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

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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:

Articles:

Links:
[http://www.dfs.unito.it/solid/RICERCA/IBA/IBA_index.html](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 their electronic properties and performances

Main physical observable: current
Current = \( F(\text{carrier density}; \text{carrier transport}) \)

Carrier generation by MeV ions
Generation profile
Recombination/trapping
Carrier lifetime \( \tau \)

Free carriers (electron/hole) transport
Two mechanisms:
Drift \( \Rightarrow \) electric field \( \mathbf{v} = \mu \cdot \mathbf{E} \)
Diffusion \( \Rightarrow \) concentration gradient
Principles of radiation detection techniques

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

Measured

Nuclear spectroscopy

Well known
IBIC principles

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

**Well known**

**Material Characterization**

**Measured**

Deposited Energy

Free charge generation and transport

Output Electrical Signal $V_{\text{out}}$
IBIC principles

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

- Measured
- Well known

Material Characterization

MeV ion energy deposition
- Electron/hole pair generation
- Charge carrier transport
- Induced Charge at the sensing electrode
- Output Signal \( V_{\text{out}} \)
Using MeV ions to probe the electronic features of semiconductors

Electrode energy loss very small (\(\approx 1\%\))

- 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

SRI M (Stopping and Range of Ion in Matter)

3 keV Photon current: \(5 \times 10^7\) photons/s

Stopping power (keV \(\mu\)m\(^{-1}\))

- IBIC

X-ray energy loss rate (keV \(\mu\)m\(^{-1}\))

- XBIC

Depth (\(\mu\)m)

\[
0 \quad 5 \quad 10 \quad 15 \quad 20 \quad 25 \quad 30
\]

\[
\begin{array}{c}
0 \\
5 \times 10^7 \\
3 \times 10^7 \\
2 \times 10^7 \\
1 \times 10^7 \\
0
\end{array}
\]

\[
\begin{array}{c}
0 \\
50 \\
100 \\
150 \\
200 \\
300
\end{array}
\]

IBIC

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IBIC principles

Incoming radiation

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

\[ Q \]

\[ V \]

MeV ion energy deposition

Electron/hole pair generation

Charge carrier transport

Induced Charge at the sensing electrode

Output Signal \( V_{out} \)

Material Characterization

Measured

Well known

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Electron/Hole pair generation

\[ N_{eh} = \frac{E_{\text{ion}}}{\varepsilon_{eh}} \]

\( \varepsilon_{eh} = \text{average energy expended by the primary ion to produce one electron/hole pair} \)

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

Incoming radiation

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

Measured

Well known

Material Characterization

MeV ion energy deposition

Electron/hole pair generation

Charge carrier transport

Induced Charge at the sensing electrode

Output Signal \( V_{\text{out}} \)
J.R. Haynes, W. Shockley,
“The mobility and life of injecting holes and electrons in germanium,
P-doped Ge;
resistivity about 15 Ω·cm;
dielectric constant =1.4pF/cm;
Dielectric relaxation time = 21 ps.
Charge neutrality maintained


IIa diamond;
resistivity about $10^{15}$ Ω·cm;
dielectric constant =0.5 pF/cm;
Dielectric relaxation time = 500 s.
Charge neutrality not maintained

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

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

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

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

- MeV ion energy deposition
- Electron/hole pair generation
- Charge carrier transport
- Induced Charge at the sensing electrode
- Output Signal $V_{\text{out}}$

Measured Well known

Material Characterization

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Physical Observable: Induced current/charge

\[ Q = q \cdot \frac{x}{d} \]
Physical Observable: Induced current/charge

\[ l(t) = q \cdot \frac{v}{d} \]

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

\[ Q(t) = \int_{0}^{T} l(t) dt \]

W. Shockley, J. Appl. Phys. 9 (1938) 635.
Charged particle in condenser

\[ Q(t) = \int_{0}^{T} l(t) \, dt \]

Electric potential

Induced charge

Electric Field

Induced current

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

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

\(\tau \approx \text{drift time}\)

