Silicon Carbide Alphavoltaic Battery

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Abstract

The development of new wide bandgap, highly radiation resistant semiconductors, such as SiC, may make it possible to use an inexpensive alpha particle emitting isotope to construct high efficiency, long lifetime radioisotope power sources. To study the possibility of producing an alphavoltaic battery, SiC photodetector diodes were irradiated with 5.5 MeV alpha particles from the radioisotope Am-241. Further studies of the radiation resistance of SiC were made using 1 MeV electrons in an accelerator facility. During the irradiation, the power output of the SiC cell was monitored and its degradation measured. Although the initial power output was considerable, a rapid decay of the power output occurred.

Basic studies of the radiation resistance of SiC were also made using deep level transient spectroscopy (DLTS). Six deep levels were found in both the unirradiated and irradiated SiC diodes. The carrier removal rate of 2.46 per 1 MeV electron measured here in SiC is very similar to the value of 2.85 per 1 MeV electron measured in InP, another highly radiation resistant semiconductor. The rapid degradation in output and considerable carrier removal rates observed here suggest that SiC has a radiation resistance similar to but not better than other radiation resistant semiconductors such as InP. The considerable initial output of the SiC battery was however, very encouraging, and further developments in SiC technology may make it possible to reduce the radiation damage rate in this application.

Introduction

The maturation of new wide bandgap, highly radiation resistant semiconductors has made it worthwhile to revisit the topic of radioisotope batteries. SiC has a desirable combination of properties for radioisotope battery design, with a bandgap of 3 eV in the 6H polytype and a radiation induced atomic displacement threshold second only to diamond.(1) These attributes may make it possible to use an inexpensive alpha particle emitting isotope to construct higher efficiency, longer lifetime radioisotope batteries. These batteries are power sources for applications where neither solar nor chemical battery power are feasible.

To simulate the operation of an alphavoltaic battery, SiC photodetector diodes were irradiated with 5.5 MeV alpha particles from the radioisotope Am-241. This isotope is inexpensive and widely available enough to be used in household smoke detectors, and has a long half life of 458 years. The operation of the SiC alphavoltaic battery is analogous to a solar cell with the exception of high energy particles impinging on the cell rather than light. Previous radioisotope battery designs were based on beta emitting isotopes such as Pm-147 and silicon diodes. (2) However, their performance was limited by the difficulty in absorbing all the energy of the high energy electron from the beta decay, the leakage current in the low bandgap Si diodes, the short lifetime of the isotope chosen and the radiation damage rate of the diodes. (3) Highly radiation resistant SiC semiconductor materials and diodes with very low leakage currents when combined with the short range of an alpha particle in the diodes may make large performance increases in radioisotope batteries possible.

Experimental

The samples used in this study were SiC photodetector diodes obtained from the Cree Corporation in Durham, NC. Details of the structure and characteristics of the diodes are described elsewhere,(4) but briefly, they are composed of a p-type SiC substrate with an aluminum doped p-type epitaxial layer and nitrogen doped n-type emitter. The diodes were analyzed by capacitance voltage technique (CV) and DLTS before irradiation. A carrier concentration in the base of (2.25 ± 0.6) x 10^16 cm^-3 was determined. The samples were then irradiated with 5.5 MeV alpha particles, under vacuum, to a total fluence of 2 x 10^11/cm^2 using a 5 millicurie Am-241 radioisotope.
source. Similar samples were also irradiated with 1 MeV electrons to a fluence of 3 x 10^{14} cm^{-2} at the National Institute of Standards and Technology. After the irradiation, the carrier concentration was measured by CV and the samples were analyzed using DLTS. DLTS analyses were conducted using the standard double boxcar integrator method developed by Lang (5), using 4 volts reverse bias and fill pulses of 4 volts for majority carrier conditions and 8 volts for minority carrier conditions. The carrier removal rate and defect introduction rates were calculated for each type of irradiation.

