Progress in MAGNEX focal plane detector

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NUMEN project@LNS
Nuclear Matrix Elements of Neutrinoless Double Beta Decays by Heavy Ion Double Charge Exchange Reactions

$[T_{1/2}]^{-1} = G_{0\nu}|M_{0\nu}|^2 |f(m_i,U_{ei})|^2$

$0\nu\beta\beta$ decay rate $[T_{1/2}]^{-1}$ can be factorized as a phase-space factor $G_{0\nu}$, the nuclear matrix element (NME) $M_{0\nu}$ and a term $f(m_i,U_{ei})$ containing the masses $m_i$ and the mixing coefficients $U_{ei}$ of the neutrino species.

The DCE ($^{18}$O,$^{18}$Ne) reaction as a probe for the $\beta^+\beta^+$ transitions and the ($^{20}$Ne,$^{20}$O), or alternatively the ($^{12}$C,$^{12}$Be), for the $\beta^-\beta^-$

$^{12}$C, $^{18}$O, $^{20}$Ne to energies between 15 and 30 MeV/u

Experimental Setup:
CS beam –MAGNEX magnetic spectrometer

Major upgrade of LNS facilities
- The CS accelerator upgrades current from 100 W to 5 - 10 kW
- The MAGNEX -focal plane detector will be upgraded from 2 khz to 500 khz
Focal Plane Detector

- Gas-filled hybrid detector
  Drift chamber 1400mm x 200mm x 100mm
  Pure isobutane pressure range: 5-100mbar; 600-800 Volt, wires 20 micron

- 60 Silicon Detectors
  \[ \rightarrow E_{\text{res}} \]

- 5 Proportional Wires
  \[ \rightarrow \Delta E \]

- 4 Induction Strip
  \[ \rightarrow x_1, x_2, x_3, x_4 \]
  \[ \rightarrow x_{\text{foc}}, \theta_{\text{foc}} \]

- 4 Drift Chamber (DC)

- Ion identification

- Ray-reconstruction

- Wall Si 500 \( \mu \)m
  20 columns, 3 rows

- Stopping 7 \times 5 \text{ cm}^2
  Detectors surface covered (300 \times 21) \text{ cm}^2

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Upgrade of Focal Plane Detector

Multiwire gas tracker and $\Delta$E stage

Limited to 1-2 kHz
It is necessary change system!

Wall of 60 Silicon detectors

Double-hit probability at 500 kHz > 30%
A much higher granularity is necessary!!!

We must change detectors

From Multiwire gas tracker $\rightarrow$ to gas tracker based on micro-pattern amplifiers (no $\Delta$E)
From 7 x 5 cm$^2$ silicon Wall $\rightarrow$ to telescopes ($\Delta$E+E) wall with higher granularity and different materials

500 kHz

Radiation hardness

10$^{14}$ ions/cm$^2$ in ten years of activity

Si detector dead @ 10$^9$ implanted ions/cm$^2$
**PID requirements for NUMEN**

- 1x1 cm² ΔE-E telescope
- thickness of ΔE stage 100 μm
- thickness of E stage 500-1000 μm
- hard to the radiation damage
- good energy resolution (1-2 %)
- High stability (electric and thermal)

<table>
<thead>
<tr>
<th>Property</th>
<th>Diamond</th>
<th>GaN</th>
<th>4H SiC</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>E_g [eV]</td>
<td>5.5</td>
<td>3.39</td>
<td><strong>3.26</strong></td>
<td>1.12</td>
</tr>
<tr>
<td>E_breakdown [V/cm]</td>
<td>10⁷</td>
<td>4·10⁶</td>
<td>2.2·10⁶</td>
<td>3·10⁵</td>
</tr>
<tr>
<td>μ_e [cm²/Vs]</td>
<td>1800</td>
<td>1000</td>
<td>800</td>
<td>1450</td>
</tr>
<tr>
<td>μ_h [cm²/Vs]</td>
<td>1200</td>
<td>30</td>
<td>115</td>
<td>450</td>
</tr>
<tr>
<td>v_sat [cm/s]</td>
<td>2.2·10⁷</td>
<td>-</td>
<td>2·10⁷</td>
<td>0.8·10⁷</td>
</tr>
<tr>
<td>Z</td>
<td>6</td>
<td>31/7</td>
<td>14/6</td>
<td>14</td>
</tr>
<tr>
<td>ε_r</td>
<td>5.7</td>
<td>9.6</td>
<td>9.7</td>
<td>11.9</td>
</tr>
<tr>
<td>e-h energy [eV]</td>
<td><strong>13</strong></td>
<td>8.9</td>
<td><strong>7.6-8.4</strong></td>
<td>3.6</td>
</tr>
<tr>
<td>Density [g/cm³]</td>
<td>3.515</td>
<td>6.15</td>
<td>3.22</td>
<td>2.33</td>
</tr>
<tr>
<td>Displacem. [eV]</td>
<td>≥15</td>
<td><strong>25</strong></td>
<td>13-20</td>
<td></td>
</tr>
</tbody>
</table>

- **Wide bandgap (3.3eV)** ⇒ It has much lower leakage current than silicon
- **Signal (for MIP !):**
  - Diamond 36 e/μm
  - SiC 51 e/μm
  - Si 89 e/μm
  ⇒ It has more charge than diamond Si/SiC≈2
- **Higher displacement than threshold silicon** ⇒ radiation harder than silicon
Radiation hardness

Understanding radiation damage in solid state detectors is vital for the experiment NUMEN and future applications.

