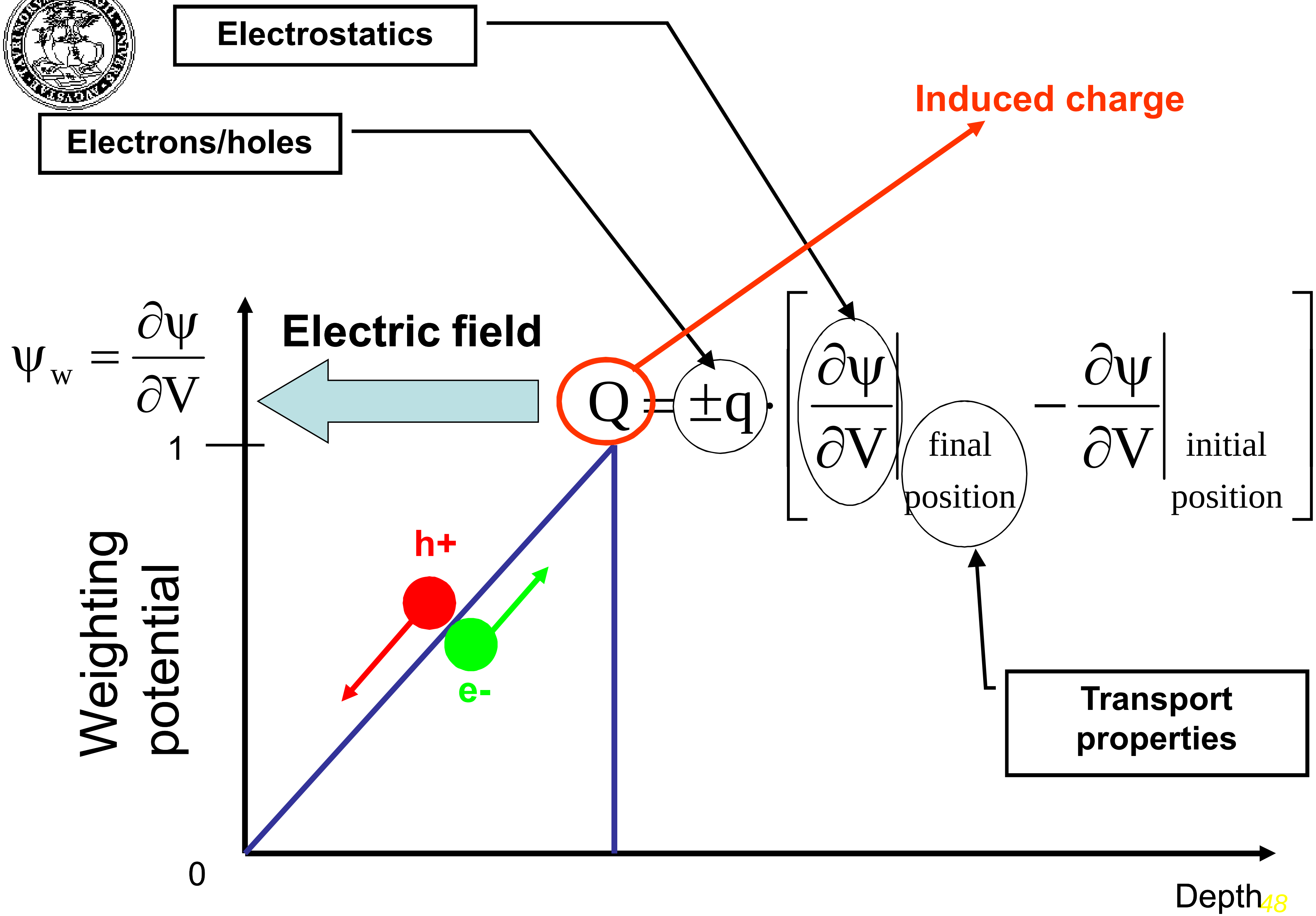
The induced charge Q into the sensing electrode

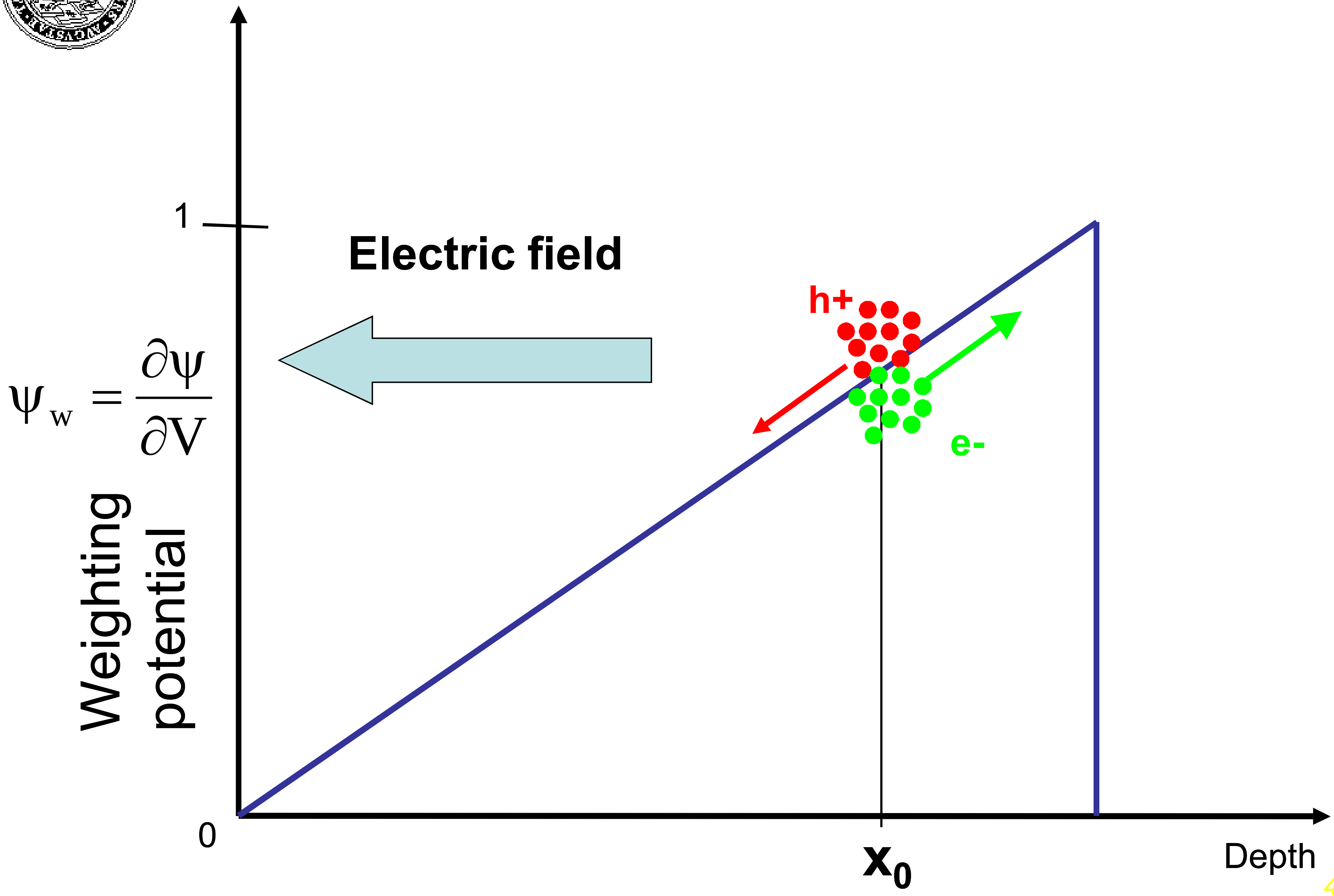
is given by the difference in the weighting potentials between any two positions (r_A and r_B) of the moving charge



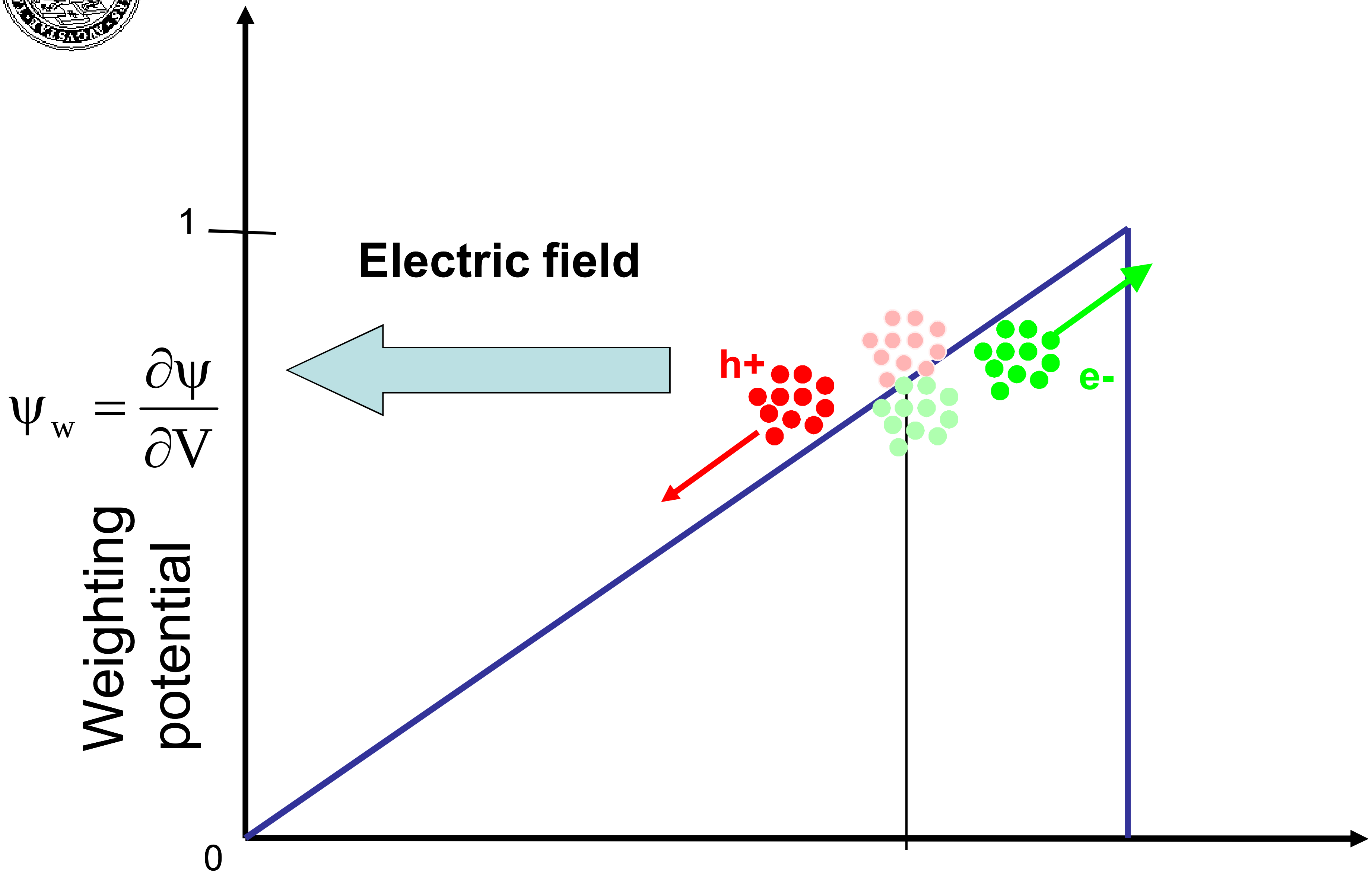
$$\mathbf{E}_w = \frac{\partial \mathbf{E}}{\partial V}$$

$$\psi_w = \frac{\partial \psi}{\partial V}$$


Electrostatics
Electrons/holes
Induced charge
Electric field
$\psi_w = \frac{\partial \psi}{\partial V}$
$Q = \pm q \cdot \left[\frac{\partial \psi}{\partial V}\Big|_{\text{final position}} - \frac{\partial \psi}{\partial V}\Big|_{\text{initial position}} \right]$
Transport properties
Weighting potential
1
0
h+
e-
Depth

