IBIC – ION BEAM INDUCED CHARGE
ion microprobe technique for testing diamond detectors, application examples, perspectives

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1. Facilities
2. IBIC
3. Application examples
1. RBI ACCELERATORS
1. TANDEM ACCELERATOR FACILITY

Ruđer Bošković Institute

- 1.0 MV HVE Tandetron accelerator
- 6.0 MV EN Tandem Van de Graaff accelerator

- IAEA beam line
- TOF ERDA
- PIXE/RBS
- In-air PIXE
- Dual-beam irradiation
- ION microprobe
- Nuclear reactions
- PIXE crystal spectrometer
- Ion microprobe
ION BEAM ANALYSIS

UNIQUENESS: numerous processes

- emitted particles (nuclear reactions) - NRA
- $\gamma$-rays (nuclear reactions) - PIGE
- Ion beam
- x-rays (ionization) - PIXE
- backscattered particles (elastic scattering) - RBS
- secondary electrons (ionization) - SEI
- light (ionization) - IL
- charge creation (ionization) - IBIC
- Recoil nuclei (elastic scattering) - ERDA
- Transmitted ions (energy loss) - STIM
- scattered particles (elastic scattering)

TARGET / SAMPLE

ERDA; RBS – depth profiling

2D imaging
Terminal voltages – 0.1 to 12 MV
Ion sources – sputtering, RF alphatross, duoplasmatron

**Good selection of ion ranges / dE/dx**

<table>
<thead>
<tr>
<th>Silicon</th>
<th>I 127-</th>
<th>Si 28</th>
<th>C 12</th>
<th>He 4</th>
<th>H 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range(µm) E=1 MeV</td>
<td>0.37</td>
<td>1.13</td>
<td>1.6</td>
<td>3.5</td>
<td>16.3</td>
</tr>
<tr>
<td>Range (µm) E=10 MeV</td>
<td>3.7</td>
<td>4.8</td>
<td>9.5</td>
<td>69.7</td>
<td>709</td>
</tr>
</tbody>
</table>
1. ACCELERATORS – Available ion beams
1. ACCELERATORS – heavy ion microprobe

Transmission image of 11 MeV C³⁺ through Cu grid

Typical resolution 1 um
Best resolution 0.4 um
• Maximum energy 15 MeV
  ME/q2
• Beam currents ≈ 0.1 fA
• Ion hit time can be determined
  by ~ 1 ns resolution
2. IBIC – ION BEAM INDUCED CHARGE

IBIC - single ion technique for imaging of microscopic distribution of charge transport properties!
- Imaging of grain boundaries, defects (such as dislocations), electric field (polarization),...
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CVD diamond (1997)
2. IBIC – ION BEAM INDUCED CHARGE

a) Ions lose their energy \( \frac{dE}{dx} \)
b) Creation of charge pairs \( \frac{e}{h} \)
c) Charge transport:
   • Drift - in electric field
   • Diffusion
d) Induced charge
e) IBIC signal

Incoming radiation

\[ V \]

\[ Q \]

\[ V_{\text{out}} \]
2. IBIC – ION BEAM INDUCED CHARGE

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

Induced charge \[ Q(t) = \int_0^T I(t) \, dt \]

W. Shockley, J. Appl. Phys. 9 (1938) 63
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Induced current
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W. Shockley, J. Appl. Phys. 9 (1938) 63
2. IBIC – ION BEAM INDUCED CHARGE

Induced current \( l(t) = q \cdot \frac{V}{d} \)

Induced charge \( Q(t) = \int_{0}^{T} l(t) \, dt \)

W. Shockley, J. Appl. Phys. 9 (1938) 63
2. IBIC – ION BEAM INDUCED CHARGE

Induced current \[ I(t) = q \cdot \frac{V}{d} \]

Induced charge \[ Q(t) = \int_0^T I(t) \, dt \]

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2. IBIC – ION BEAM INDUCED CHARGE

Induced current \[ I(t) = q \cdot \frac{V}{d} \]  
Induced charge \[ Q(t) = \int_{0}^{T} I(t) dt \]

2. IBIC – ION BEAM INDUCED CHARGE

τ - charge carrier lifetime

Velocity; \( v = \mu E = d/T_R \)

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

\[
Q(t) = \int_0^T I(t)dt
\]

\[
l(t) = q \cdot \frac{v}{d} \cdot \exp \left( -\frac{t}{\tau} \right)
\]
2. IBIC – ION BEAM INDUCED CHARGE

TRIBIC – time resolved IBIC (by cathode)

\[ \mu = \frac{d^2}{t_r V} \]

Electron mobility:
\[ \mu_e = 781 \text{ cm}^2/\text{Vs} \]

Dependence on electric field → electron mobility
2. IBIC – ION BEAM INDUCED CHARGE

IBIC line scan (anode to cathode) CdZnTe

For CCE=100%

\[(\mu \tau)_e = (1.4) \times 10^{-3} \text{ cm}^2/\text{V} \]
\[(\mu \tau)_h = 1 \times 10^{-5} \text{ cm}^2/\text{V} \]