\(\tau \rightarrow \infty\)
Ilα 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:  \( v = \mu E = \frac{d}{T_R} \)

Mobility:  \( \mu = \frac{d^2}{(T_R \cdot V_{Bias})} \)
The current is induced by the motion of charges in presence of an electric field.

\[ v = \mu \cdot E \]

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

**Shockley-Ramo Theorem**

**Induced current**
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

1.5 or 2.0 MeV H+

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

1.5 MeV H+ 2 MeV H+

Applied Bias Voltage (V)

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Generation of electrons and holes in the

**Depletion Region**

- **Electrons**
- **Holes**

**Neutral Region**

- **Electrons**
- **Holes**

**Complete charge collection**

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

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Frontal ion Irradiation

Contribution from the neutral region

Contribution from the depletion layer

\[ Q = Q_{\text{Depl}} + Q_{\text{Neutr}} \propto \int_{0}^{w} \left( \frac{dE}{dx} \right) \cdot dx + \int_{w}^{d} \left( \frac{dE}{dx} \right) \cdot \exp \left[ -\frac{x - W}{L_p} \right] \cdot dx \]

4H-SiC Schottky diode

Energy Loss (keV/\(\mu\)m) vs Depth (\(\mu\)m)

Applied Bias Voltage (V)

CCE

1.5 MeV

2 MeV

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Frontal ion irradiation

\[ Q = Q_{\text{Depl}} + Q_{\text{Neut}} \propto \left[ \int_{0}^{w} \left( \frac{dE}{dx} \right) \cdot dx \right] + \left[ \int_{w}^{d} \left( \frac{dE}{dx} \right) \cdot \exp \left[ -\frac{x - W}{L_p} \right] \cdot dx \right] \]

Contribution from the neutral region

Contribution from the depletion layer

4H-SiC Schottky diode

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Frontal ion irradiation

Contribution from the depletion layer

Contribution from the neutral region

\[ Q = Q_{\text{Depl}} + Q_{\text{Neutr}} \propto \left[ \int_{0}^{w} \left( \frac{dE}{dx} \right) \cdot dx \right] + \left[ \int_{w}^{d} \left( \frac{dE}{dx} \right) \cdot \exp \left[ -\frac{x - W}{L_p} \right] \cdot dx \right] \]

Frontal ion irradiation

4H-SiC Schottky diode

1.5 MeV

2 MeV

Energy Loss (keV/\(\mu\)m)

Depth (\(\mu\)m)

Applied Bias Voltage (V)

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Bragg peak
Frontal ion Irradiation

Contribution from the neutral region

Contribution from the depletion layer

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

4H-SiC Schottky diode

Energy Loss (keV/\(\mu m\))

Depth (\(\mu m\))

Applied Bias Voltage (V)

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\[ Q = Q_{\text{Depl}} + Q_{\text{Neutr}} \propto \int_{0}^{W} \left( \frac{dE}{dx} \right) \cdot dx + \int_{W}^{d} \left( \frac{dE}{dx} \right) \cdot \exp \left[ -\frac{x-W}{L_p} \right] \cdot dx \]

**Active region width**

**Contribution from the neutral region**

**Contribution from the depletion layer**

**4H-SiC Schottky diode**

Applied Bias Voltage (V)

Depletion Layer (\(\mu m\))

Bias Voltage (V)

L_p = (9.0 ± 0.3) \(\mu m\)

D_p = 3 \(\text{cm}^2/\text{s}\)

\(\tau_p = 270 \text{ ns}\)

Minority carrier diffusion length

1.5 MeV - 2 MeV

CCE

0.0 0.2 0.4 0.6 0.8 1.0

0 20 40 60 80 100 120 140

0,0 0,2 0,4 0,6 0,8 1,0

0 20 40 60 80 100 120 140

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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

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

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).