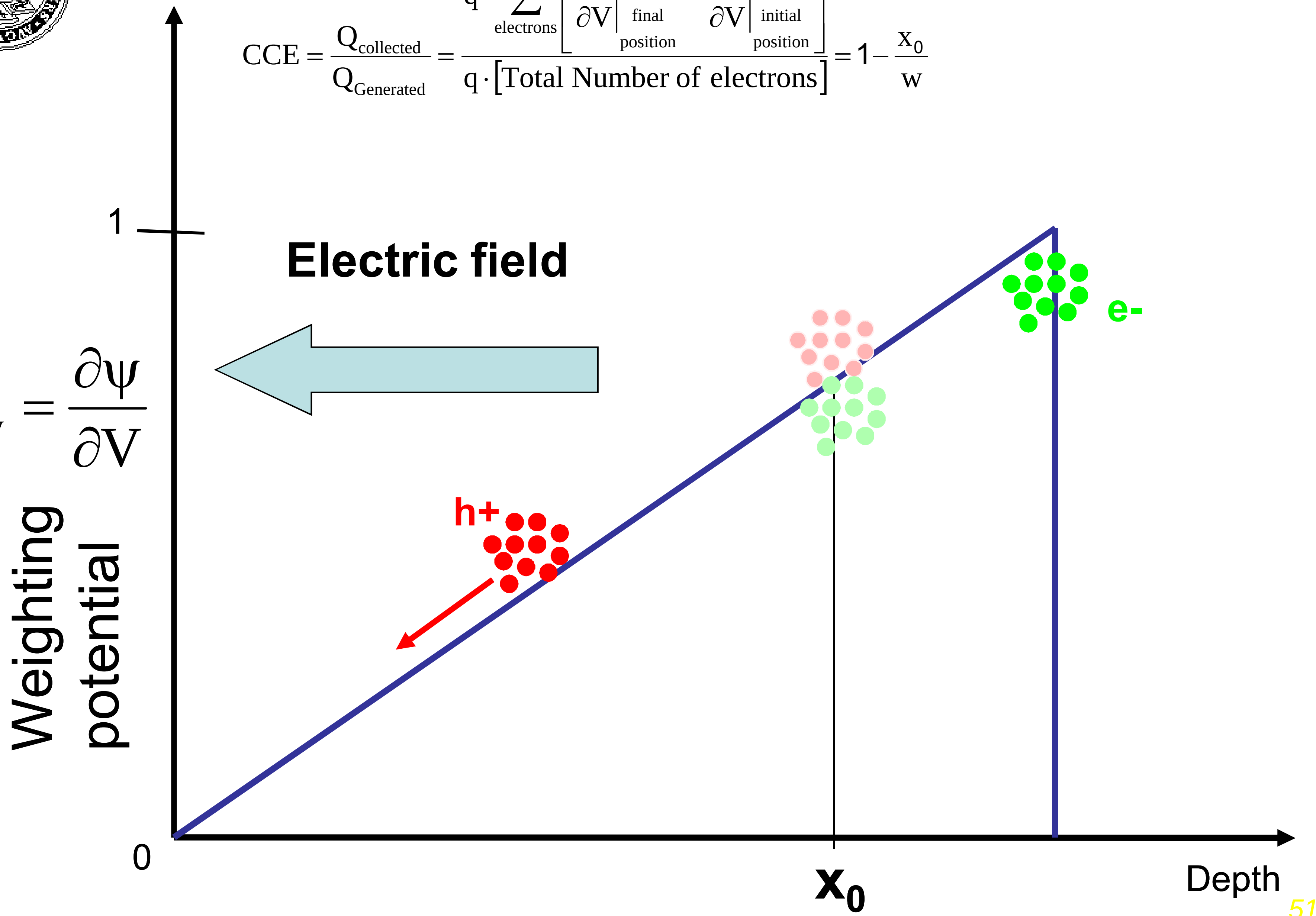


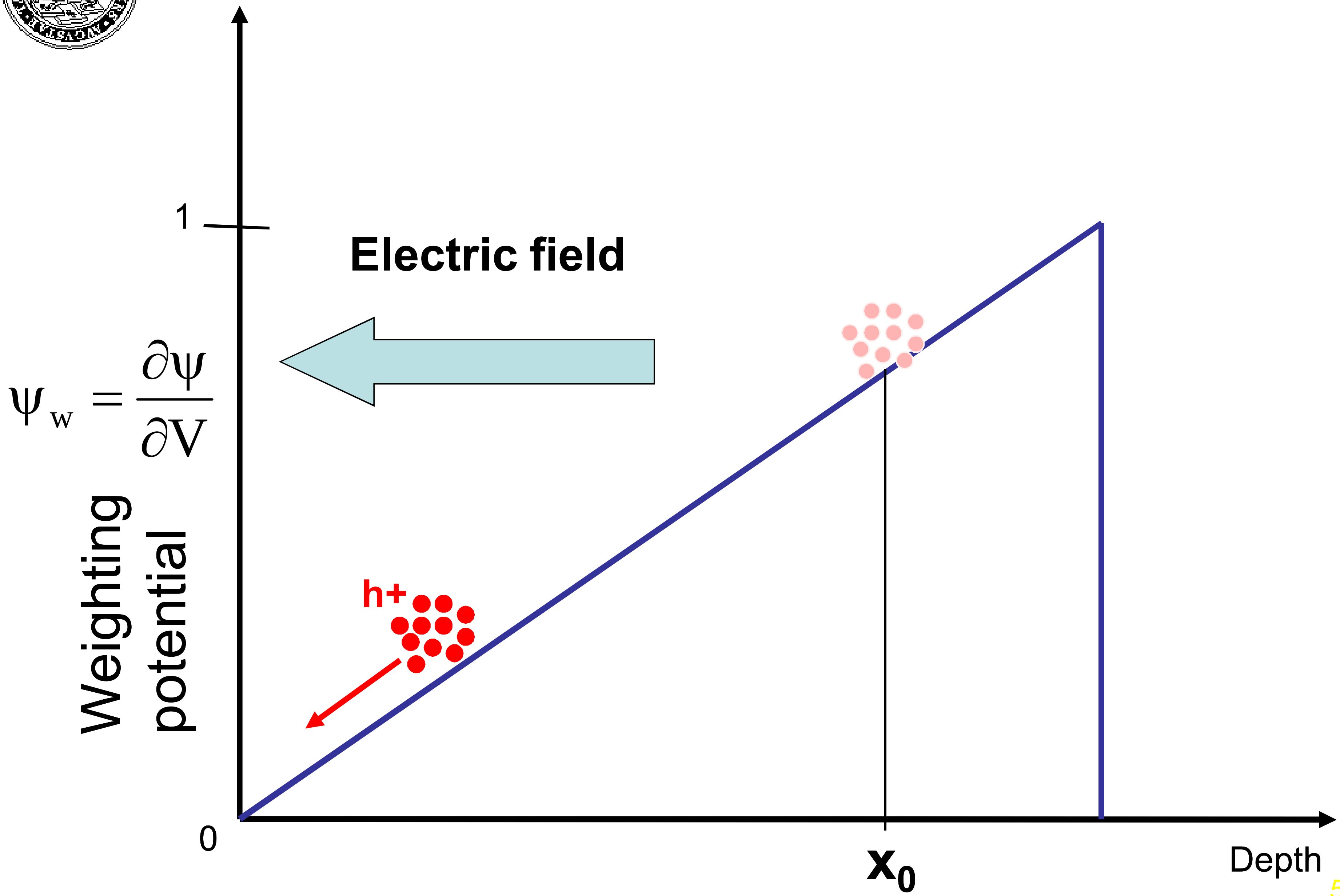
1
0
Electric field
h+
e-
$\psi_w = \frac{\partial \psi}{\partial V}$
Weighting potential
x_0
Depth


1
0
Electric field
h+
e-
Weighting potential
$\psi_w = \frac{\partial \psi}{\partial V}$

$$\mathrm{CCE} = \frac{Q_{\mathrm{collected}}}{Q_{\mathrm{Generated}}} = \frac{q \cdot \sum_{\mathrm{electrons}} \left[\left.\frac{\partial\psi}{\partial V}\right|_{\substack{\mathrm{final}\\ \mathrm{position}}} - \left.\frac{\partial\psi}{\partial V}\right|_{\substack{\mathrm{initial}\\ \mathrm{position}}} \right]}{q \cdot [\text{Total Number of electrons}]} = 1 - \frac{x_0}{w}$$

$$\psi_w = \frac{\partial\psi}{\partial V}$$



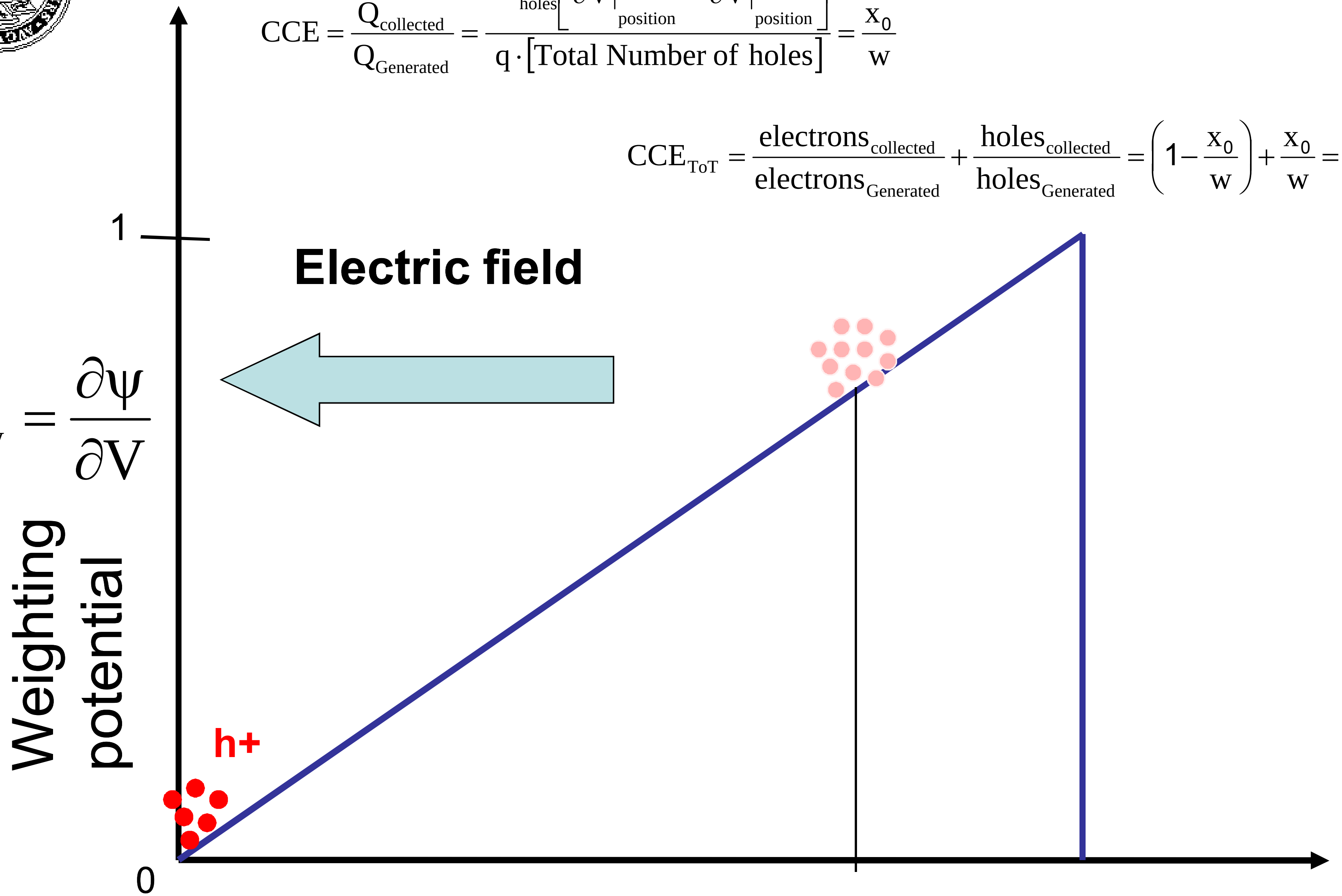


$\psi_w = \frac{\partial \psi}{\partial V}$
Weighting potential
1
0
Electric field
h+
x_0
Depth

$$CCE = \frac{Q_{collected}}{Q_{Generated}} = \frac{q \cdot \sum_{holes} \left[\left.\frac{\partial \psi}{\partial V}\right|_{\substack{final \\ position}} - \left.\frac{\partial \psi}{\partial V}\right|_{\substack{initial \\ position}} \right]}{q \cdot [\text{Total Number of holes}]} = \frac{x_0}{w}$$

$$CCE_{ToT} = \frac{electrons_{collected}}{electrons_{Generated}} + \frac{holes_{collected}}{holes_{Generated}} = \left(1 - \frac{x_0}{w}\right) + \frac{x_0}{w} = 1$$

$$\psi_w = \frac{\partial \psi}{\partial V}$$



To evaluate the total induced charge

Magnetic effects are negligible;

Electric field propagates instantaneously

Free carrier velocities much smaller than the light speed

Excess charge does not significantly perturb the electric field

Evaluate the actual potential ψ by solving the Poisson's equation

↓

Evaluate the Gunn's weighting potential

$$\frac{\partial \psi}{\partial V}$$

V is the bias potential at the sensitive electrode

→

Solve the transport (continuity) equations

↓

$$Q = q \cdot \left(\left. \frac{\partial \psi}{\partial V} \right|_{r_B} - \left. \frac{\partial \psi}{\partial V} \right|_{r_A} \right)$$

The induced charge Q into the sensing electrode is given by the difference in the weighting potentials between any two positions (r_A and r_B) of the moving charge

Basic assumptions

Free carrier velocities much smaller than the light speed → Magnetic effects are negligible; Electric field propagates instantaneously

ELECTROSTATICS

$$\begin{cases} \frac{\partial n}{\partial t} = \vec{\nabla} \cdot \vec{J}_n + G_n - U_n \\ \frac{\partial p}{\partial t} = -\vec{\nabla} \cdot \vec{J}_p + G_p - U_p \\ \vec{\nabla} \cdot (\varepsilon \cdot \vec{\nabla}\phi) = \rho(p,n) \end{cases}$$

Excess charge does not significantly perturb the field within the detector

Quasi-steady-state mode

$$\begin{cases} \frac{\partial n}{\partial t} = \vec{\nabla} \cdot \vec{J}_n + G_n - U_n \\ \frac{\partial p}{\partial t} = -\vec{\nabla} \cdot \vec{J}_p + G_p - U_p \end{cases}$$

$$\vec{\nabla} \cdot (\varepsilon \cdot \vec{\nabla}\phi) = \rho(p,n)$$

Linearization of U

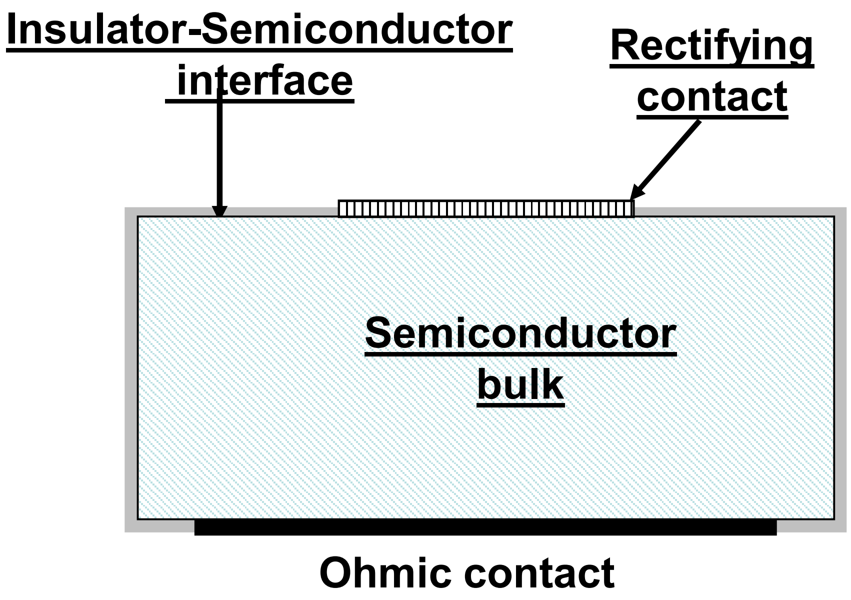
$$\frac{\partial n}{\partial t} = \vec{\nabla} \cdot \vec{J}_n + G_n - \frac{n}{\tau_n}$$

$$\frac{\partial p}{\partial t} = -\vec{\nabla} \cdot \vec{J}_p + G_p - \frac{p}{\tau_p}$$

$$\vec{\nabla} \cdot (\varepsilon \cdot \vec{\nabla}\phi) = \rho(p,n)$$

Basic formalism

Boundary conditions



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 actual potential ϕ by solving the Poisson's equation

$$\vec{\nabla}\cdot\left(\varepsilon\cdot\vec{\nabla}\phi\right) = \rho(p,n)$$

⇓

Evaluate the induced charge

$$Q(r_0,t) = -\oint \varepsilon\cdot\vec{\nabla}\phi(r_0,t)\cdot d\vec{S}$$

Evaluate the induced current

$$I(r_0,t) = \frac{dQ(r_0,t)}{dt}$$

Initial conditions

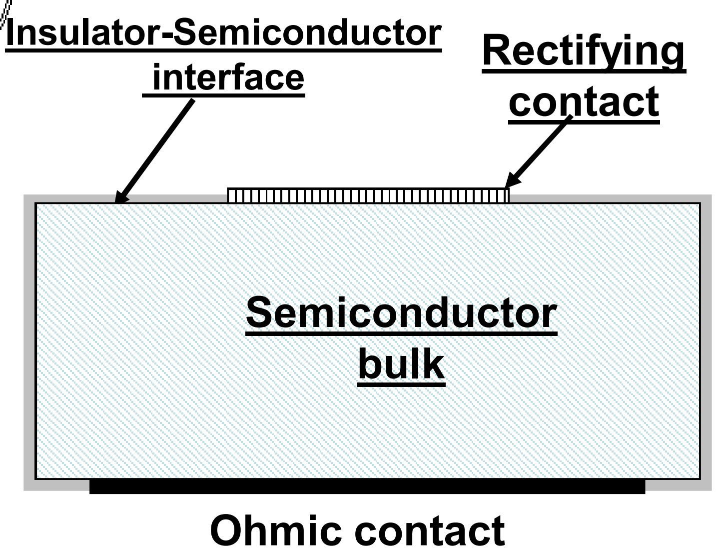
For mapping charge pulses

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

$r_0 =$ Generation point at $t = 0$

Formalism based on the Gunn's theorem

Boundary conditions



Initial conditions

For mapping charge pulses

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

$r_0 =$ 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 weighted potential

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

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

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

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.