**Results**

During the irradiation the power output of the SiC cell was monitored using a sensitive electrometer, and its degradation with time was measured. Although the initial power output was considerable, a rapid decay of the power output occurred, as shown in Figure 1. Additional diode designs that had unthinned and thus thicker emitters, and diodes with larger area, were made and similarly tested, but no reduction in degradation was observed. The initial power output of the simulated SiC alphavoltaic battery was 1.613 volts at 0.183 nanoamps for a sample composed of two 1x1 mm square photodiodes. This corresponds to a power output of 0.015 W/cm². Nearly identical results were achieved with a string of 5 diodes. After 100 hours the power output had fallen to 0.0085 W/cm². This represents a degradation of 58%. This is a relatively low value when compared with Si-based betavoltaic batteries. (3) This is an impressive result which reflects the advantages of ease of collection of alpha particle energy, the wide bandgap and low leakage current of SiC. The radiation damage issue however, still imposed a severe limitation on the application of this technology and so was studied further.

Studies of the radiation resistance of SiC were made using deep level transient spectroscopy (DLTS) and measurements of the carrier removal and defect introduction rate were made. The majority and minority DLTS spectra of the alpha particle irradiated SiC are shown in Figures 2 and 3. Six deep levels were found in both the irradiated and unirradiated SiC diodes. The measured electrical characteristics and concentrations of the traps are given in Table 1. The large amount of damage after alpha particle irradiations made it difficult to resolve all 6 levels in the irradiated samples and so data for only four are reported.

![Figure 1. Normalized current output of simulated alphavoltaic battery](image1)

![Figure 2. Majority carrier DLTS spectrum of alpha-irradiated SiC.](image2)
These experiments were supplemented by electron irradiation of similar SiC diodes in an accelerator facility. This combination of information allowed the comparison of the radiation resistance of SiC with other semiconductors, information that has been lacking up to this point.

One such comparison is the radiation induced carrier removal rate as shown in Figure 4. The carrier removal rate of 2.46 per 1 MeV electron measured in SiC here is very similar to the value of 2.85 per 1 MeV electron measured in InP, another highly radiation resistant semiconductor.(6) The carrier removal rate for 5.5 MeV alpha particles was \(7.8 \times 10^4\) per alpha particle. No comparison was attempted for alpha irradiations due to the scarcity of data.

The introduction rate of defects for 1 MeV electrons and 5.5 MeV alpha particles was calculated from the defect concentration data. The defect concentration for electron irradiations was calculated at several points during the irradiations. A linear dependence of defect concentration on electron fluence was found and the defect introduction rate reported was calculated from a least squares fit of the defect concentration vs electron fluence. In the case of the alpha particle irradiations a linear dependence was assumed and the introduction rate calculated from a single data point. The introduction rate of majority carrier defects in SiC was 0.08 per 1 MeV electron. In the case of 5.5 MeV alpha particles the majority carrier defect introduction rate was 455 per 5.5 MeV alpha. The greater weight, higher charge and slower speed of the alpha particle are responsible for its greater damage rate. It is interesting to compare the majority carrier defect introduction rates in SiC and InP. During 1 MeV irradiations of similarly doped p-type InP a majority carrier defect introduction rate of 2.61 was measured.(6) It should be pointed out that defect introduction rates are up to an order of magnitude lower in more highly doped InP and also vary with type of doping. (7) While it appears that SiC has a much lower defect introduction rate than InP, DLTS commonly only reveals defects to a depth of 0.1 to 0.7 eV from the band.

Table 1. Radiation-induced defects, characteristics and concentrations after alpha irradiation to \(2 \times 10^{11}/\text{cm}^2\) and electron irradiation to \(3 \times 10^{15}/\text{cm}^2\).

