ULTRA-HIGH EFFICIENCY HIGH POWER DENSITY THINNED-DOWN SILICON CARBIDE BETAVOLTAICS

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Abstract: We report on the demonstration of a one-sided exposure *11.2%* ultra-high efficiency 50µm-thick thinned-down silicon carbide betavoltaic under ^{63}Ni irradiation. Using e-beam radiation we also demonstrate that the efficiency can be further increased to 23.6%, while the device thickness can be decreased to below 30µm. Compared to the best SiC betavoltaics reported so far [1] [2], our devices have an efficiency improvement of 3-4X, with a fuel fill factor improvement of 8-10X, which will lead to an overall power density improvement of 30-40X. Compared to the best available planar silicon betavoltaics [3], our devices have a power density improvement of 100X (6X in efficiency, and 16X improvement in fuel fill factor.)

Keywords: Betavoltaic, SiC, Power generator, ^{63}Ni

INTRODUCTION

With very high energy densities of 1-10 MJ/cc [4] (compared to 1-20 kJ/cc for conventional electrochemical and hydrocarbon fuels [5]), and a long half-life of 1-100 years, radioisotope fueled batteries are ideal for applications requiring compact, long lifetime power supplies, such as remote sensing and implantable devices. Furthermore, low energy β emitters (^{63}Ni, ^{147}Pm, etc.) have little or no safety concerns, and Promethium-147 powered betavoltaics have been implanted inside humans for powering cardiac pacemakers in the past [3].

To achieve compact radioisotope batteries, the power density of the device should be as high as possible. The power output density of a betavoltaic battery can be expressed as follows

$$P_{out} = P_{fuel} FFF \eta_{fuel} \eta_{\beta} \tag{1}$$

where P_{fuel} is the fuel power density, FFF is the fuel fill factor (volume percentage of the radioisotope fuel), η_{fuel} is radioisotope thin-film emission efficiency, and η_{β} is betavoltaic conversion efficiency. P_{fuel} and η_{fuel} are determined by the radioisotope material. While higher energy β-emitting isotopes such as ^{137}Cs and ^{90}Sr have higher fuel power densities, due to their high energy related x-ray generation, significant shielding is needed, which decreases the overall power density of the battery. ^{63}Ni emits β-particles with an average kinetic energy of 17.3keV, with a penetration depth of less than 10µm in most solids. As a result, devices powered by ^{63}Ni thin-films can be deployed safely with millimeter or even microscale shields. In this paper, we focus on improving the FFF and η_{β} to maximize the power density of a betavoltaic battery.

Different techniques of improving the FFF of a betavoltaic battery by patterning and etching of its active device layers have been previously reported [6] [7]. However, in both those cases, the leakage currents were significantly increased due to the damage to the semiconductor materials in the etching process, hence very low conversion efficiencies were reported. In our design, only non-active substrate regions are etched away, so the FFF can be improved without sacrificing the conversion efficiency.

The thicknesses of the SiC and silicon wafers range from 300µm to 500µm, where only the top ~ 20µm is the active functioning region for a betavoltaic battery (Figure 1(a).) Therefore, regular planar betavoltaics waste over 90% of their volume, but a FFF improvement of 8X can be achieved by thinning down the non-active substrate to 30µm. Furthermore,

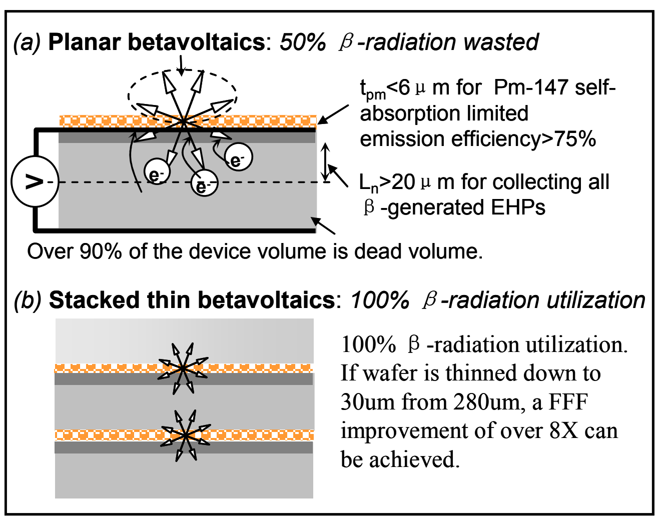

Figure 1. Schematic illustrations for the design showing advantages of the thin SiC betavoltaic design.