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

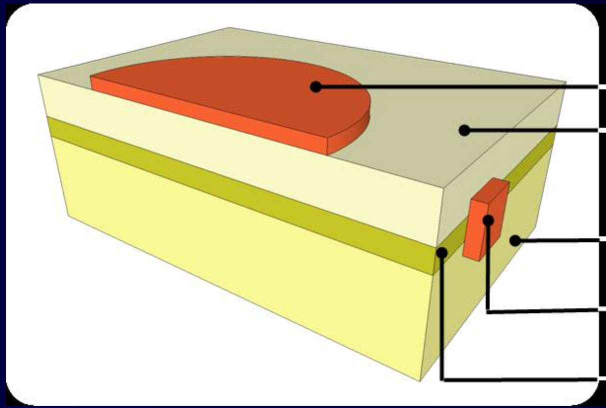
$$Q = q\left[\left.\frac{\partial\psi}{\partial V}\right|_{r} - \left.\frac{\partial\psi}{\partial V}\right|_{r}\right]$$

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

Lateral IBIC of a diamond Schottky diode



- ✓ Diamond Schottky diode structure:
  - ✓ homoepitaxial growth on HPHT substrates
  - ✓ (type Ib, 4×4×0.4 mm^3) slightly B doped (Acceptor concentration ≈ 10^{13}-10^{14} cm^{-3})
  - ✓ heavily B-doped buffer layer as back contact (Acceptor concentration ≈ 10^{18}-10^{19} cm^{-3})
  - ✓ 25 μm thick intrinsic layer as active volume
- ✓ Schottky contact: frontal Al circular contact (∅ = 2 mm, 200 nm thick) on intrinsic layer
- ✓ back contact on B-doped layer → ohmic contact
- ✓ sample cleaved in order to expose its cross section for IBIC characterization

ideality factor: $n = (1.51 \pm 0.04)$

series resistance: $R_s = (5.1 \pm 1.6)$ kΩ

→ back B-doped contact

shunt resistance: $R_{sh} = (900 \pm 6)$ GΩ

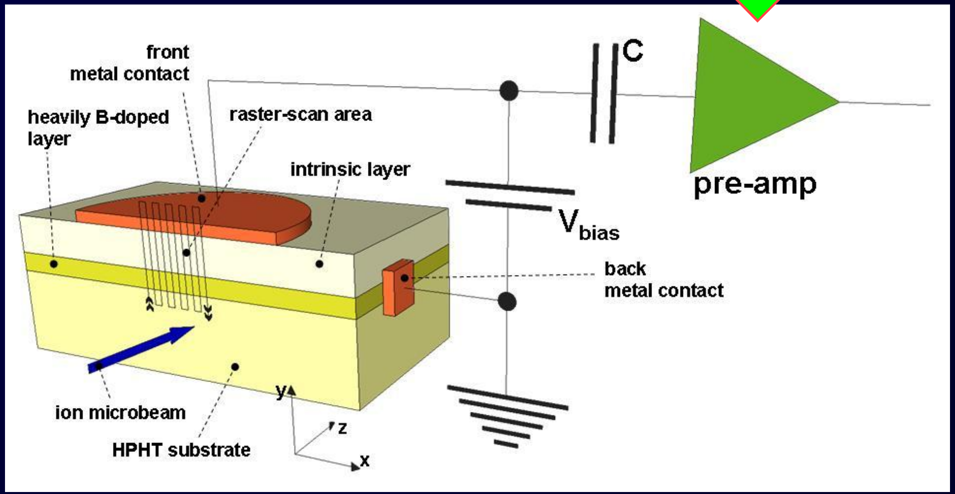
@ 50 V -> I<50 pA

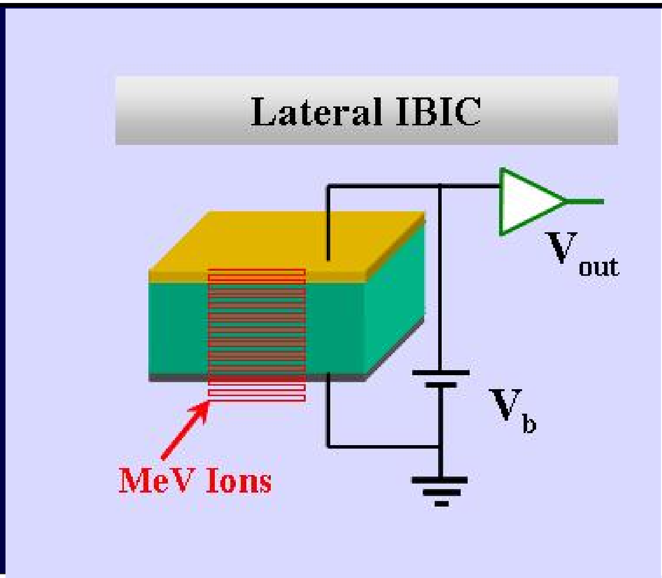
S. Almaviva et al. “*Synthetic single crystal diamond dosimeters for conformal radiation therapy application*”, Diamond & Related Materials 19 (2010) 217–220

Lateral IBIC measurements performed at the ion microbeam line of the AN2000 accelerator of the National Laboratories of Legnaro (LNL-INFN)

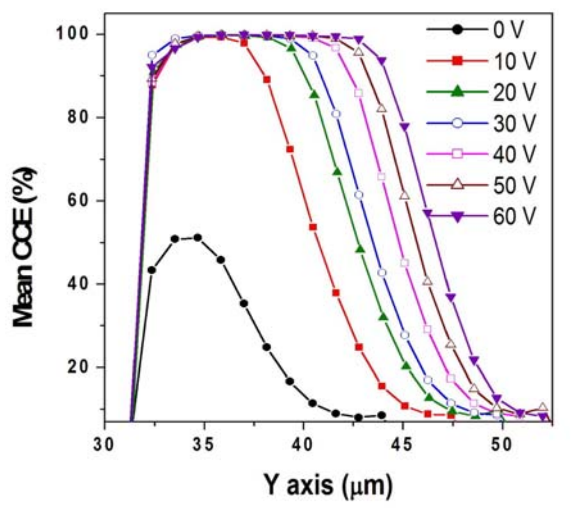
charge sensitive electronic chain and synchronous signal acquistition with microbeam scanning

- ✓ ion species and energy: H^+ @ 2 MeV
- ✓ ion current: $\leq 10^3$ ions s^{-1} → no pile up or charging effects
- ✓ ion beam spot on the sample: FWHM = 3 µm
- ✓ raster-scanned area: S = 62×62 μm^2

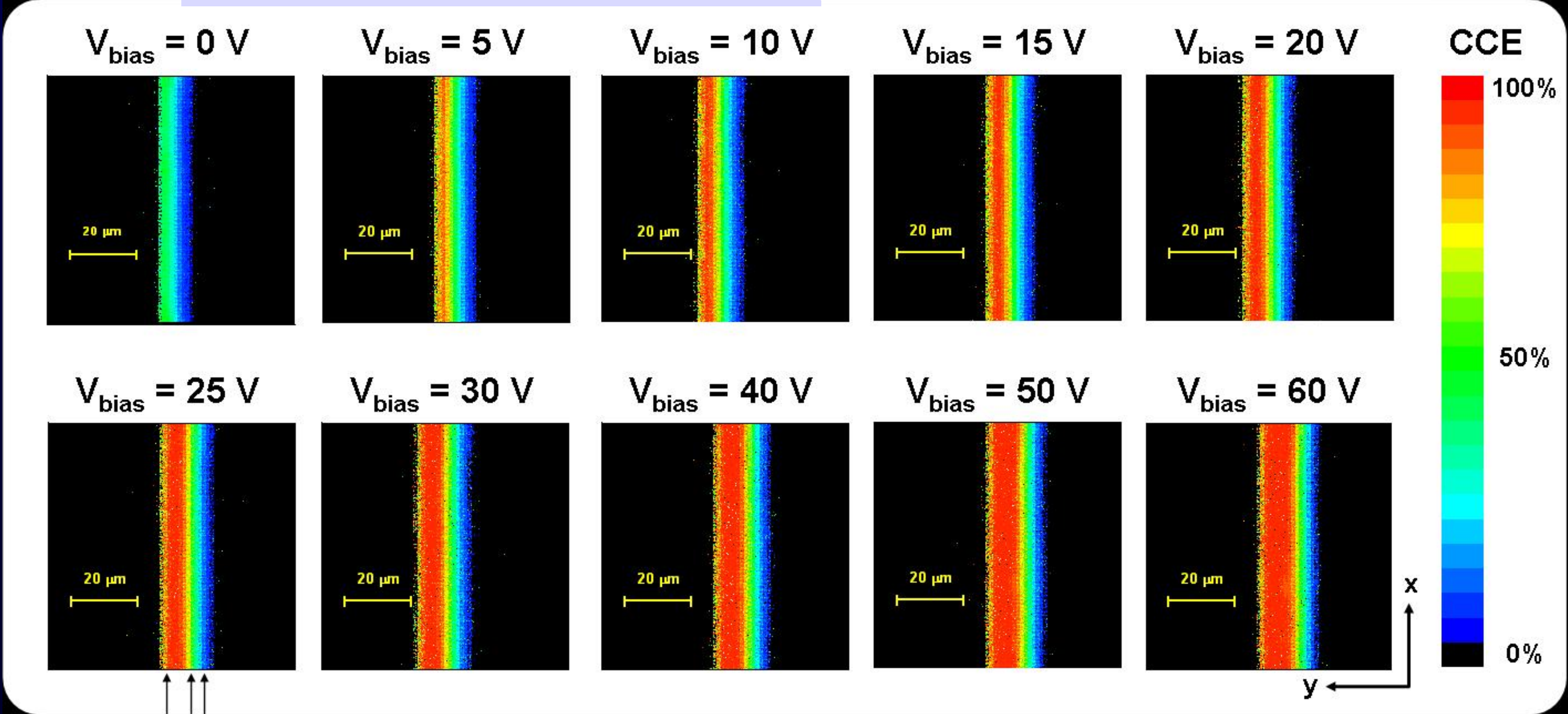




Lateral IBIC
V out
V b
MeV Ions

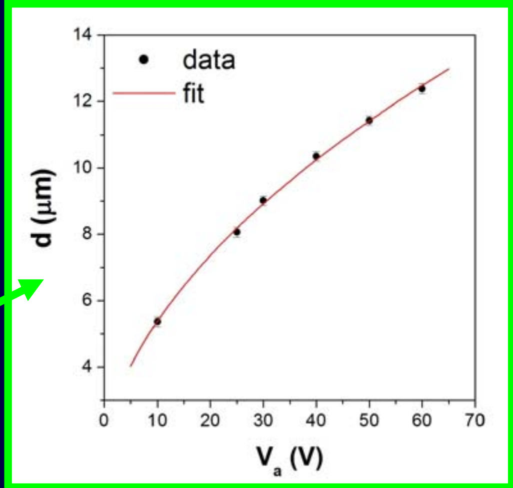


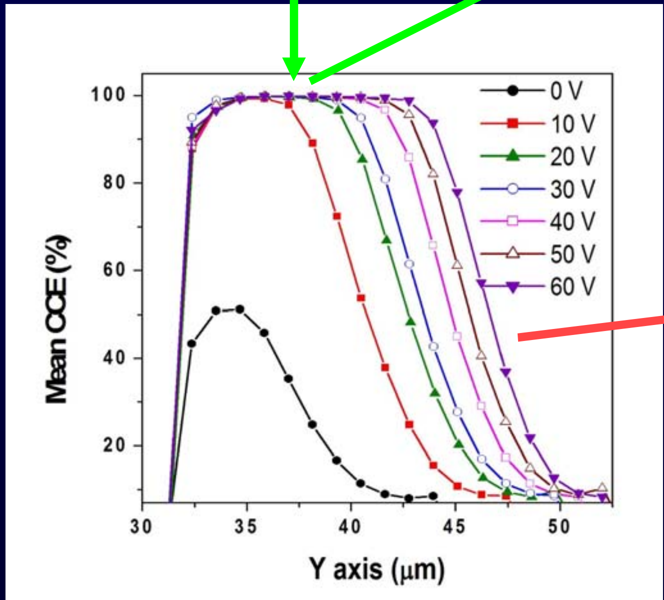
0 V
10 V
20 V
30 V
40 V
50 V
60 V
Mean CCE (%)
Y axis (μm)

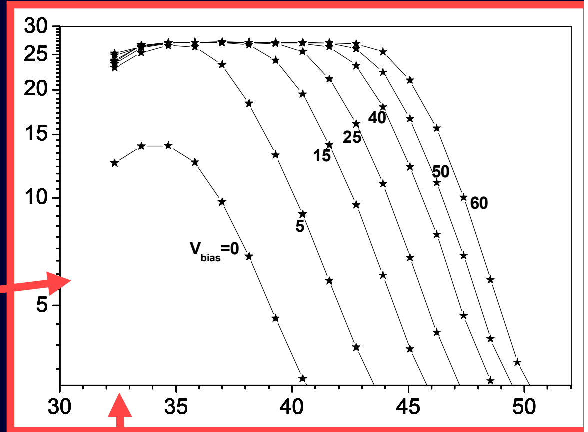


V bias = 0 V
V bias = 5 V
V bias = 10 V
V bias = 15 V
V bias = 20 V
V bias = 25 V
V bias = 30 V
V bias = 40 V
V bias = 50 V
V bias = 60 V
20 μm
CCE
100%
50%
0%
x
y

Plateaux: Depletion region (active region) Vs. Bias voltage







Exponential-like decay outside the highly efficient depletion region

$$\text{Electron diffusion length: } L_e = \sqrt{D_e \cdot \tau_e} = (2.57 \pm 0.17)\mu m$$