**Defects** in the semiconductor lattice create energy levels in the band gap between valence and conduction band. Depending on the position of these energy levels the following effects will occur:

- **Modification of the effective doping concentration**
  - Shift of the depletion voltage.
  - caused by shallow energy levels (close to the band edges).
- **Trapping of charge carriers**
  - reduced lifetime of charge carriers
  - Mainly caused by deep energy levels.
- **Easier thermal excitement of electron(-) and hole(+)**
  - increase of the leakage current
Displacement

The minimum energy transfer in a collision to dislocate a silicon atom is $E_{\text{min}} \approx 15$ eV (depending on the crystal orientation).

The energy at which the dislocation probability in silicon is 50% is $E_d \approx 25$ eV (displacement energy).

Below $E_d$ only lattice oscillations are exited and no damage occurs.

**POINT DEFECT.**
A vacancy-interstitial pair is called a Frenkel-defect.

**CLUSTER DEFECT**
In hard impacts the primary knock-on atom displaces additional atoms. These defects are called cluster defects.
Radiation hardness

\[ I_{\text{gen}} \propto A W N_t T^2 e^{-\frac{(E_c - E_t)}{kT}} \]

- \( A \) = detector area
- \( W \) = term related to the junction thickness
- \( N_t \) = number of traps/defect
- \( E_c \) = energy of conduction band
- \( E_t \) = energy of trapping levels

The generation current depends exponentially on the energy level \( E_t \) of the trapping level.

The levels in the mid-gap region are undesired and increase leakage current.

\( \Phi = 1 \times 10^9 - 1 \times 10^{13} \) ioni/cm\(^2\)

SiC are less sensitive to the radiation damage.
Displacementes by SRIM2013

SRIM - The stopping and range of ions in matter (2010)
Volume 268, Issues 11-12, June 2010, Pages 1818-1823
James F. Ziegler | M. D. Ziegler | J. P. Biersack

Data Analysis

Random Localization on Detector Surface
Simulation (SRIM2013) of defect formation with radiation and diffusion. The simulations show the microscopic picture of defect distribution.

About 2MeV.A O18 produce a quite homogeneous vacancy distribution, while more energetic with 60MeV.A form more cluster (circle) and discrete defects.

The plots are projections over 1\(\mu\)m of depth(z) and correspond to a fluence of 10^{14} part(MeV.A/cm^2)
Vacancies on Si & SiC

**Si 100um**

<table>
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<tr>
<th>Fluency (particle/cm²)</th>
<th>N° Vacancies</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>1.0E+00</td>
</tr>
<tr>
<td></td>
<td>1.0E+01</td>
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<tr>
<td></td>
<td>1.0E+02</td>
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<tr>
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<tr>
<td></td>
<td>1.0E+07</td>
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<tr>
<td></td>
<td>1.0E+08</td>
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</table>

**SiC 100um**

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<th>N° Vacancies</th>
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<tbody>
<tr>
<td></td>
<td>1.0E+00</td>
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<tr>
<td></td>
<td>1.0E+01</td>
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<tr>
<td></td>
<td>1.0E+02</td>
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<tr>
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<tr>
<td></td>
<td>1.0E+07</td>
</tr>
<tr>
<td></td>
<td>1.0E+08</td>
</tr>
</tbody>
</table>

- O+Si
- p+Si
- O+SiC
- p+SiC
Two SiC were irradiated using $^{16}$O ions at 35.2 MeV. The ratio between the peak centroid of the $^{16}$O energy spectrum after the irradiation over the same peak centroid before the irradiation & fluence. It is evident that, by increasing the fluence, the energy peak, for both SiC moves toward lower channels, indicating an increasing incompleteness in the charge collection.

De Napoli et al., NIM in Physics Research A 600 (2009) 618–623
Raciti et al. Nuclear Physics A 834 (2010) 784c–787c
SiC detector construction: state of art

The Schottky diodes are fabricated on epitaxial layer grown onto high-purity 4H–SiC n-type substrate.

Detector \( \Delta E \)
oxidation and metallization front

Detector \( E \)
epitaxy of anode and cathode on intrinsic semi-insulating substrate

NEW

100\( \mu \)m

100-1000\( \mu \)m

LASER ABLATION

reduction thickness and metallization back
Detector telescope SiC with Geant4 simulation
Collaboration

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