Dependence on temperature
2. IBIC – ION BEAM INDUCED CHARGE

TRIBIC – time resolved IBIC

Dependence on temperature

Identification of defects
Irradiation of certain regions in test samples will increase defect concentration and decrease IBIC signal.
3. ION BEAM INDUCED DEFECTS

EVOLUTION OF DEFECT CONCENTRATION

<table>
<thead>
<tr>
<th>CdZnTe</th>
</tr>
</thead>
<tbody>
<tr>
<td>after $5 \cdot 10^9$ p/cm²</td>
</tr>
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</table>

Mobility of defects (as in CdZnTe)

Irradiated area
Recombination of defects in time

5 minutes
3. ION BEAM INDUCED DEFECTS

EVOLOYUTION OF DEFECT CONCENTRATION

Recombination of defects in time

Annealing 24 hours on 150°

Measurements of recombination lifetimes!
Si PIN diode
- irradiated by 9 fluences
- by p, He, Li, Cl of 5 um range
- tested by IBIC using protons
3. ION BEAM INDUCED DEFECTS
RADIATION HARDNESS TESTS - SILICON

Si PIN diode
- irradiated by 9 fluences
- by p, He, Li, Cl of 5 um range
- tested by IBIC using p and He

\[ \frac{Q_0}{Q} = 1 + K_{ed} \cdot \Phi \cdot NIEL_{ave} \]

<table>
<thead>
<tr>
<th>$K_{ed}$ (g/MeV)</th>
<th>H impl. Si</th>
<th>He impl. Si</th>
<th>Li impl. Si</th>
<th>Cl impl. Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>H probe</td>
<td>(4.1±0.4) • 10^{-15}</td>
<td>(8.6±0.3) • 10^{-15}</td>
<td>(7.7±0.1) • 10^{-15}</td>
<td>(1.22±0.01) • 10^{-14}</td>
</tr>
<tr>
<td>He probe</td>
<td>no data</td>
<td>(1.44±0.06) • 10^{-14}</td>
<td>(1.45±0.04) • 10^{-14}</td>
<td>(1.49±0.01) • 10^{-14}</td>
</tr>
</tbody>
</table>
Diamond detectors
1 mm², 500 um thick

Irradiation and IBIC tests by 11 MeV C ions

Si pin diode
sc CVD diamond
3. ION BEAM INDUCED DEFECTS

RADIATION HARDNESS TESTS – SC CVD DIAMOND

Diamond detectors
1 mm², 500 um thick
+/- 500 V bias

Irradiation and
IBIC tests by 8 MeV C ions
EU - FP7 NETWORK SPIRIT

Support of Public and Industrial Research using Ion beam Technology

- Transnational access
- Networking
- Joint research activities

SPIRIT Partners:
- Forschungszentrum Dresden-Rossendorf (FZD)
- CNRS –CENBG Bordeaux (CNRS)
- Katholieke Universiteit Leuven + IMEC (KUL)
- Jozef Stefan Institut Ljubljana (JSI)
- Universität der Bundeswehr München + TUM (UBW)
- CEA –JANNUS Saclay and CIMAP Caen (CEA)
- University of Surrey (SUR)
- Institute Tecnologico e Nuclear Lisboa (ITN)
- University de Pierre et Marie Curie (UPMC)
- Rudjer Boskovic Institute Zagreb (RBI)
- Swiss Federal Institute of Technology (ETHZ)
ION BEAM MODIFICATION
CONDUCTIVE LINES IN DIAMOND

Damage profile of 6 MeV C ions in diamond (SRIM simulation)

- If the diamond lattice gets damaged / distorted above a critical threshold, it converts to graphite upon thermal annealing.
- Graphite is a very different material with respect to diamond: it is soft, electrically conductive and etchable.

\[
\begin{align*}
\text{damage density threshold} & \leq 9 \times 10^{22} \text{ cm}^{-3} & \rightarrow & \text{(partial) recovery of pristine structure upon thermal annealing} \\
& > 9 \times 10^{22} \text{ cm}^{-3} & \rightarrow & \text{conversion to a graphite-like phase upon thermal annealing}
\end{align*}
\]
ION BEAM MODIFICATION
CONDUCTIVE LINES IN DIAMOND

Implantation with three-dimensional masking

- evaporation of Cr-Au adhesion layer
- deposition of semi-spherical Au contact mask
- implantation with scanning ion microbeam
- mask removal

A: Cr layer
B: Au layer
C: Au contact mask
D: scanning ion beam (6 MeV C)
E: buried graphitic channel

ION BEAM MODIFICATION
CONDUCTIVE LINES IN DIAMOND

Electrical characterisation:

\[ R = 3.5, \ 1.5 \ \text{M}\Omega \text{ channels} \]
\[ 2 \& 3 + \text{geometry} \rightarrow \rho = 0.9, \ 1.1 \ \Omega \text{ cm} \]