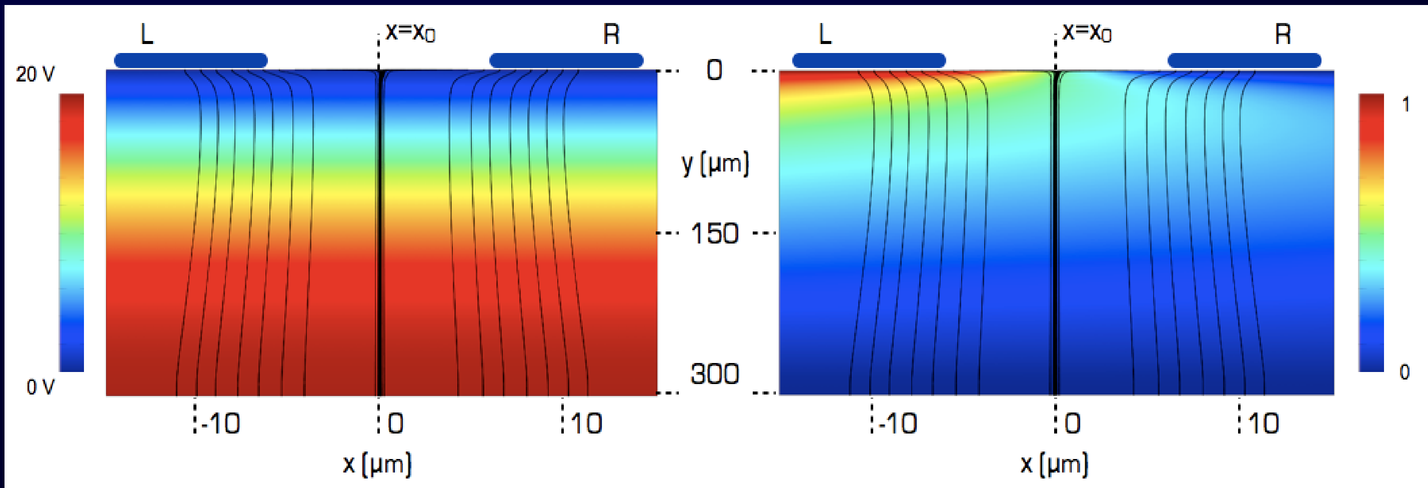
$$\text{Mobility} \cdot \text{lifetime}: \mu_e \cdot \tau_e = (2.57 \pm 0.3) V / cm^2$$

A. Lo Giudice et al, Physica Status Solidi Rapid Research Letters 5 (2011) 80-82

The induced charge Q at the sensing electrode is given by the difference in the weighting potentials between any two positions (r_A and r_B) of the moving charge

$$Q = q \cdot \left(\left. \frac{\partial \psi}{\partial V} \right|_{\substack{\text{final} \\ \text{position}}} - \left. \frac{\partial \psi}{\partial V} \right|_{\substack{\text{initial} \\ \text{position}}} \right)$$

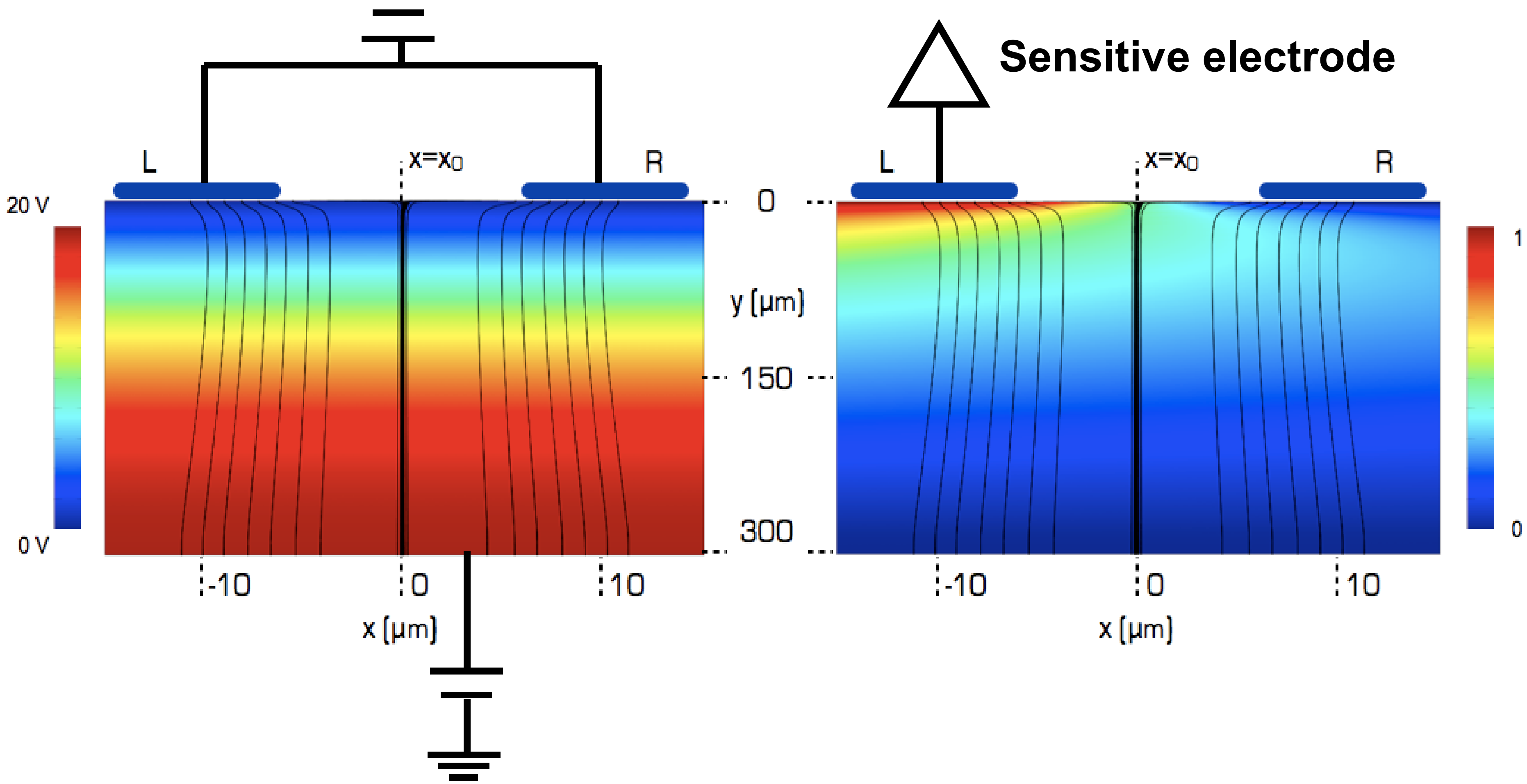
CHARGE SHARING IN MULTIELECTRODE DEVICES

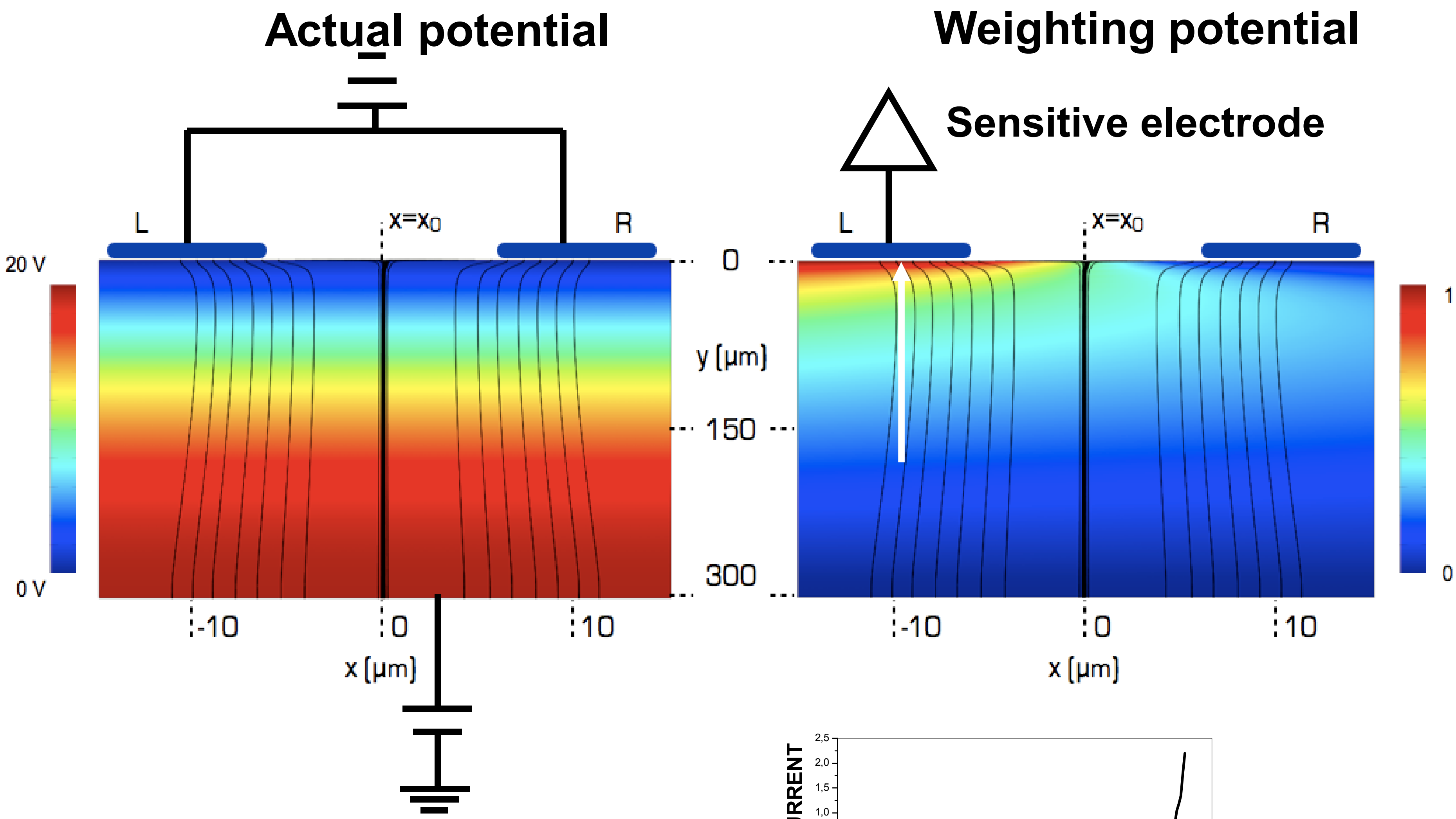


Actual potential **Weighting potential**

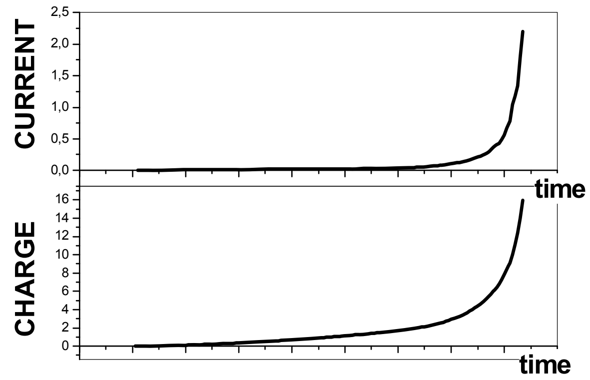
Actual potential

Weighting potential

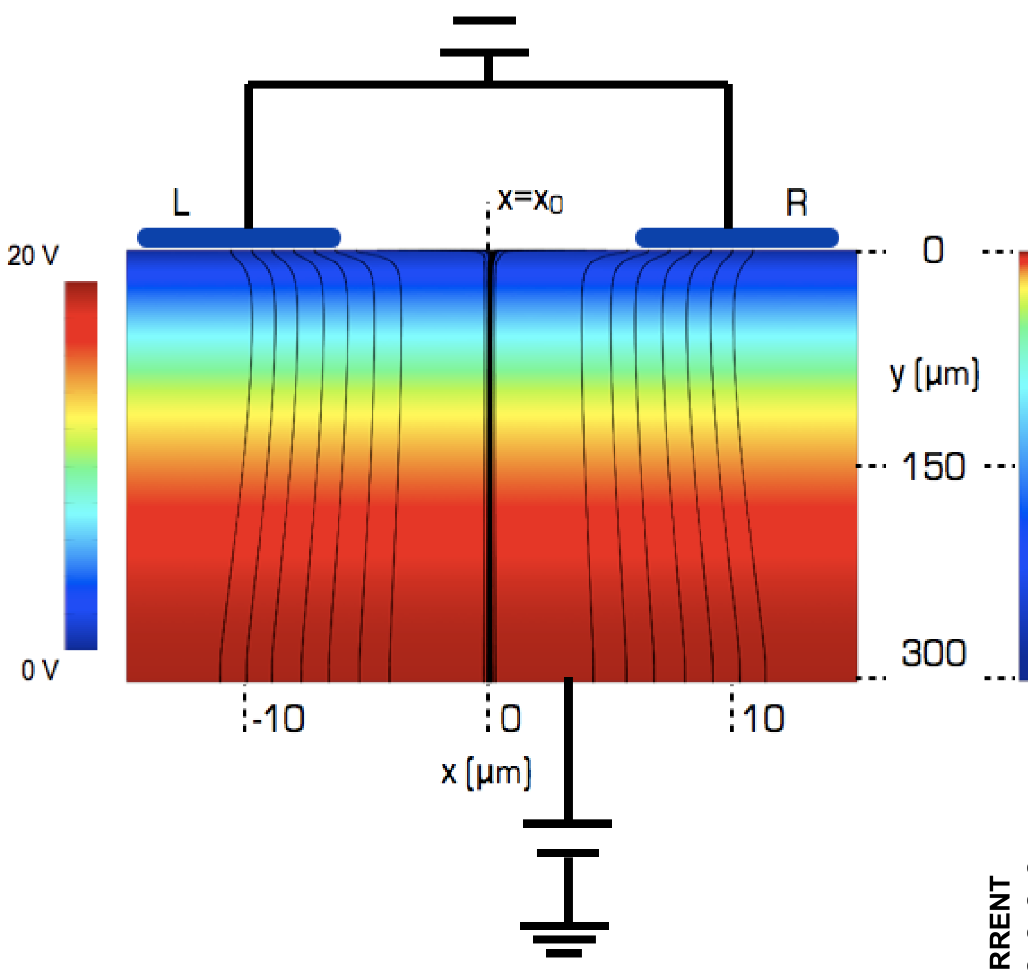




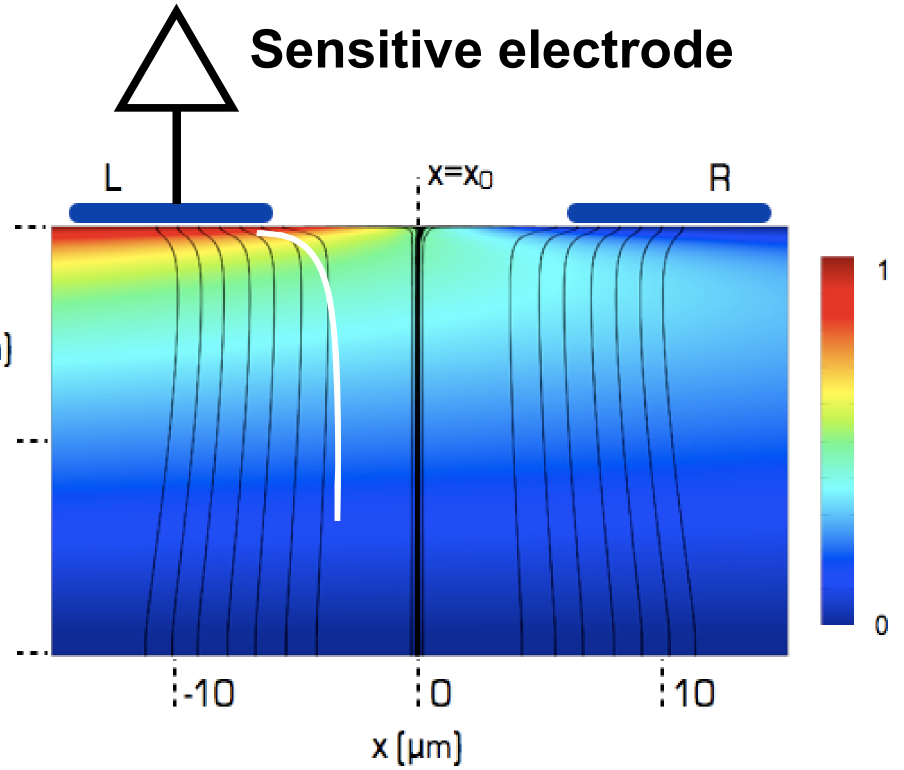
$$Q = q \cdot \left(\frac{\partial \psi}{\partial V}\Big|_{\substack{\text{final}\\\text{position}}} - \frac{\partial \psi}{\partial V}\Big|_{\substack{\text{initial}\\\text{position}}} \right)$$