Time resolved IBIC (TRIBIC)
Silicon Power diode Mesa Rectifier

Proton beam (2-3-4 MeV) → Mesa Rectifier 168

Charge sensitive preamplifier → Shaping amplifier → ADC → IBIC

Digital oscilloscope → TRIBIC

Electrodes (Ag-Ni-Cr) → Passivation “Mesa Glass”

Ballistic deficit

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Time resolved IBIC (TRIBIC) Silicon Power diode Mesa Rectifier

lifetime

\[ \tau_0 = (5 \pm 1) \mu s \]
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.
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 *, S. Fazinic *, I. Bogdanovic *

Fig. 2. Contour plot of the spectrum reported in Fig. 1. Ion-counting contours are displayed. The region contains 128 x 128 pixels, but it has been visualized in a 64 x 64 representation.
Intra-crystalline charge transport


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Under illumination

Dark conditions

Polycrystalline CVD diamond Frontal IBIC

IBIC imaging with 2 MeV H+

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 the charge collection efficiency is always highest near to the anode.
GaAs Schottky diode
Frontal IBIC

Effects of inhomogeneous carbon doping

Poor spectral resolution

Frontal ion irradiation

Schottky electrode

50 μm thick N-type epitaxial 4H-SiC layer

Depth (μm)

Energy Loss (keV/μm)$^{-1}$

0, 0.7, 0.9, 1.1, 1.3, 1.5, 1.7

Neutral region

Diffusion transport

Incomplete collection

CCE

Surface defects

Depletion region

Fast drift transport

Complete collection

1 mm

Diffusion transport

Incomplete collection

Bulk defects

Surface defects

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°.

Polished and passivated lateral surface
Leakage current below 100 nA @ 100 V

5 MeV proton

Ion Microbeam Facility of Ruder Boskovich Institute, Zagreb (HR)
Lateral IBIC
Si p-n diode

Depletion Region

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

Bias voltage = 20.3 V

Collection efficiency

Depth (\(\mu m\))

3 MeV proton

\[ L_p = \sqrt{D_p \cdot \tau_p} \]

Minority carrier diffusion length

Pristine diode

Au doped diode

Bias voltage = 20.3 V

Bias voltage = 60.4 V

Collection efficiency

Depth (μm)

L_p = (61.4 ± 0.8) μm

L_p = (27.3 ± 0.8) μm

τ = (2.90 ± 0.08) μs

τ = (0.57 ± 0.03) μs

58.7 V

20.3 V

58.7 V

20.3 V

41.7 V

71.3 V

28 V

60.4 V

90.6 V

117.5 V

90.6 V

117.5 V

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Pulse shapes calculation

Shockley-Ramo theorem

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

Gunn’s theorem

Gunn’s theorem

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.

Weighting field

I = -q \cdot \mathbf{v} \cdot \frac{\partial E}{\partial V}
Induced current into the sensing electrode

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

Equation of motion:

\[ \mathbf{v} = \frac{\mathbf{d} \mathbf{r}}{\mathbf{d}t} \]

Weighting field

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

Weighting potential:

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

\[ Q = \int_{t_A}^{t_B} I \, dt = -q \int_{r_A}^{r_B} \mathbf{v} \cdot \mathbf{E}_w \, dt = -q \int_{r_A}^{r_B} \mathbf{E}_w \, d\mathbf{r} = q \mathbf{v} \left( \psi_w (r_B) - \psi_w (r_A) \right) = q \left( \frac{\partial \psi}{\partial V} \bigg|_{r_B} - \frac{\partial \psi}{\partial V} \bigg|_{r_A} \right) \]
\[ \psi_w = \frac{\partial \psi}{\partial V} \]

**Electrostatics**

**Electrons/holes**

**Induced charge**

Electric field

\[ Q = \pm q \]

**Transport properties**
Electric field

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

Electric field

Weighting potential

Depth

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

\[ CCE_{\text{Tot}} = \frac{\text{electrons}_{\text{collected}}}{\text{electrons}_{\text{Generated}}} + \frac{\text{holes}_{\text{collected}}}{\text{holes}_{\text{Generated}}} = \left(1 - \frac{x_0}{w}\right) + \frac{x_0}{w} = 1 \]

\[ \psi_w = \frac{\partial \psi}{\partial V} \]