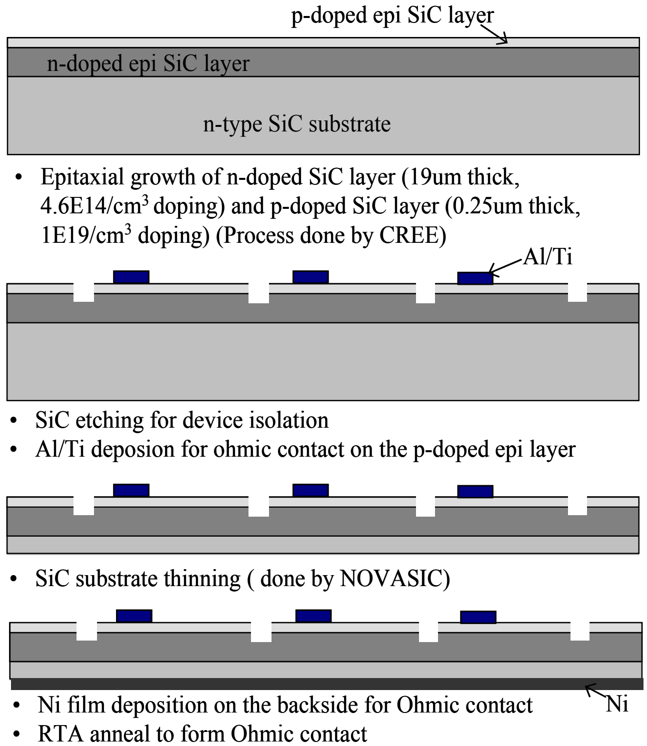

Figure 2. Fabrication process of the thin SiC betavoltaics

in a planar device, all of the electrons irradiated away from substrate are wasted, which is 50% of all electrons. By stacking thinned-down devices together, all of the electrons will be utilized, which decreases the radioactivity needed for a battery. Besides higher FFF values, less radioactivity also provides a safer device.

FABRICATION

The process flow of the thin SiC betavoltaics is illustrated in Figure 2. The SiC wafer substrate has too many defects to be the active device layer, so a 19µm thick n-doped SiC epitaxial layer followed by a 0.25µm thick p-doped SiC epitaxial layer are grown on top of the substrate as active device layers. The n-doped layer is designed to be thick enough to collect most of the radioactive electrons. The p-doped layer has a much higher doping level ($10^{19}/cm^2$) than the n-doped layer ($4.6\times10^{14}/cm^2$) to create a large voltage across the depletion region. The performances of the thick SiC betavoltaics are first tested. For prototype thin devices, 1cm^2 dies are thinned down to 50µm from the initial 280µm after device isolation etching on the wafer. The devices are metallized with Ti/Al on the p-doped epi-layer and Ni on the n-doped substrate, followed with a rapid thermal anneal (RTA) to ensure good ohmic contact.