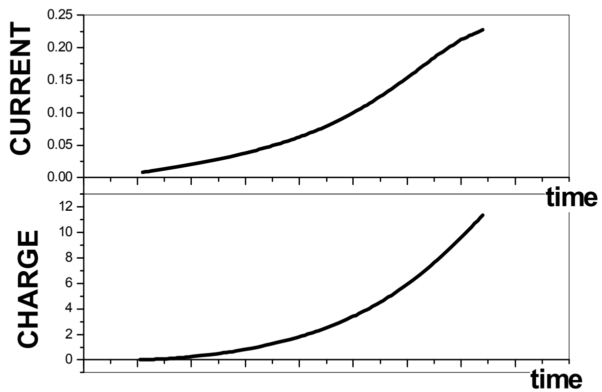
Actual potential



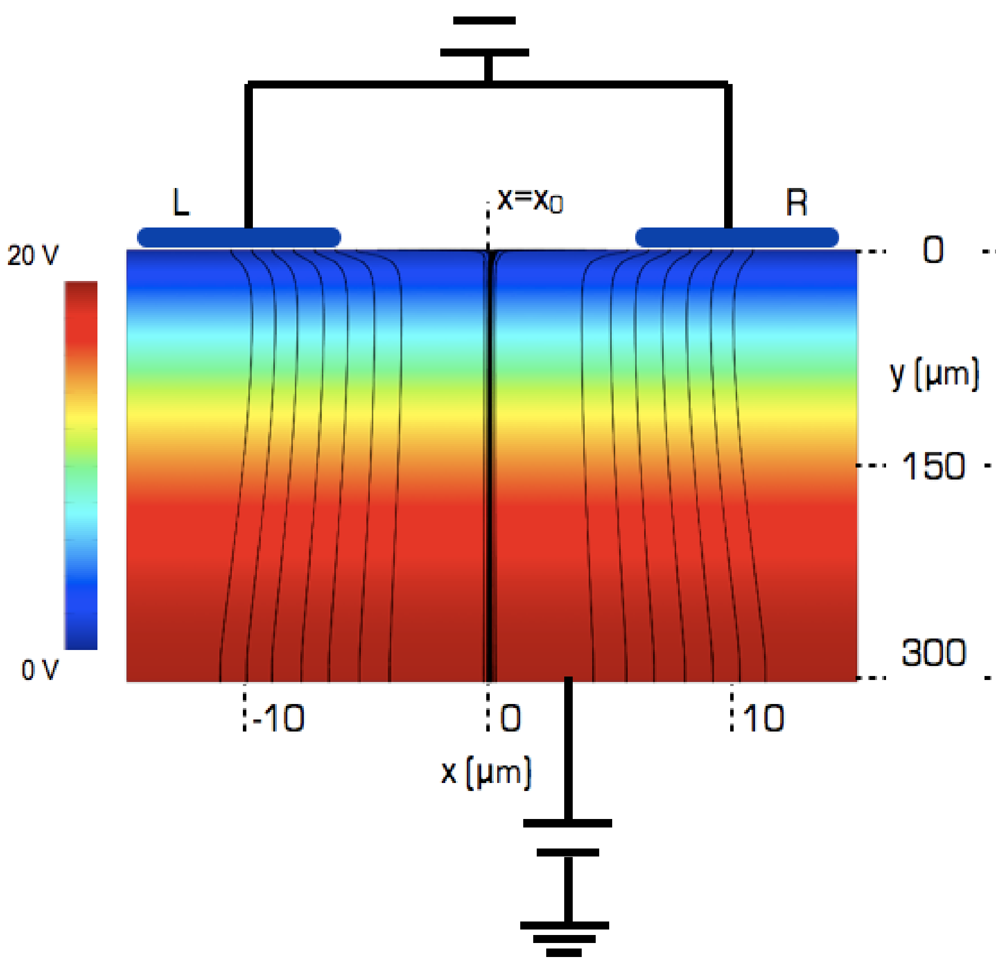
Weighting potential



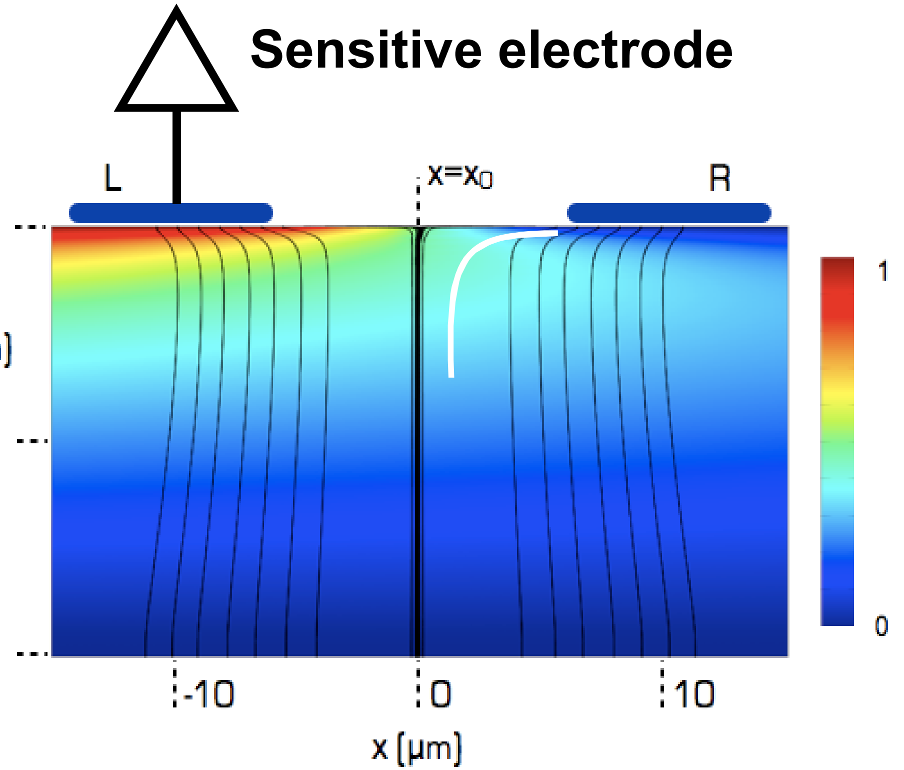
$$Q = q\cdot\left(\left.\frac{\partial\psi}{\partial V}\right|_{\substack{\text{final}\\ \text{position}}} - \left.\frac{\partial\psi}{\partial V}\right|_{\substack{\text{initial}\\ \text{position}}}\right)$$

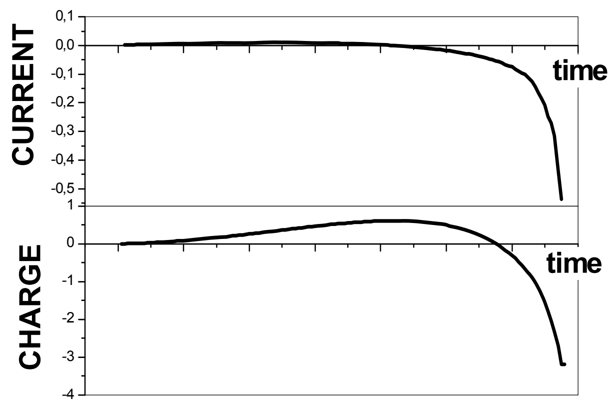


Actual potential



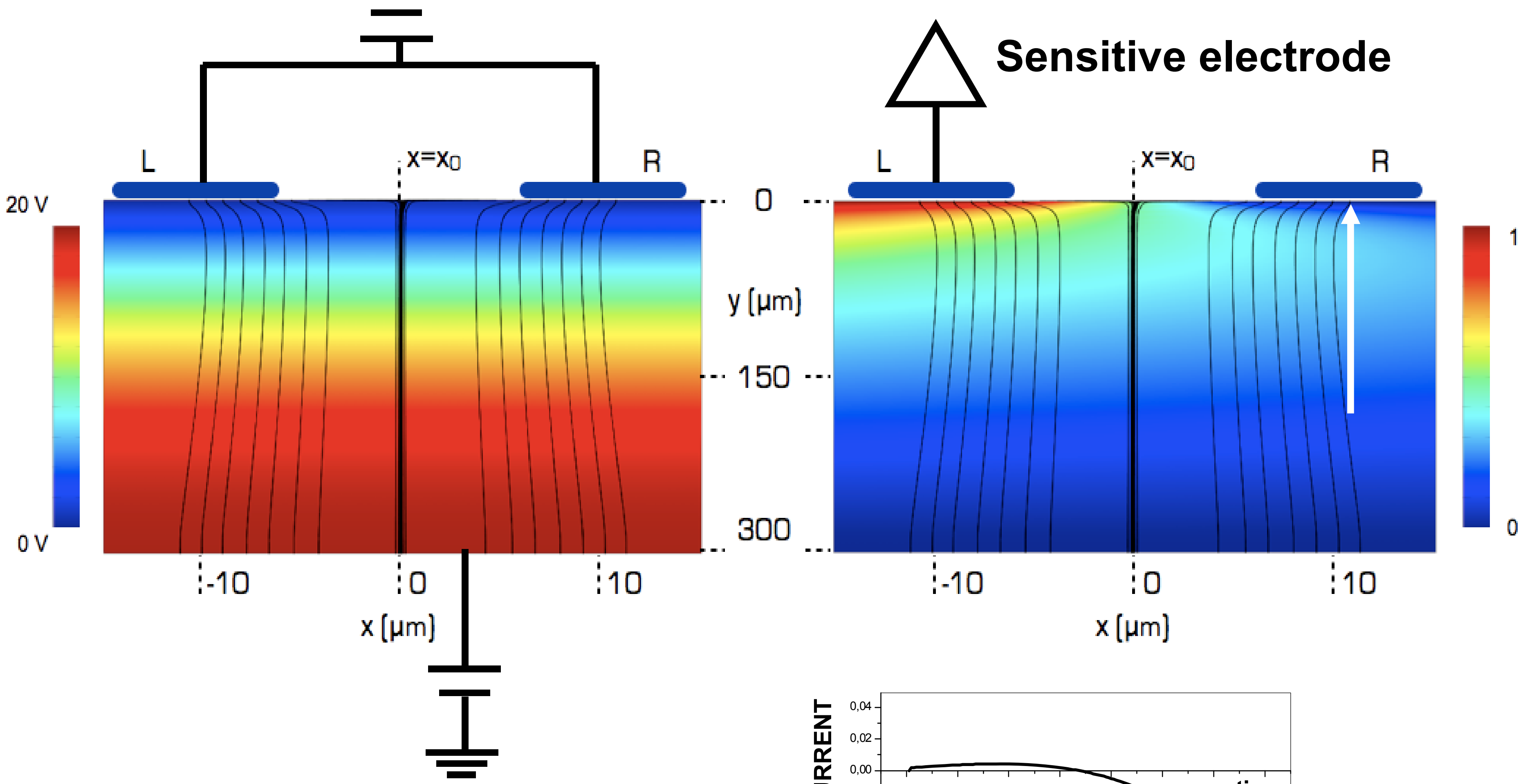
Weighting potential



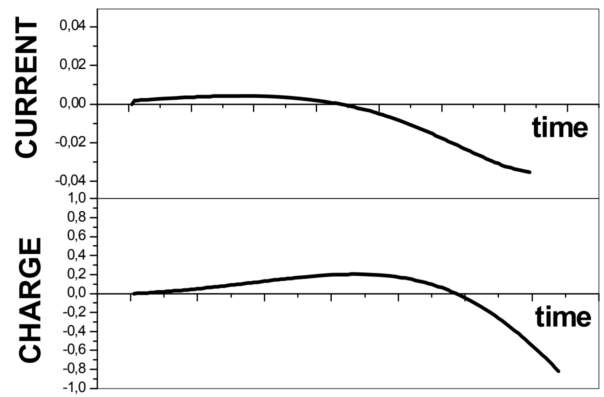


$$Q = q \cdot \left(\left. \frac{\partial \psi}{\partial V} \right|_{\substack{\text{final} \\ \text{position}}} - \left. \frac{\partial \psi}{\partial V} \right|_{\substack{\text{initial} \\ \text{position}}} \right)$$

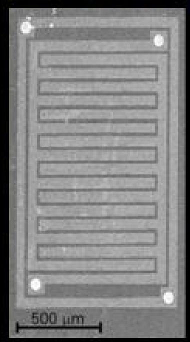
Actual potential   Weighting potential



$$Q = q \cdot \left(\left.\frac{\partial \psi}{\partial V}\right|_{\substack{\text{final}\\\text{position}}} - \left.\frac{\partial \psi}{\partial V}\right|_{\substack{\text{initial}\\\text{position}}} \right)$$

