Direct Conversion of D-³He Protons Using a Silicon PIN Junction Diode

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Project Goals

• Proof of principle for using a solid state device as a means to convert D-³He fusion protons to electric power

• Measure the efficiency of such a device and compare with theoretical predictions

• Characterize the damage induced in such a device under proton fluxes similar to those in a power reactor.
Direct Conversion Theory

- Semiconductor devices have an inherent voltage drop due to p-type and n-type dopant. Charge carriers (e⁻ / holes[⁺]) induced in the semiconductor will move in response to an electric field.

Inherent Voltage drop creates a built-in electric field which creates an electric current from any charge carriers created from incoming radiation.
Direct Conversion Theory Continued

Pre-proton impact

- P-positive dopant (boron)
- I-intrinsic (pure) silicon
- N-negative dopant (phosphorus)

14.7 MeV proton impact

- Electronic Stopping of the proton causes formation of e-/hole pairs in Silicon

Post proton impact

- Either the inherent voltage across the PIN junction or an applied voltage will cause the electrons and holes to move, inducing a current
Efficiency of Direct Conversion

- The following defines the expected efficiency of the PIN diode energy conversion scheme.
- \( V_{\text{diode}} \) = Effective voltage drop of diode (max @ inherent voltage [\( \sim 1V \) in Si])
  - Typically \( V_{\text{diode}} \sim 0.7V_{\text{inherent}} \)
  - Dopant concentration has a significant effect on \( V_{\text{inherent}} \)
- \( \gamma \equiv \) proton flux (protons/cm\(^2\)s)
- \( E_{\text{pair}} \equiv \) Energy required to create \( e^-/\text{hole} \) pair in Si (3.62eV – Knoll [Table 11.1])
- \( E_p \equiv \) Energy of incident proton
- The following calculation is with Si:

\[
P_{\text{in}} = \gamma eE_p \text{ (eV)}
\]

\[
P_{\text{out}} = V_{\text{diode}} \text{ (Volts)} \frac{\gamma eE_p \text{ (eV)}}{E_{\text{pair}} \text{ (eV)}}
\]

\[
\eta = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{V_{\text{diode}}}{E_{\text{pair}}} \approx \frac{0.7 \text{ (Volts)}}{3.62 \text{ (Volts)}} = 19\%
\]

<table>
<thead>
<tr>
<th>Material</th>
<th>Si</th>
<th>Ge</th>
<th>GaAs</th>
<th>SiC</th>
<th>Diamond</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{\text{inherent}} ) (V)</td>
<td>1.1</td>
<td>0.7</td>
<td>1.4</td>
<td>2.4</td>
<td>5.5</td>
</tr>
<tr>
<td>( E_{\text{pair}} ) (eV)</td>
<td>3.6</td>
<td>3.0</td>
<td>4.7</td>
<td>8.8</td>
<td>16.5</td>
</tr>
<tr>
<td>( V_{\text{diode}} ) (V)</td>
<td>0.7</td>
<td>0.4</td>
<td>0.9</td>
<td>1.5</td>
<td>3.5</td>
</tr>
</tbody>
</table>
Direct Conversion Efficiency Depends on “Inherent Voltage Drop” and e⁻/hole Pair Creation Energy

Theoretical Efficiencies for solid state devices range from ~10% - 25% over a range dopant concentrations.
Configuration of UW-IEC D-^{3}He Proton Direct Conversion Experiment

- Current PIN junction configuration
  - 300um Pb shield (X-Ray shielding)
  - 500um Si PIN junction diode (to limit damage at end of trajectory)
- This utilizes about 6MeV of 14.7MeV available in the D-3He proton.
- PIN diode face is 10cm\(^2\) \(\longrightarrow\) \(\sim\)1nA of current with IEC proton rates of 1x10\(^7\)
Configuration of UW-IEC D-³He Proton Direct Conversion Experiment
PROBLEM: Charge Carrier Lifetime can Limit the Usefulness of 500 μm Thick PIN Junction Design

- Typical lifetimes of e-/hole in Si is ~10-100 μs.
- V_{inherent} = 1V \rightarrow \text{E-field} = 2000V/cm (in a 500 μm thick PIN junction)
- In a 2000V/cm E-field a charge carrier spends ~10-20 μs in the junction. (Recombination is possible)

Solution:
By layering smaller junctions in series or in parallel this problem can be avoided.
Conversion Efficiency and Proton Damage Effects will be Measured

• Once principle has been proven on IEC device a 3MeV linear accelerator will be used for:
  – Measuring the efficiency of PIN junction technique
  – Examining the effect of radiation damage on conversion efficiency and device performance.
Summary

- The theoretical efficiency of a PIN junction direction energy conversion device has been calculated to be ~20%.
- An experiment is in progress at the University of Wisconsin to prove the principle of using a PIN junction to convert D-^3^He protons to electric power.
- Future experiments are planned to measure the efficiency of a PIN junction converter and analyze the degradation of device performance due to radiation damage from protons.
Future Work

- Efficiency and radiation damage measurements on accelerator have yet to be done.
- Multi-junction design would be more useful for power conversion applications. This design is more expensive to fabricate but should eventually be tested.
How a Diode Works

• Proton Detectors operate in reverse bias mode

• Direct Conversion depends on inherent voltage drop with 0V applied.

When we bring P-type & N-type together a depletion zone is created around the junction. This produces a barrier, blocking charge flow.

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Theoretical Power Conversion Efficiency is Affected by Real Diode Characteristics

Real PIN Diode Characteristics

Ideal PIN Diode Characteristics

\[ P_{\text{real}} \approx 0.7P_{\text{ideal}} \]