<table>
<thead>
<tr>
<th>Peak (\Delta E), Cross Section (\sigma \text{ cm}^2)</th>
<th>Post ((\alpha))-Irradiation Concentration (\times 10^{13} \text{ cm}^{-3})</th>
<th>Post ((e^-))-Irradiation Concentration (\times 10^{13} \text{ cm}^{-3})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E_+ - 0.69) (1.34 \times 10^{-16})</td>
<td>(5.04 \pm 1.3)</td>
<td>(15.4 \pm 3.5)</td>
</tr>
<tr>
<td>(E_+ - 0.56) (1.97 \times 10^{-15})</td>
<td>(3.86 \pm 0.60)</td>
<td>(4.3 \pm 3.0)</td>
</tr>
<tr>
<td>(E_+ - 0.50) (1.66 \times 10^{-14})</td>
<td>(---------)</td>
<td>(5.0 \pm 1.4)</td>
</tr>
<tr>
<td>(E_- - 0.58) (4.08 \times 10^{-17})</td>
<td>(18.3 \pm 0.1)</td>
<td>(5.3 \pm 2.9)</td>
</tr>
<tr>
<td>(E_- - 0.48) (8.89 \times 10^{-17})</td>
<td>(---------)</td>
<td>(6.6 \pm 3.6)</td>
</tr>
<tr>
<td>(E_- - 0.38) (2.92 \times 10^{-17})</td>
<td>(21.3 \pm 0.25)</td>
<td>(11.7 \pm 1.5)</td>
</tr>
<tr>
<td>α particle fluence</td>
<td>J_02 A/cm²</td>
<td></td>
</tr>
<tr>
<td>-------------------</td>
<td>-----------</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>9.45 x 10^{-24}</td>
<td></td>
</tr>
<tr>
<td>2 x 10^{11}/cm²</td>
<td>7.85 x 10^{-20}</td>
<td></td>
</tr>
<tr>
<td>1 x 10^{12}/cm²</td>
<td>5.17 x 10^{-19}</td>
<td></td>
</tr>
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**Table II. Recombination current in SiC Diodes**

...edges, therefore in both cases there may be defects that remained undetected.

The comparison of carriers removed by the formation of radiation induced defect complexes may be a better indicator of the actual extent of radiation damage. The similar carrier removal rates between InP and SiC suggest that InP and SiC have very similar radiation resistance.

No differences were observed between the levels generated by alpha or electron irradiation and no new defect levels were observed in this study. This is evidence that the implanted He nuclei from the alpha particles do not form an electrically active level themselves. The levels observed by DLTS here are those commonly observed in p-type SiC. The majority carrier defects observed here are dopant defect related complexes related to Al doping and B impurities. (8,9) The two lower energy levels are boron related and are referred to as the D center. These complexes were also observed in the as-grown material due to the formation of dopant complexes with intrinsic defects. The defects observed in the minority carrier DLTS spectra are those referred to as the E and Z centers which related to Al dopant defect complexes and to an intrinsic and electron radiation induced defects. (10)

The effect of the deep levels on the diode output was also investigated after irradiation. Diode IV curves were taken and the recombination dark current J_02 was measured. The results are presented in Table 2 for the alpha particle irradiations.

The degradation in diode output with time thus appears to be due to an increase in the recombination/generation current in the diodes due to the increase in the concentration of deep level defects. The effect of irradiation on the diffusion component of the recombination current was not measurable, suggesting that in this case that it may have been dominated by sample dependent effects such as leakage at the diodes edges.

**Conclusions**

These experiments suggest that an alpha particle based radioisotope battery based on a wide band gap semiconductor material can achieve much higher efficiency than the state of the art Si and beta isotope based design. However, alpha particle emitting radioisotopes cause rapid degradation of the diodes used in the battery construction. The rapid degradation and considerable carrier removal rates observed here suggest that SiC has a radiation resistance similar to but not better than other radiation resistant semiconductors such as InP. Although the SiC technology and the radiation resistance of SiC has not been exhaustively studied here, this rapid degradation may make it difficult to fabricate an alpha particle based radioisotope battery. Many of the desirable characteristics of SiC however, may be used to improve the existing radioisotope battery designs based on beta emitting radioisotopes.

**References**