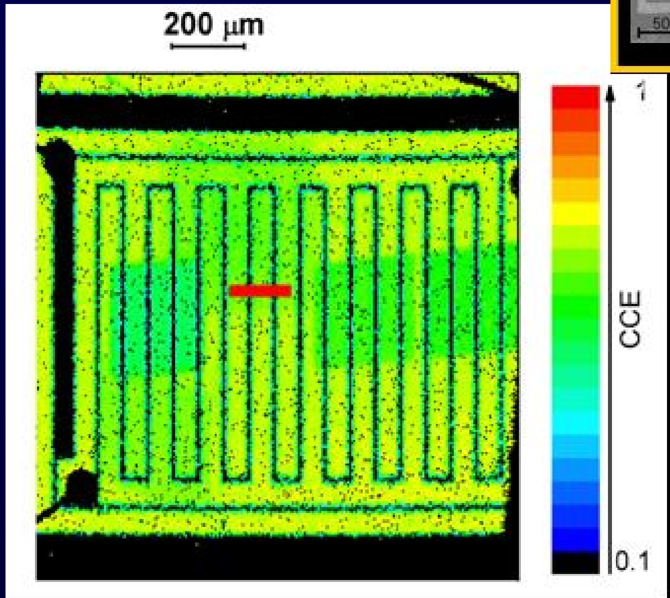


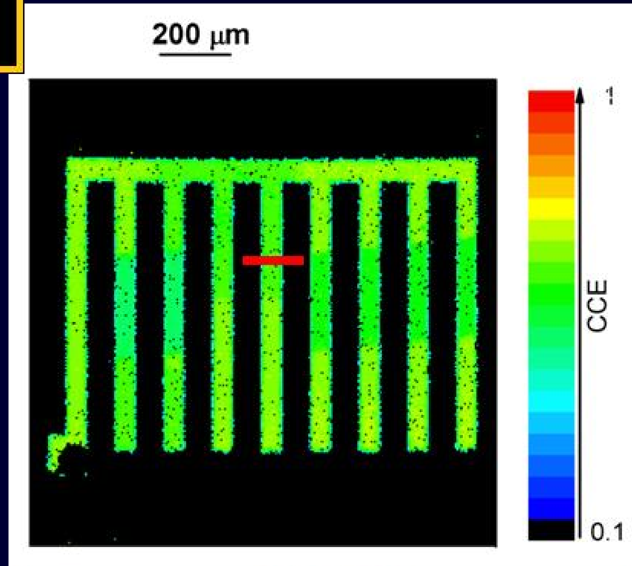
4H-SiC Schottky diode



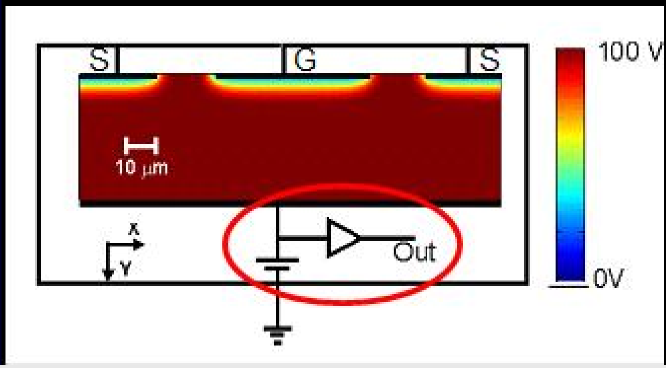
Inter-digitated frontal electrodes

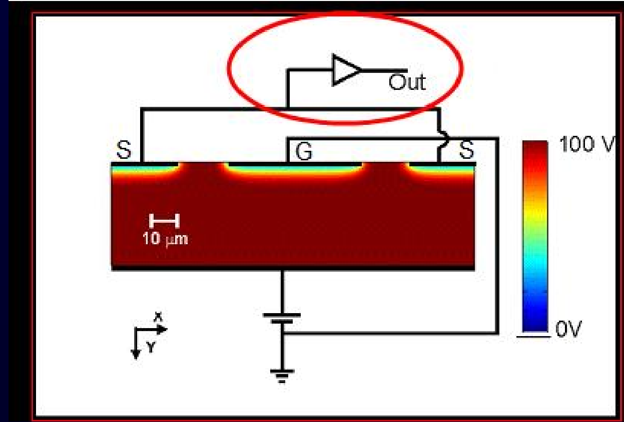
- Finger width: 50 μm
- Finger length: 700 μm
- Finger-finger gap = 20 μm;
- Finger-guard ring = 70 μm.





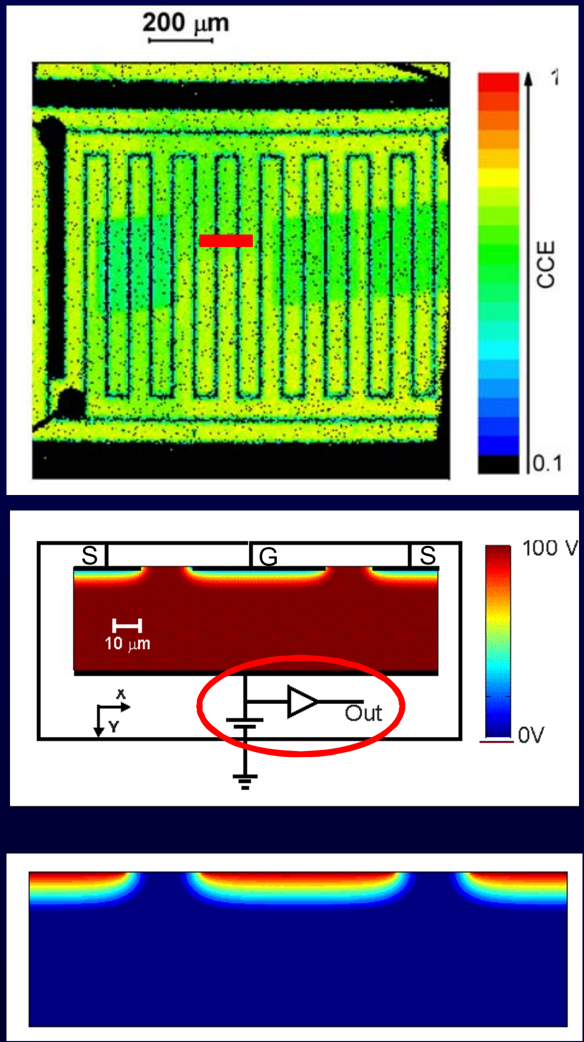
IBIC map
1.5 MeV H^+

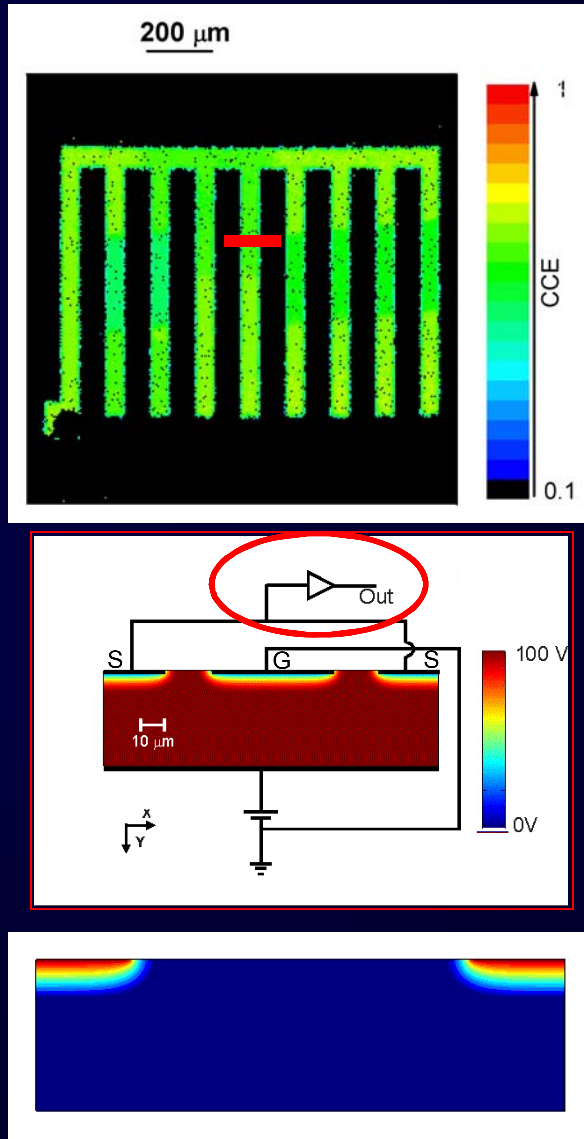




Electrostatic Potential map
V_{bias}=100V

E.Vittone et al. Nuclear Instruments and Methods in Physics Research B 266 (2008) 1312–1318.