Electric field
To evaluate the total induced charge

Evaluate the actual potential $\psi$ 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

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

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

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**

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

**Quasi-steady-state mode**

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

Excess charge does not significantly perturb the field within the detector

**Linearization of U**

\[
\begin{align*}
\frac{\partial n}{\partial t} &= \vec{\nabla} \cdot \vec{J}_n + G_n - \frac{n}{\tau_n} \\
\frac{\partial p}{\partial t} &= -\vec{\nabla} \cdot \vec{J}_p + G_p - \frac{p}{\tau_p} \\
\vec{\nabla} \cdot (\varepsilon \vec{\nabla} \phi) &= \rho(p,n)
\end{align*}
\]
Basic formalism

Boundary conditions

Insulator-Semiconductor interface
Rectifying contact

Semiconductor bulk
Ohmic contact

Initial conditions
For mapping charge pulses
\[ G_{n,p} = \delta(r - r_0) \cdot \delta(t) \]
\[ r_0 = \text{Generation point at } t = 0 \]

Solve the continuity equations using the potential \( \phi_0 \) defined by boundary conditions, space charge
\[
\frac{\partial n}{\partial t} = + \vec{\nabla} \cdot (- \mu_n \cdot \vec{\nabla} \phi_0 \cdot n + D_n \cdot \vec{\nabla} n) + G_n - \frac{n}{\tau_n}
\]
\[
\frac{\partial p}{\partial t} = - \vec{\nabla} \cdot (+ \mu_p \cdot \vec{\nabla} \phi_0 \cdot p - D_p \cdot \vec{\nabla} p) + G_p - \frac{p}{\tau_p}
\]

Evaluate the actual potential \( \phi \) by solving the Poisson’s equation
\[
\vec{\nabla} \cdot (\varepsilon \cdot \vec{\nabla} \phi) = \rho(p,n)
\]

Evaluate the induced charge
\[
Q(r_0, t) = - \int \varepsilon \cdot \vec{\nabla} \phi(r_0, t) \cdot d\vec{S}
\]
Evaluate the induced current
\[
l(r_0, t) = \frac{dQ(r_0, t)}{dt}
\]
Formalism based on the Gunn’s theorem

**Boundary conditions**

- Insulator-Semiconductor interface
- Rectifying contact

**Semiconductor bulk**

**Ohmic contact**

**Initial conditions**

For mapping charge pulses

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

\[ r_0 = \text{Generation point at } t = 0 \]

**Solve the continuity equations using the potential \( \phi_0 \) defined by boundary conditions, space charge**

\[
\frac{\partial n}{\partial t} = +\vec{\nabla} \cdot ( - \mu_n \cdot \vec{v}_n \cdot n + D_n \cdot \vec{\nabla} n ) + G_n - \frac{n}{\tau_n} \\
\frac{\partial p}{\partial t} = -\vec{\nabla} \cdot ( + \mu_p \cdot \vec{v}_p \cdot p - D_p \cdot \vec{\nabla} p ) + G_p - \frac{p}{\tau_p}
\]

**Evaluate the Gunn's weighted potential**

\[
\frac{\partial E}{\partial V_i}
\]

by solving the Poisson’s equation

\[ \vec{\nabla} \cdot (\varepsilon \cdot \vec{E}) = \rho \]

The potentials of all the other conductors are held constant

**Evaluate the induced charge**

\[
Q_i(t) = -q \int_0^t dt' \int_{\Omega} \left\{ n(r, t'; r_0) \cdot v_n(r) + p(r, t'; r_0) \cdot v_p(r) \right\} \frac{\partial E(r)}{\partial V_i} \bigg|_v
\]
The continuity equation involves linear operators. The charge induced from electrons can be evaluated by solving a single, time dependent adjoint equation.

