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Using a single junction PIN (p-type, intrinsic, n-type) diode made of silicon and doped with boron and phosphorus high energy protons have been converted to electricity, through ionization from electronic stopping in the silicon, at an efficiency of 0.2%. A simulation of 3.02 MeV D-D protons has been performed using a 3 MeV linear accelerator. Proton fluxes of ~3x10^{10} *protons·cm*$^{-2}$*s*$^{-1}$ *were incident on a PIN diode with 0.7 cm*^{2} *of surface area facing the incident protons. Losses in efficiency as a function of proton fluence are compared with dpa (displacements per atom) rates calculated using the Monte Carlo ion transport code TRIM (Transport and Ranges of Ions in Matter).*

I. INTRODUCTION

The purpose of this work is to examine the viability of using semiconductors to convert the kinetic energy of high-energy protons from advanced fuel cycle fusion reactions to electricity. The D-D and D-^{3}He fusion reactions both produce high-energy protons of 3.02 MeV and 14.7 MeV respectively. It is possible to convert these high-energy protons directly into electricity by allowing them to impact a PIN junction diode. The PIN junction diodes are characterized by a large intrinsic region between heavily doped P-type and N-type regions. This provides a large active region for electron-hole pair creation while minimizing the heavily doped regions where charge carrier recombination is more likely. As electronic stopping slows down the protons, they create electron-hole pairs along their trajectory. This process creates a usable voltage and current in a similar manner to photons inducing a voltage and current in a photovoltaic device.

As protons slow down in the semiconductor material, some will undergo scattering collisions with silicon atoms occupying lattice sites. These collisions produce vacancies and interstitials that form recombination centers for charge carriers produced in the PIN junction by locally changing the band structure of the semiconductor material. An important aspect of the viability of solid-state direct conversion technology involves determining how this damage affects the performance of the direct conversion device.

II. THEORY

Below is a theoretical treatment of how an ideal diode acts to convert particle kinetic energy to electricity under a flux of high-energy charged particles. The current in the form of charge carriers generated in the PIN junction is given by:

$$I_{gen} = \frac{A\gamma\, eE_p}{E_{pair}} \qquad (1)$$

where A is the surface area of the junction, γ is the proton flux in (protons·cm^{-2}s^{-1}), E_{pair} is the energy required to create an e^-/hole pair (3.62 eV in Si), and E_p is the energy of an incident proton.

In addition to the current generated by proton irradiation there is also a *dark current* present at all times in the PIN junction that is related to thermal excitation of charge carriers in the diode. The *ideal diode equation* defines the dark current in the PIN junction as follows:

$$I_{dark} = I_s\left[\exp\left(\frac{V}{V_{th}}\right) - 1\right] \qquad (2)$$

Here V_{th} is defined as the thermal voltage (0.025eV at 300 K ambient temperature) and I_s is defined as the saturation current [1]. The saturation is given below.

$$I_s = \frac{AeL}{\tau}\frac{n_0^2}{n_{maj}}\exp\left({-E_g}/{V_{th}}\right) \qquad (3)$$

Here n_{maj} represents the number of majority carriers present in the intrinsic region of the PIN diode. A is the surface area of the PIN diode. L is the charge carrier diffusion length, which is defined in terms of the diffusion coefficient of charge carriers in the semiconductor material. The quantity τ represents the average carrier lifetimes of the electrons and holes in the semiconductor material. These values were both assumed to be ~1x10^{-4}s in the intrinsic region [2]. The quantity n_0 is given by the following expression [3, 4].

$$n_0 = 2.546 \times 10^{19} \left(\frac{m_{de} m_{dh}}{m_0^2} \right)^{3/4} \left(\frac{T}{300K} \right)^{3/2} \quad (4)$$

Where m_{de} and m_{dh} represent the density of states values for electron and hole effective mass, and m_0 is the electron mass.

The total current produced in the PIN junction diode is the difference between I_{gen} and I_{dark}

$$I_{out} = I_{gen} - I_{dark} = \frac{\gamma e E_p}{E_{pair}} - I_s \left[\exp\left(\frac{V}{V_{th}} \right) - 1 \right] \quad (5)$$

With the I_{out} set to zero an expression for the open circuit voltage, V_{OC},, can be obtained. Similarly the short circuit current, I_{sc}, can be obtained by assuming zero voltage drop across the PIN diode. These two expressions are detailed below:

$$V_{OC} = V_{th} \ln\left(\frac{\gamma e E_p}{E_{pair} I_s} + 1 \right) \quad (6)$$

$$I_{sc} = I_{gen} + I_s \approx I_{gen} \quad (7)$$

The I_{sc} in most cases can be considered equal to I_{gen} since the saturation current is usually very small when compared to the current generated by irradiation. Also note that V_{OC} is dependent on I_s where smaller I_s values lead to larger relative open-circuit voltages for a given semiconductor material. This is significant because wide bandgap semiconductors have vanishingly small saturation currents that lead to higher relative values of V_{OC} for wide bandgap materials. This implies that wide band-gap materials will be inherently more efficient at converting energy from high-energy charged particles to electricity than narrow band-gap semiconductors.