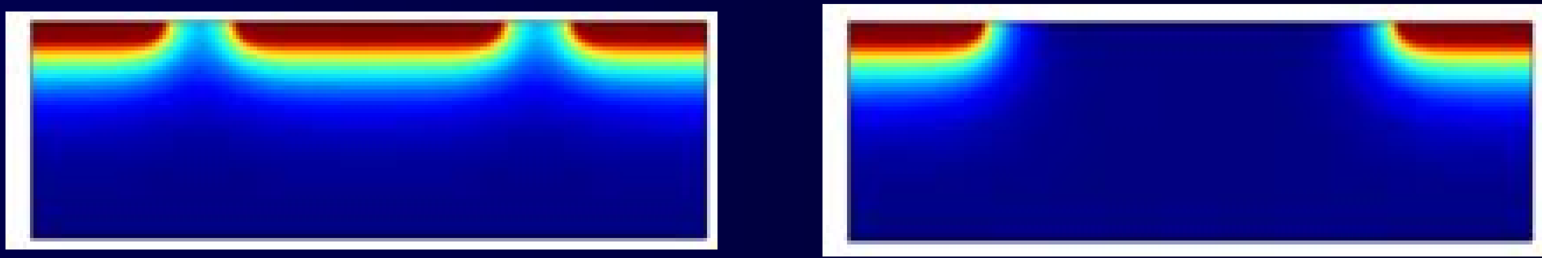




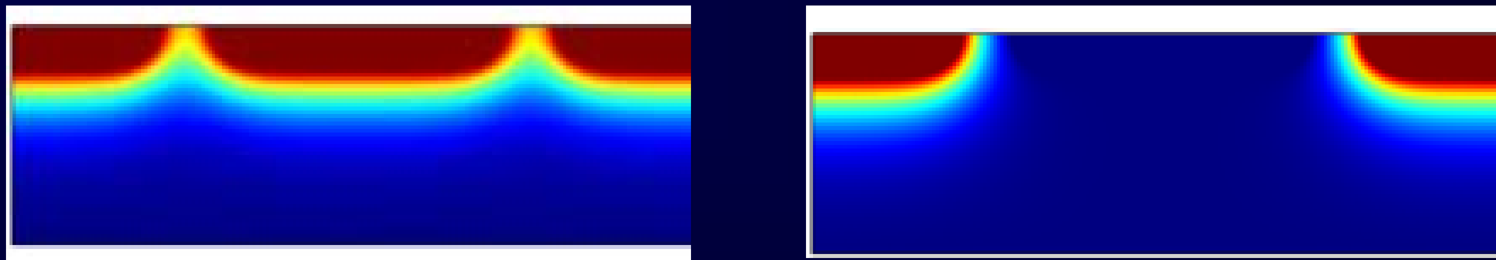
Weighting potential maps

Calculated CCE maps

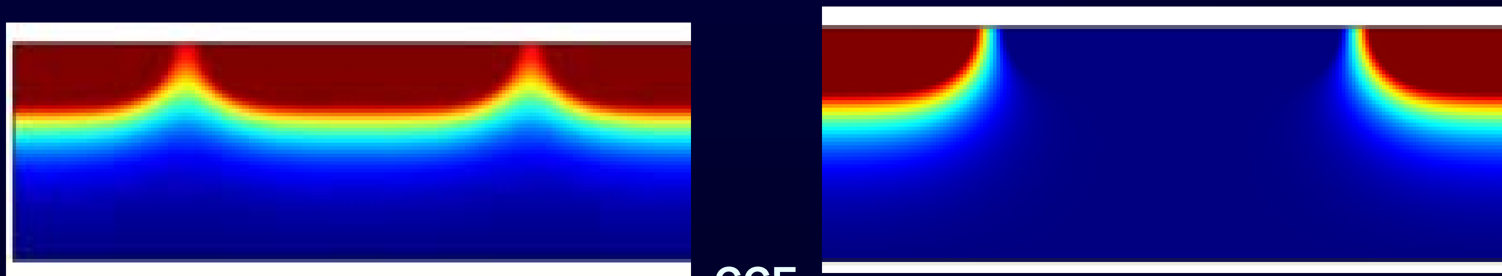
10 V



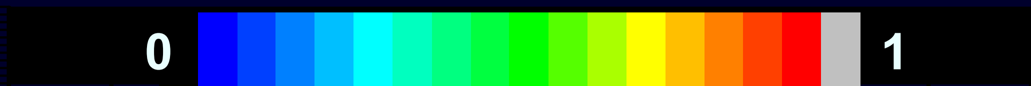
70 V



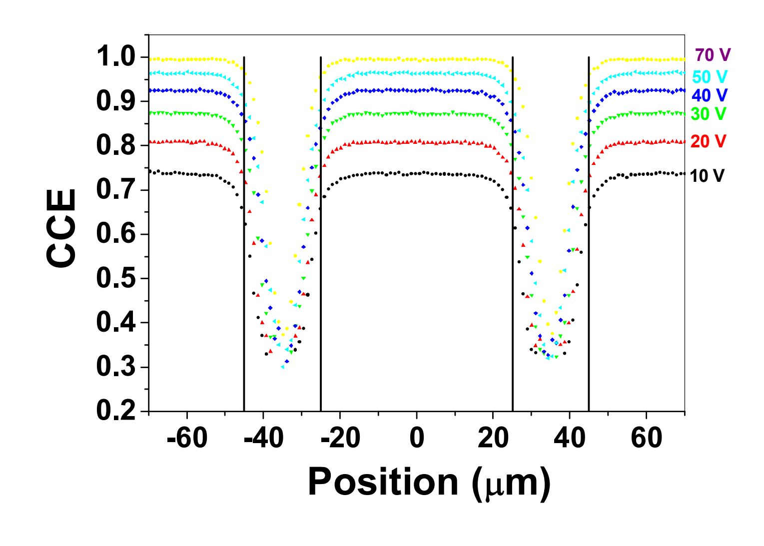
130 V

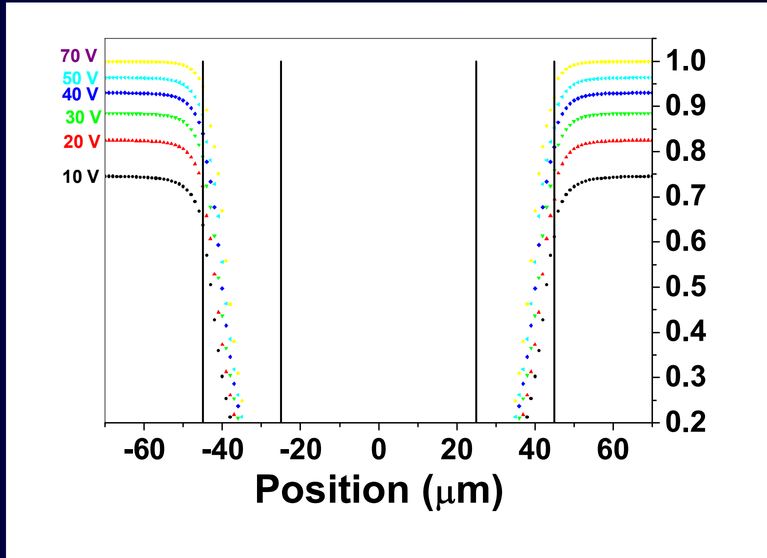


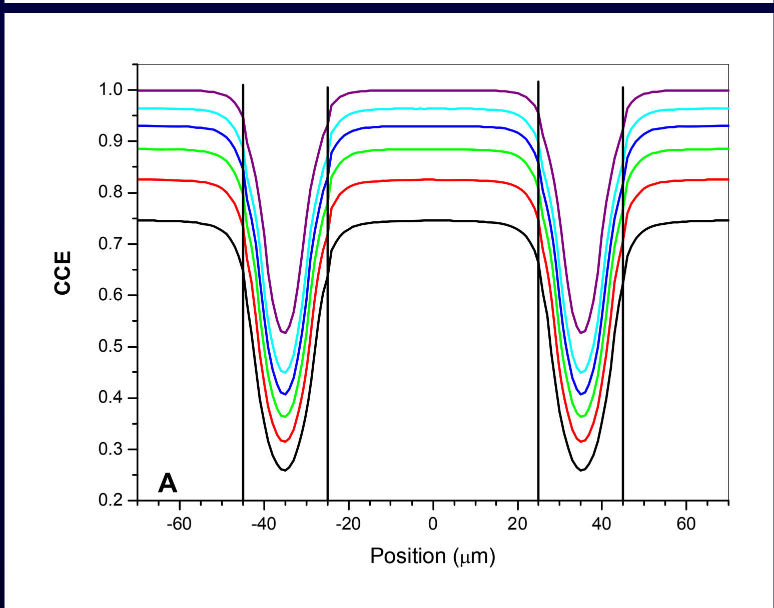
CCE

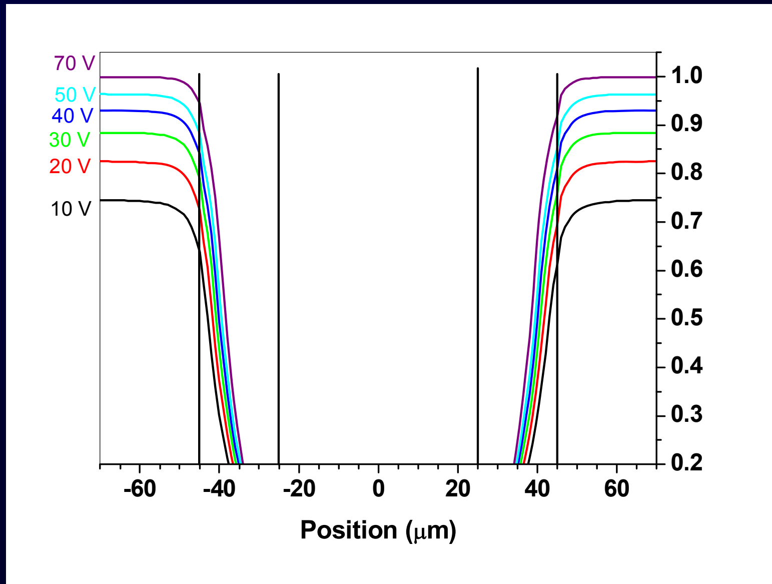


0.9 MeV protons



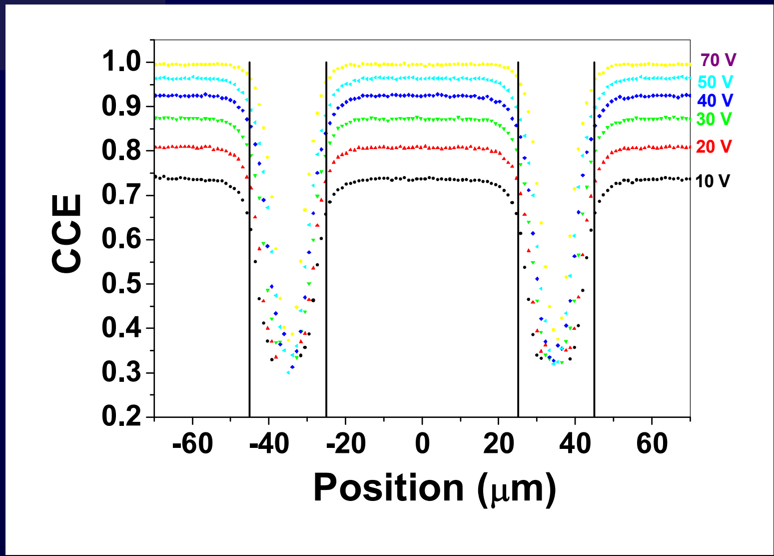


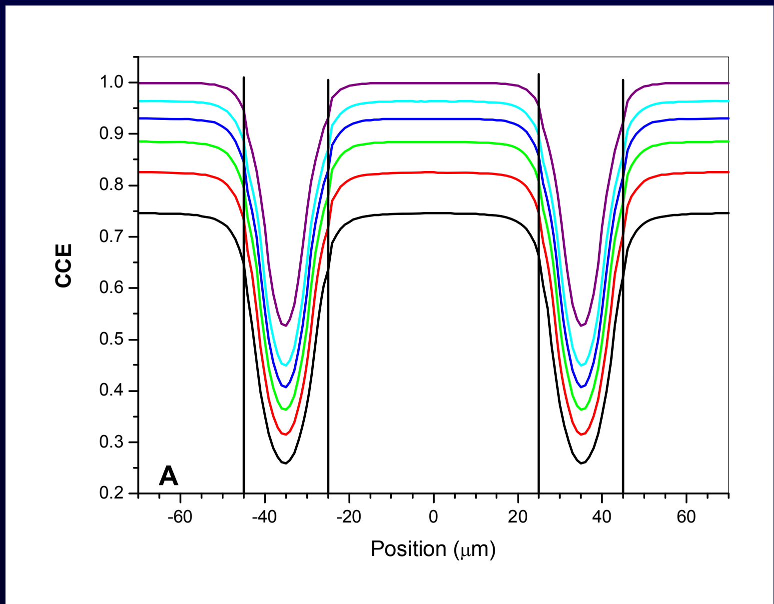


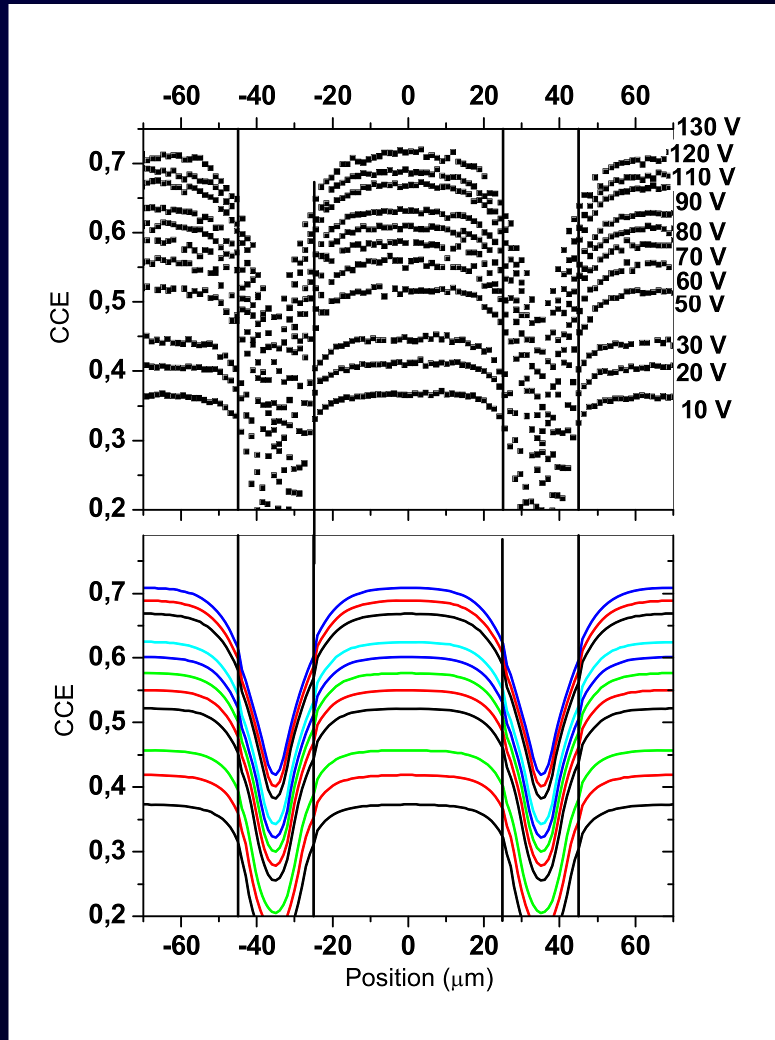


0.9 MeV protons

1.5 MeV protons

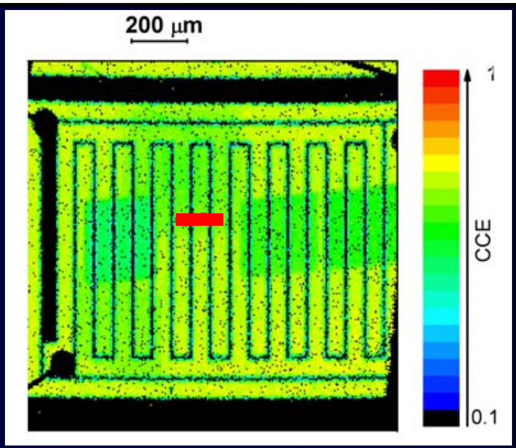


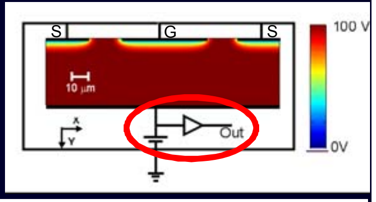


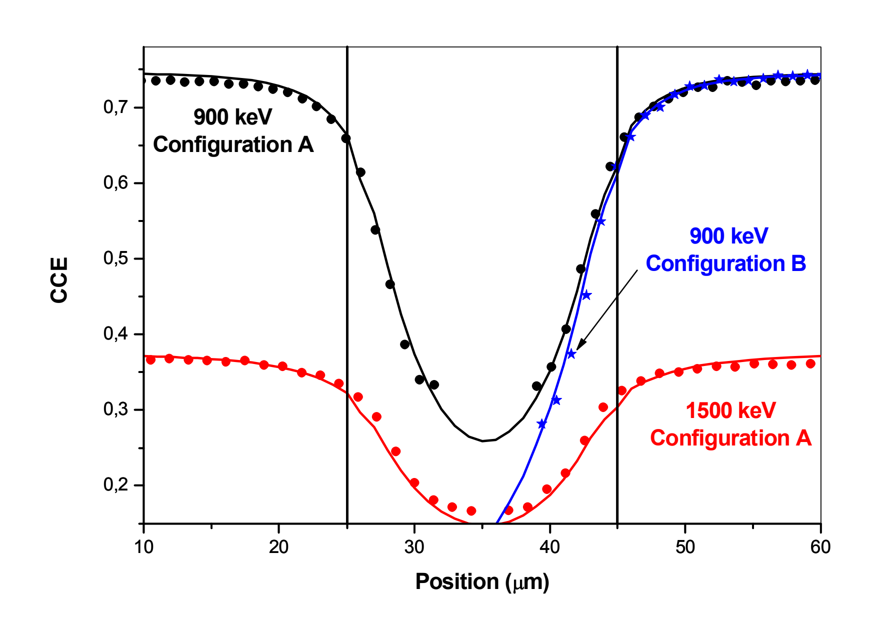


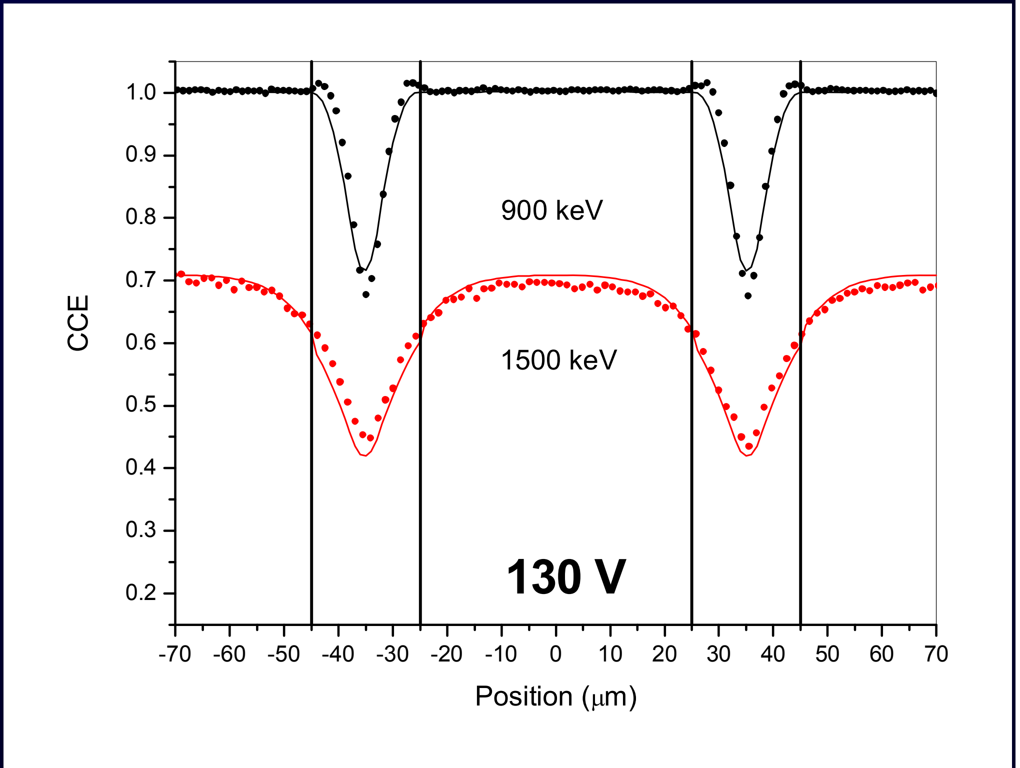
CCE profile details

hole diffusion length = 8.7 μm.
hole lifetime = τp = 250 ns





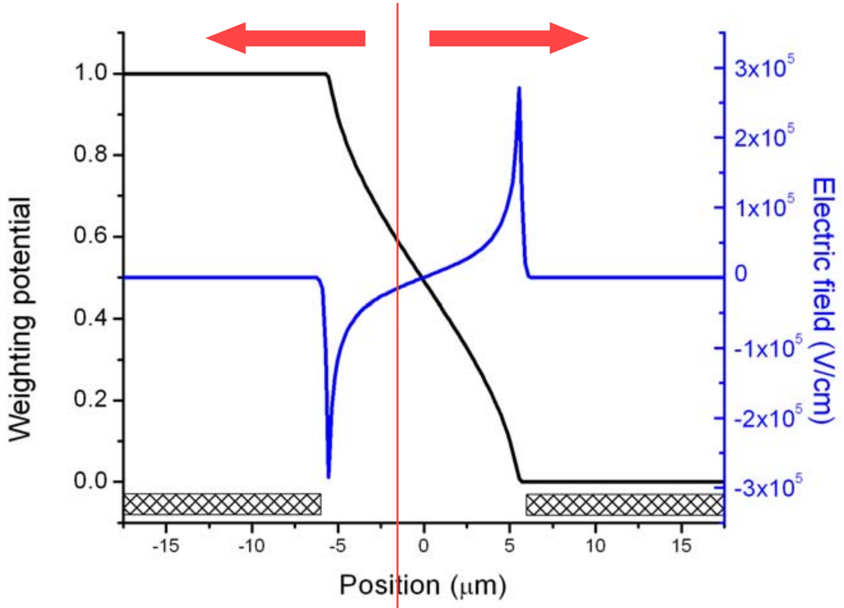




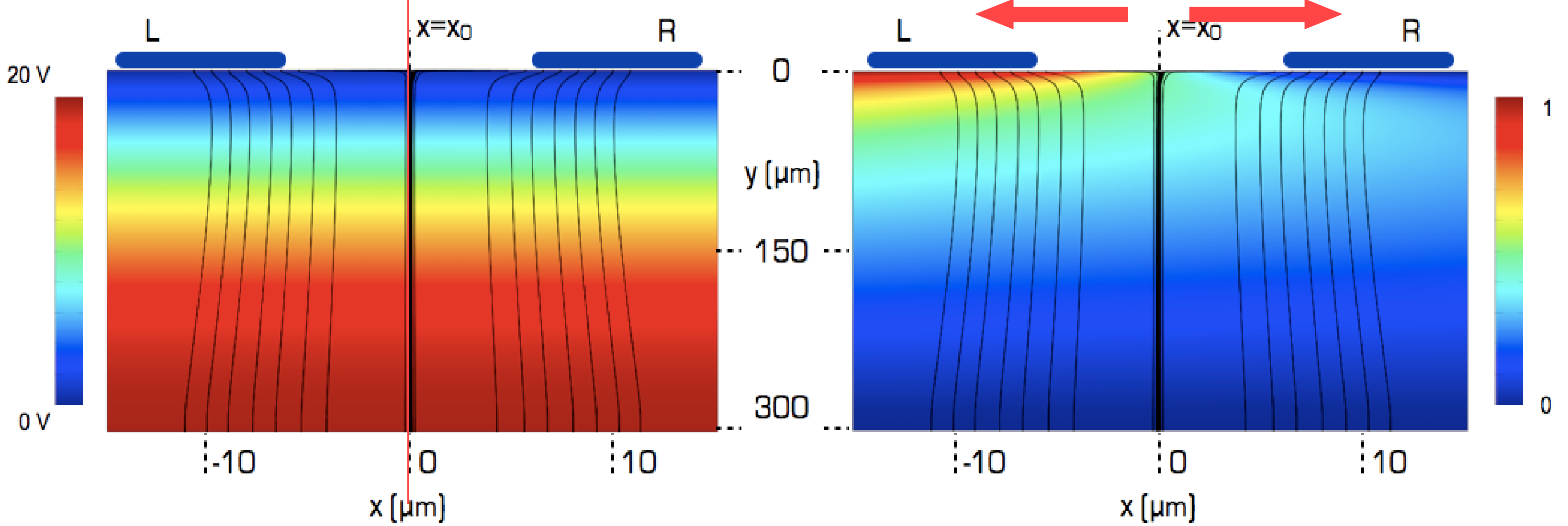
The electrode edges are highlighted by the vertical black line.

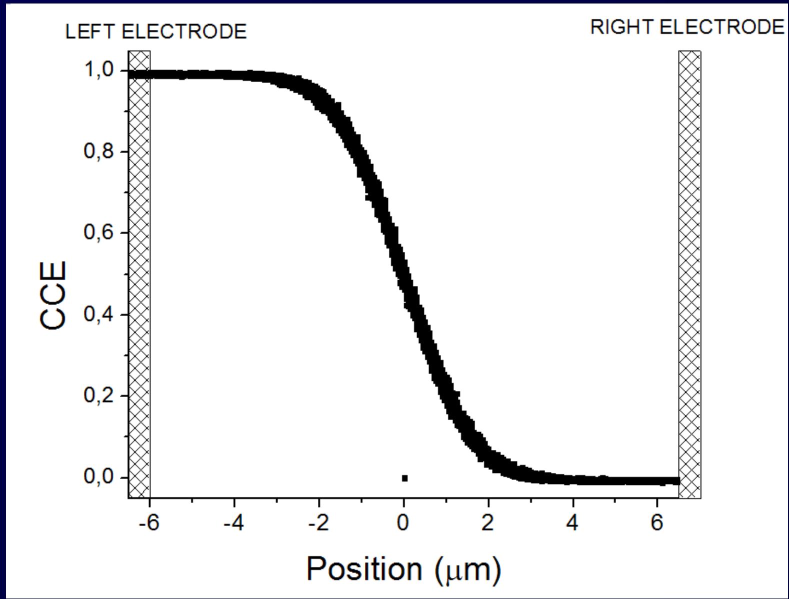
Trieste
14.08.2012

Horizontal electric field

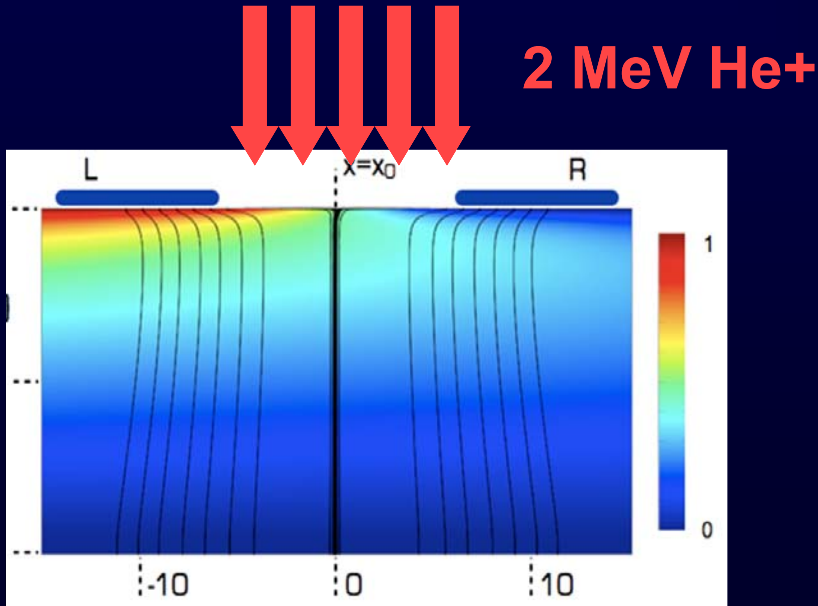


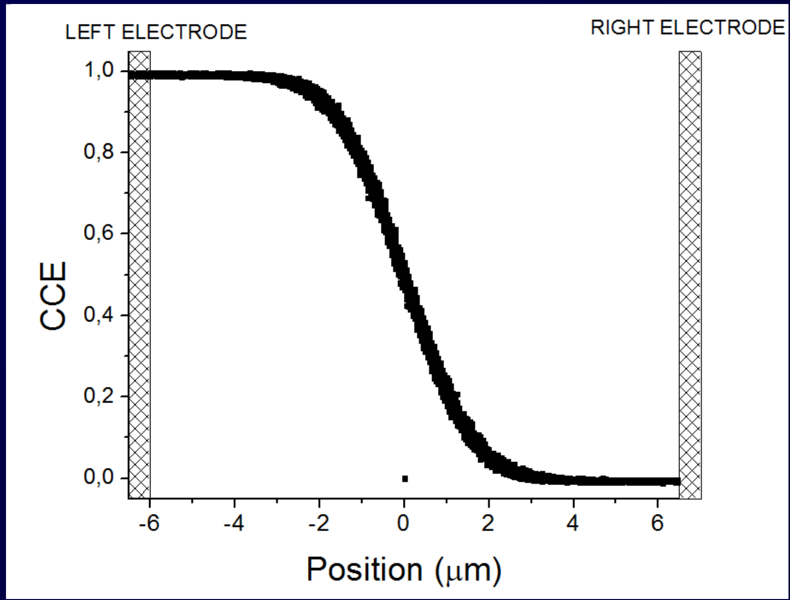
$$Q = q \cdot \left(\left.\frac{\partial \psi}{\partial V}\right|_{\substack{\text{final}\\ \text{position}}} - \left.\frac{\partial \psi}{\partial V}\right|_{\substack{\text{initial}\\ \text{position}}} \right)$$