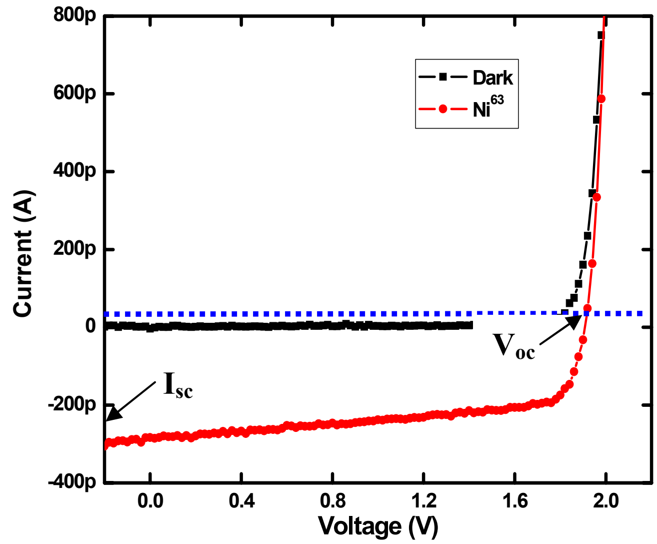

Figure 3. Measured IV characteristic of regular-thickness SiC betavoltaic under Ni^{63} electron irradiation.

TESTING

Energy conversion characteristics of regular-thickness SiC betavoltaics were first measured under electron irradiations from a ^{63}Ni source, which has a radioactivity of 1.5mCi/cm^2. The I-V curves of a device with 1mm × 1mm area are plotted in Figure 3. Under electron irradiation from ^{63}Ni, the device has a short-circuit current of 300pA with an open-circuit voltage of 1.9V. An ultra-high conversion efficiency of 22.3% was achieved (341nW of output power vs. 1.53nW of input power at 1.76V), which is almost 4 times the best previously reported results [1].

The betavoltaic devices are further characterized in a scanning electron microscope by irradiating them with 20pA-2nA electron beams (corresponding to ~3mCi-~300mCi of radioactivity) accelerated at voltages up to 30kV (SEM limit). The conversion efficiency of the device is low at low electron energies (Figure 4.) This is due to the energy loss for electrons to go through the heavily p-doped SiC carbide layer, where the electron-hole pairs generated by the incoming electrons are quickly recombined. As the electron energy increases, and more electrons reach the depletion region, the percentage of the energy absorbed without electron-hole pairs generation in the p-doped SiC decreases. Therefore, the conversion efficiency increases until it reaches the maximum efficiency for the betavoltaic device, which is 23.6%. Further increases of the electron energy could lead to decreases in the overall conversion efficiency, if the electron penetration depth in the SiC

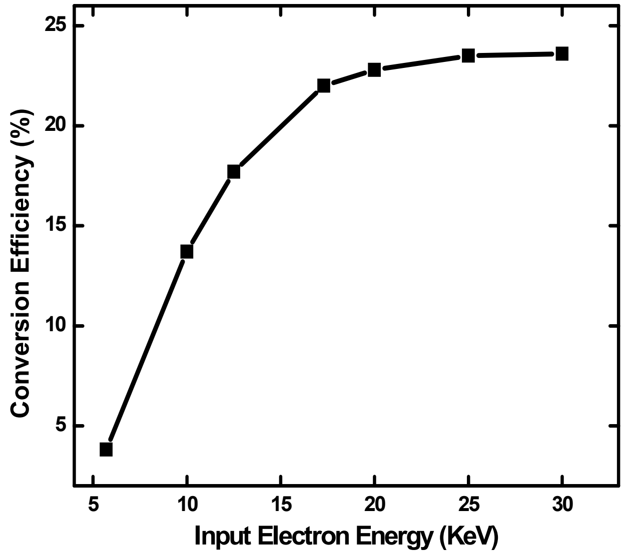

Figure 4. Measured conversion efficiency at different input electron energies for the regular-thickness device

is larger than the diffusion length of the EHS in the low n-doped epitaxial layer.

The electron-hole pair (EHP) multiplication factor (number of EHPs generated per input electron) is plotted in Figure 5. A near straight line at high energies indicates the device could work at even higher input electron energy (>30keV) with the same efficiency. Therefore, ^{147}Pm, which has a higher average electron energy (62keV) and higher power density (2.05W/cc, compared to ~13.4mW/cc for ^{63}Ni) can be used as a radioisotope source to further increase the power density of the betavoltaic battery.