For the case of the idealized PIN diode, where the device is considered to be a perfect rectifier, the power output from the device can be expressed as the product of the short-circuit current and the open circuit voltage. Obviously, no diode behaves as a perfect rectifier. To account for the leakage currents and contact resistances inherent in real devices a form factor, denoted *FF*, is introduced to account for the non-idealities of experimental diodes. The ratio of the maximum power output of a real diode to the product of V_{OC} and I_{sc} is the form factor. Thus the efficiency of a radiation cell can be defined as follows:

$$\eta = \frac{I_{sc} V_{OC} FF}{P_{in}} = \frac{V_{OC} I_{sc} FF}{\gamma e E_p} \quad (8)$$

It is not the case that the E_{pair} is the same as the band-gap energy of the semiconductor material, E_g. From work done by Klein [5] we find that the following expression relates the E_g to E_{pair}.

$$E_{pair} = 2.8 E_g + \varepsilon \quad (9)$$
$$(0.5eV \le \varepsilon \le 1.0eV)$$

This expression is supported by the data shown in Figure 1 that illustrates the relation between E_g and E_{pair} shown in equation 9.

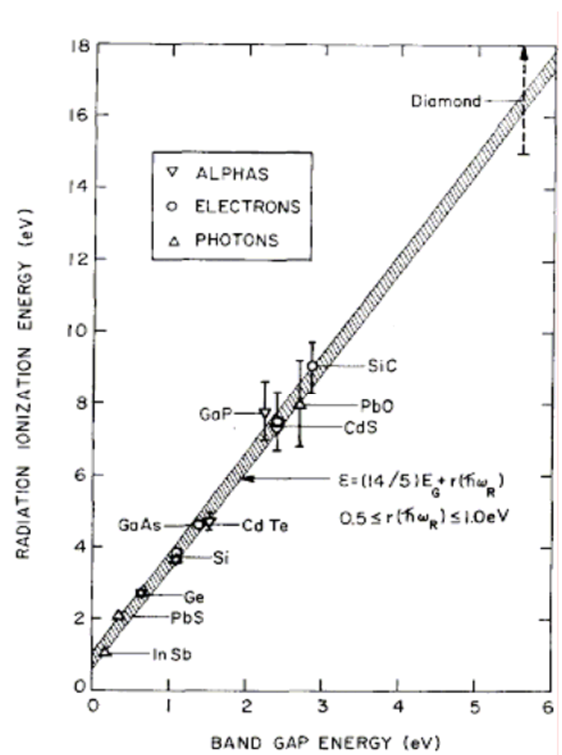

Figure 1: Electron/Hole Pair Production Energy for Varying Semiconductor Materials [5]

Since wider bandgap materials can support values of V_{OC} that are closer to E_g it becomes apparent that wider bandgap semiconductors would be more efficient when used for high-energy charged particle direct energy conversion.

III. EXPERIMENTAL SETUP

To prove the principle of using a solid-state device as a means to convert high-energy protons to electricity, initial experiments were performed in the University of Wisconsin Ion Beam Lab. These experiments utilized 3 MeV protons produced from a linear accelerator, see Figure 2, to simulate D-D fusion protons. The experiments were performed at room temperature. Measurements of the power output of the PIN diode sample were carried out during the irradiations. The proton beam has a narrow Gaussian spatial profile when focused into the test section of the beam-line. The beam is then rastered to attain a uniform fluence across the exposed area of the sample. The proton flux on the sample was determined to be between 1×10^{10} and 5×10^{10} protons·cm^{-2}s^{-1}. The large uncertainty is due to inherent uncertainties in running very low beam currents in the linear accelerator.

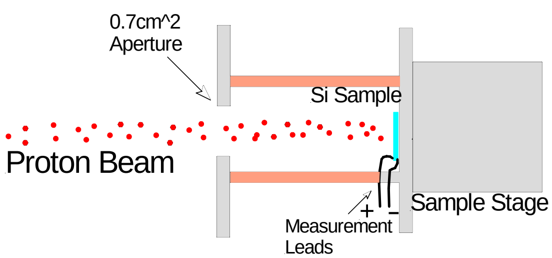

Figure 2: This is the setup used to irradiate the PIN junction silicon diodes with 3MeV protons

The experiments in the ion beam lab focused on achieving two major results, measuring the efficiency of using a silicon PIN junction diode to convert the kinetic energy of high-energy protons to electricity, and characterizing how the initial efficiency is degraded with increasing proton fluence. These experiments revealed the degree to which damage from the proton beam degrades device performance, and the energy conversion efficiency.