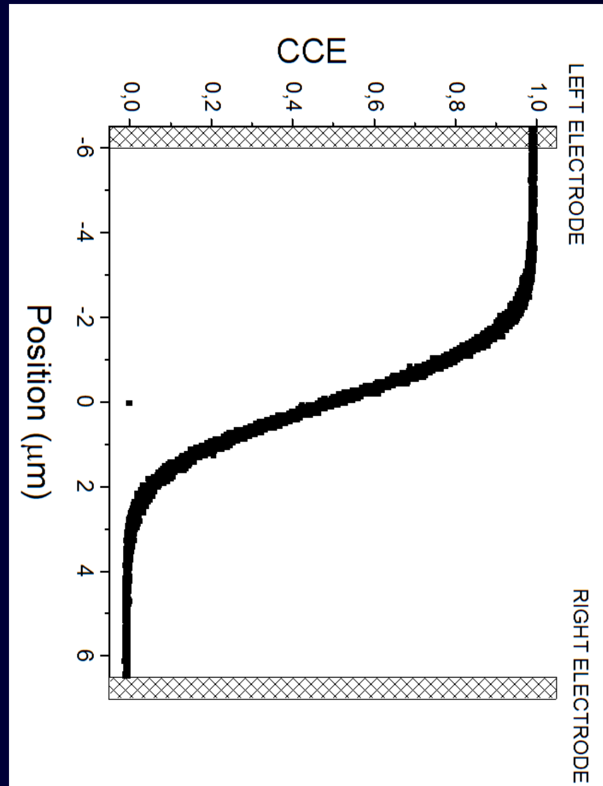




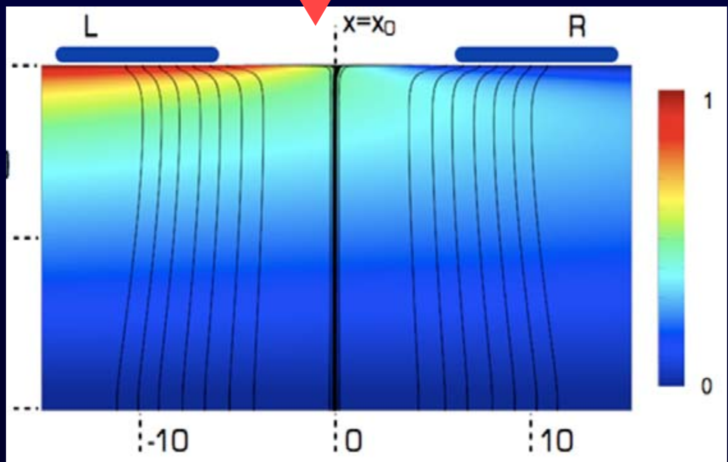
CCE AS FUNCTION OF ION STRIKE POSITION







2 MeV He+

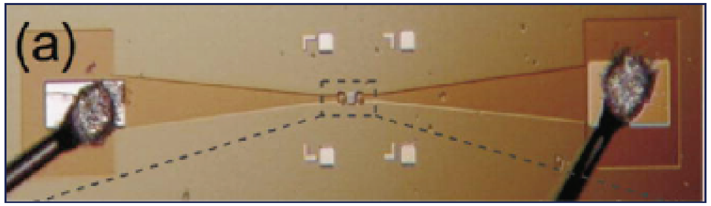


ION STRIKE POSITION AS FUNCTION OF CCE

POSITION SENSITIVE DETECTOR

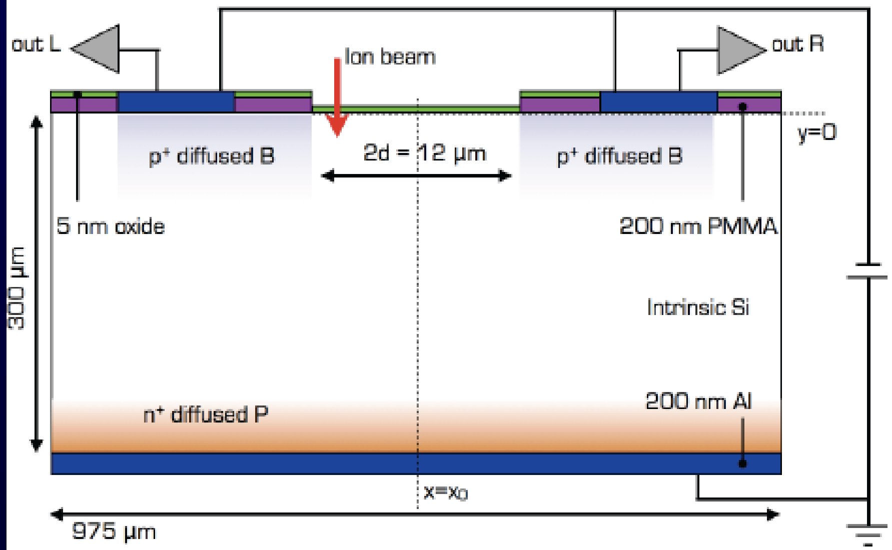
Position sensitivity - proof of concept: three-electrodes test device

L.M. Jong et al., Nuclear Instr. Meth. B 269 (2011) 2336

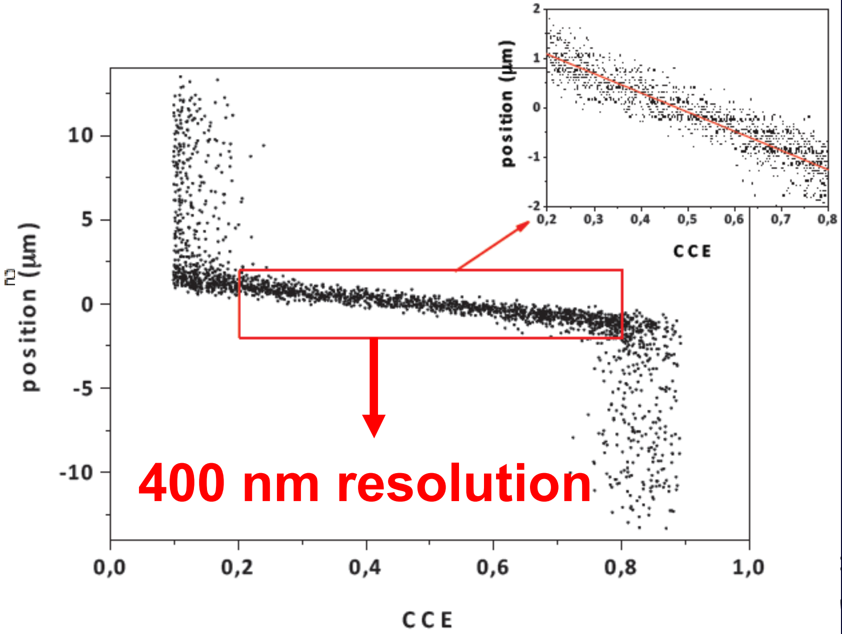


Top view

2 MeV He beam @ NEC 5U Pelletron, Melbourne
1 μm spot size



Cross sectional scheme



J. Forneris et al.
***Modeling of ion beam induced charge sharing experiments for the design of high resolution position sensitive detectors*, Submitted to NIMB**

A SUB-MICROMETER POSITION SENSITIVE DETECTOR

IBIC
(Ion Beam Induced Charge Collection)

Analytical technique suitable for the measurement of transport properties in semiconductor materials and devices

- **Control of in-depth generation profile**
- **Suitable for finished devices (bulk analysis).**
- **Micrometer resolution**
- **CCE profiles: Active layer extension; Diffusion length**
- **Robust theory; FEM and MC approaches**
- **Analysis of multi-electrode devices**
- **In-situ analysis of radiation damage**

Thanks Jacopo for the Applets

Thanks for your kind attention