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Theory and applications of the Ion Beam Induced Charge (IBIC) technique

Candidate

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Jacopo Forneris

Tutor
Prof. Ettore Vittone

Coordinator
Prof. Guido Boffetta

"I may not have gone where I intended to go,
but I think I have ended up where I needed to be".

Douglas Adams
The long dark tea-time of the soul
1988

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Table of Notations

Δx	Space step on a discrete grid
Δt	Time step on a discrete grid
δn (δp)	Re-distribution of electron (hole) volume density due to charge screening within the Debye's length
ε	Dielectric constant
μ_n (μ_p)	Electron (hole) mobility
ρ_0	Volume charge density at the electrostatic equilibrium
ρ'	Probe charge density generated within the device volume
Σ_i	Surface of the *i*-th Dirichlet integration boundary
τ_n (τ_p)	Electron (hole) lifetime
ϕ_{bi}	Built-in potential
ψ_0	Electric potential at the electrostatic equilibrium
ψ	Total electric potential in presence of a volume probe charge density
ψ'	Electric potential associated with the volume probe charge density ψ-ψ_0
Ω	Device integration volume
A	Electrode's surface
$C(V)$	Voltage dependent capacitance
CCE	Charge collection efficiency
D_n (D_p)	Electron (hole) diffusivity
$d\mathbf{s}$	Integration area element on the electrodes surface
e	Absolute value of the elementary electric charge
$\mathbf{E}_0$	Electric field at the electrostatic equilibrium
$\mathbf{E}$	Total electric field in presence of a volume probe charge density
$\mathbf{E}'$	Electric potential associated with the volume probe charge density
$\mathbf{J}_0$	Electric current density at the electrostatic equilibrium
$\mathbf{J}'$	Electric current density of excess charge carriers
i_j	Current induced at the *j*-th electrode
$i_{j,G}$	Contribution of the Gunn's term to the current induced at the *j*-th electrode
$i_{j,C}$	Contribution of the coupling term to the current induced at the *j*-th electrode
L_n (L_p)	Electron (hole) diffusion length
$\mathbf{n}$	Normal vector to the integration domain's bounding surface
N_D (N_A)	Ionized donor (acceptor) volume density
n_0 (p_0)	Native volume density of free electrons (holes) at the electrostatic equilibrium
n_{init} (p_{init})	Native volume density of free electrons (holes) at the electrostatic equilibrium in an unbiased semiconductor
n' (p')	Excess electron (hole) volume density generated within the device volume
n (p)	Total (native and generated) electron (hole) volume density
n^+ (p^+)	Solution of the adjoint electron (hole) continuity equation
$P_{0,n}$ ($P_{0,p}$)	Probability for the electron (hole) to remain at the same position during the time interval Δt

$P_{\pm\mathrm{x},n}$ ($P_{\pm\mathrm{x},p}$)	Probability for the electron (hole) to move a step right/left during the time interval Δt
$P_{dec,p}(\mathbf{x})$	Probability for the electron (hole) to recombine during the time interval Δt
$\mathbf{Q}$	Total induced charge vector associated with a multi-electrode device
$\mathbf{Q}_{e,h}$	Total induced charge vector associated with electron (hole) motion a multi-electrode device
Q	Total charge stored within the device volume
$Q_{j,0}$	Charge bore by the *j*-th electrode at the electrostatic equilibrium
Q_j	Charge instantaneously bore by the *j*-th electrode
$Q_{j,G}$	Contribution of the Gunn's term to the charge instantaneously bore by the *j*-th electrode
$Q_{j,C}$	Contribution of the coupling term to the charge instantaneously bore by the *j*-th electrode
q	Point-like probe charge density generated within the device volume
q_j	Total charge induced at the *j*-th electrode by the probe charge distribution
$q_{j,G}$	Contribution of the Gunn's term to the total charge induced at the *j*-th electrode by the probe charge distribution
$q_{j,C}$	Contribution of the coupling term to the total charge induced at the *j*-th electrode by the probe charge distribution
R_{np}	Linearized Shockley-Read-Hall recombination term
s_0	Surface charge density at the Neumann boundaries of a device in electrostatic equilibrium
t	Generic time parameter
t_0	Instant of excess probe charge density generation
T	Integration time associated with the external electronic chain
V_i	Voltage applied at the *i*-th electrode
$\mathbf{v}$	Carriers drift velocity vector
w	Depletion region width
$\mathbf{x}$	Generic space coordinates vector
$\mathbf{x}_B$	Space coordinates vector at the volume boundary surface
$\mathbf{x}_I$	Space coordinates vector associated with the initial position of a point-like probe charge
$\mathbf{x}_F$	Space coordinates vector associated with the final position of a point-like probe charge
$\partial\psi_0/\partial V_j$	Weighting potential associated with the *j*-th electrode
$\partial\mathbf{E}_0/\partial V_j$	Weighting field associated with the *j*-th electrode

Preface

The Ion Beam Induced Charge (IBIC) microscopy is an analytical technique that exploits the interaction of MeV ion beams, focused down to a micrometer spot size, with matter to investigate the electronic properties of semiconductor materials and devices.

The reasons for the increasing utilization of the technique for material characterization are given by the wide availability of linear accelerator machines and by the expertise in ionizing radiation detection and signal amplification, both due to the development of nuclear physics research in the past century. On the other hand, the reliability of the IBIC microscopy lies on the existence of a solid theoretical model, allowing to extract from the experimental results almost all the parameters required for the characterization of the electrical and electronic properties of the sample under test.

In my Dissertation, the main features of the IBIC technique are investigated and discussed, together with an overview of the underlying theoretical model and the associated numerical methods for the simulation of experiments.

Theoretical and numerical predictions are tested and validated against experimental data, and are exploited both to perform a characterization of the electronic properties of materials, and to face new challenging applications in physics and technology, such as the development of innovative 2- and 3-dimensional position sensitive ionizing radiation detectors.

In **Chapter 1**, the IBIC microscopy will be introduced in its main features, through the discussion of the underlying physical phenomena, such as ion-matter interaction and charge induction mechanisms, and of the relevant applications in physics experiments and technology development.

In **Chapter 2**, a systematic analysis of the induced charge pulse formation at the electrodes of a semiconductor device is presented. The discussion will focus on charge induction theorems, on relevant application examples and on charge sharing phenomena in multi-electrode devices.

The implementation of the theoretical results for the development of suitable numerical tools to simulate the IBIC signal formation is discussed in **Chapter 3**.

The resulting model, equipped with valuable simulation techniques, will be then validated and exploited in **Chapter 4** in order to model the results of IBIC experiments, aiming at the characterization of emerging wide band-gap semiconductor materials as well as at the optimization of advanced charge sharing particle detection systems.

Finally, **Chapter 5** is devoted to the analysis and the development of novel fully ion-beam-micromachined 3-dimensional diamond particle detectors with integrated graphitic electrodes.