\[
\frac{\partial n^+}{\partial t} = + \nabla \cdot \left( + \mu_n \cdot \nabla \phi_0 \cdot n^+ + D_n \cdot \nabla n^+ \right) + G_n^* - \frac{n^+}{\tau_n}
\]

\[
n^+ = Q_{in}
\]

\[
G_n^* = \mu_n \cdot \nabla \phi \cdot \frac{\partial E}{\partial V_i}
\]

Monte Carlo Method

Shockley-Ramo-Gunn Theory

A charge moving in a non-zero electric field induces a current to the sensitive electrode. \( \frac{\partial \psi}{\partial V} \) is the *Gunn’s weighting potential*, where \( \psi \) is the electric potential and \( V \) the bias voltage.

\[
Q = q \left[ \left| \frac{\partial \psi}{\partial V} \right|_r - \left| \frac{\partial \psi}{\partial V} \right|_l \right]
\]

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)

Lateral IBIC of a diamond Schottky diode

- Diamond Schottky diode structure:
  - homoepitaxial growth on HPHT substrates
  - (type Ib, 4x4x0.4 mm³) slightly B doped (Acceptor concentration ≈ 10¹³-10¹⁴ cm⁻³)
  - heavily B-doped buffer layer as back contact (Acceptor concentration ≈ 10¹⁸-10¹⁹ cm⁻³)
  - 25 µm thick intrinsic layer as active volume
- Schottky contact: frontal Al circular contact (Ø = 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 ± 0.04)
Series resistance: Rₛ = (5.1 ± 1.6) kΩ → back B-doped contact
Shunt resistance: Rₑₗ = (900 ± 6) GΩ
@ 50 V → I<50 pA

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

- 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: \(S = 62 \times 62\) μm\(^2\)
Plateaux: Depletion region (active region) Vs. Bias voltage

Exponential-like decay outside the highly efficient depletion region

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

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

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:

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

**CHARGE SHARING IN MULTIELECTRODE DEVICES**
\[ Q = q \left( \frac{\partial \psi}{\partial V} \bigg|_{\text{final position}} - \frac{\partial \psi}{\partial V} \bigg|_{\text{initial position}} \right) \]
Actual potential

Weighting potential

Sensitive electrode

\[ Q = q \left( \frac{\partial \psi}{\partial V} \bigg|_{\text{final position}} - \frac{\partial \psi}{\partial V} \bigg|_{\text{initial position}} \right) \]

Actual potential

Weighting potential

Sensitive electrode

\[ Q = q \left( \frac{\partial \psi}{\partial V} \bigg|_{\text{final position}} - \frac{\partial \psi}{\partial V} \bigg|_{\text{initial position}} \right) \]
\[ Q = q \left( \frac{\partial \psi}{\partial V} \bigg|_{\text{final position}} - \frac{\partial \psi}{\partial V} \bigg|_{\text{initial position}} \right) \]


\[ Q = q \cdot \left( \frac{\partial \psi}{\partial V} \right)_{\text{final position}} - \left. \frac{\partial \psi}{\partial V} \right|_{\text{initial position}} \]
**IBIC map**

1.5 MeV H⁺

**Electrostatic Potential map**

$V_{bias} = 100V$

Weighting potential maps

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Calculated CCE maps

10 V

70 V

130 V

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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.
Horizontal electric field

\[ \nabla \cdot \mathbf{E} = \frac{\partial \psi}{\partial V} \left|_{\text{final position}} \right. - \frac{\partial \psi}{\partial V} \left|_{\text{initial position}} \right. \]

\[ Q = q \cdot \left( \frac{\partial \psi}{\partial V} \right|_{\text{final position}} - \frac{\partial \psi}{\partial V} \left|_{\text{initial position}} \right. \]
CCE as Function of Ion Strike Position

2 MeV He+
A SUB-MICROMETER POSITION SENSITIVE DETECTOR

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

Trieste
14.08.2012
Joint ICTP-IAEA Workshop on Physics of Radiation Effect and its Simulation for Non-Metallic Condensed Matter

Position sensitivity - proof of concept: three-electrodes test device
L.M. Jong et al., Nuclear Instr. Meth. B 269 (2011) 2336

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

400 nm resolution
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