IV. EXPERIMENTAL RESULTS

The silicon PIN junction diode was successful in converting the kinetic energy of high-energy protons to electricity. The maximum achieved conversion efficiency for the device was between 0.2% and 0.8%. The uncertainty for η is due to the uncertainty in proton flux mentioned above. It should be noted that the form factor for this PIN diode was 0.35, a relatively low value. With a more efficient design, form factors of 0.7-0.8 may be attainable that could raise the efficiency somewhat further. The maximum achieved power output per unit area from the PIN diode was 40μW·cm^{-2}.

Figures 3 and 4 show the resulting decays in efficiency and power output with increased proton fluence.

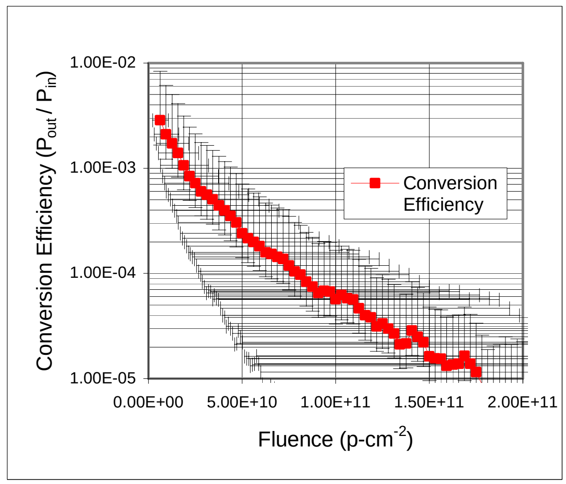

Figure 3: Conversion efficiency as a function of proton fluence for a silicon PIN junction diode.

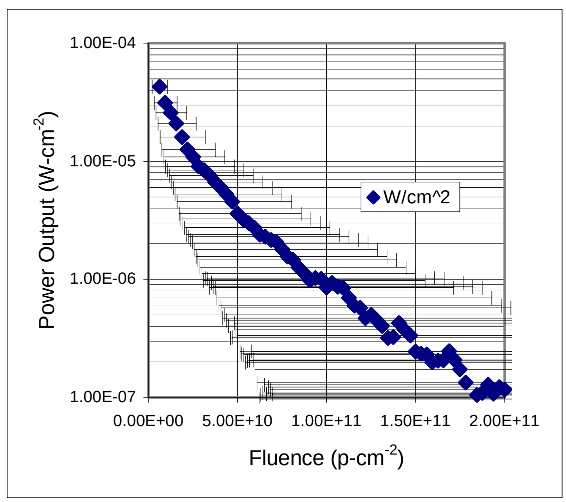

Figure 4: Power output per unit area as a function proton fluence for silicon PIN diode.

As is shown in the above figures the performance of the PIN diode degraded rapidly with proton fluence. Even under the modest proton fluxes applied in this experiment the device lasted only a few seconds before the power output and conversion efficiency had fallen by two orders of magnitude. This shows that at room temperature the device is very sensitive to lattice damage. Future experiments will focus on the effects of operating the devices at high temperatures, in order to ascertain whether or not the lattice damage can be annealed out as it occurs.

V. TRIM SIMULATIONS

The amount of lattice damage present in the device at different proton fluences was simulated using TRIM [6]. The simulations as shown in Figure 5 where fluence is correlated to differing levels of damage measured in *dpa,* displacements per atom.

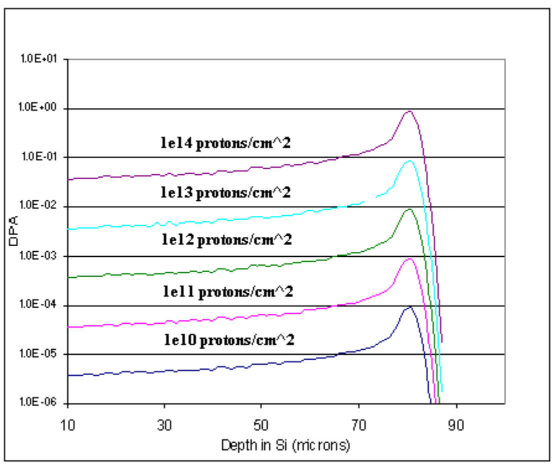

Figure 5: DPA as a function of depth in Si for varying proton fluences.

The data and simulation together indicate that silicon based charged particle direct conversion devices undergo a factor of 100 power output reductions for damage levels as low as $1x10^{-3}$ dpa.

VI. CONCLUSIONS

The prospects for using a solid state device to convert fusion protons to electricity depends on finding a way to mitigate the damage produced by the protons as they traverse the PIN junction. It has been shown that the power output and conversion efficiency of such a device are extremely sensitive to damage from scattering collisions that occur in the junction. A solution would be to operate the devices at higher temperatures, and thus annealing out the damage as it is created. It is unclear whether this can be done at temperatures high enough to quickly anneal out the vacancies and interstitials that are produced by the scattering collisions while still maintaining temperatures low enough that the p-type and n-type dopants in the silicon do not diffuse extensively. If the annealing could be carried out without affecting the dopant profile extensively then this could be a solution for the damage problem.

ACKNOWLEDGMENTS

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