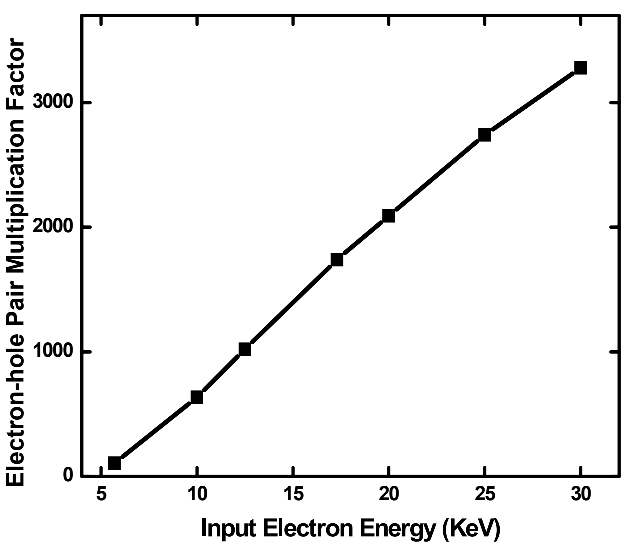

Figure 5. Measured EHPs multiplication factor at different input electron energies for the regular-thickness device

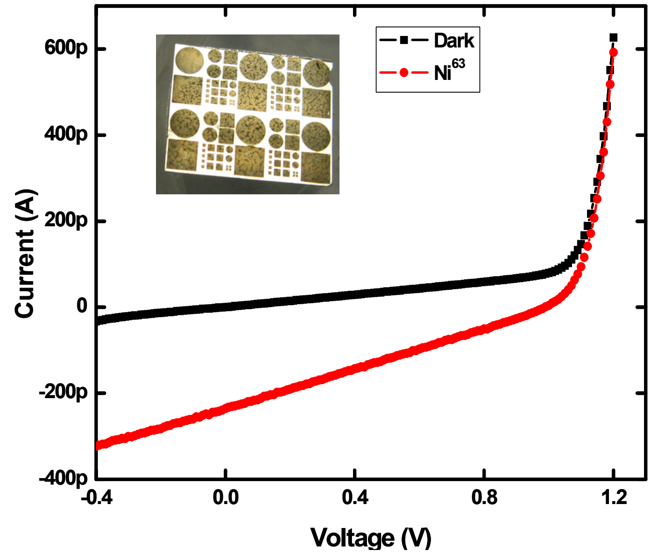

Figure 6. Photograph and measured IV characteristic of 50µm-thick SiC betavoltaic under Ni^{63} electron irradiation.

To demonstrate the concept of thinned-down betavoltaics, a 1cm×1cm 280µm-thick SiC betavolatic die is thinned down to 50µm from the backside of the substrate (as shown in Figure 2,) which gives a more than 4X improvement on the FFF of the devices. The thickness of the devices can be further thinned down to 30µm (limited by the current SiC wafer thinning technology), which could provide a FFF improvement of 8X. The thinned-down SiC betavoltaic is tested under Ni^{63} irradiation, but only 11.2% conversion efficiency is achieved (figure 6). This is due to the lack of protection for the p-doped epitaxial layer in the wafer thinning process. The damage to epitaxial layers causes a higher leakage current, which lowers the open-circuit voltage and the conversion efficiency. With a carrier wafer to protect the epitaxial layers in the wafer-thinning process, a conversion efficiency of 22.3% is expected for the thinned-down SiC betavoltaics with ^{63}Ni irradiation. Even with the prototype device, a powered density increase of 170% is achieved.

CONCLUSIONS

In this paper, we report high efficiency SiC betavoltaics of 23.6% under ^{63}Ni irradiation, which is about 4 times greater than the best results reported in the literature. To further increase the power density, the SiC betavoltaics die is thinned down to 50µm, which gives a FFF improvement of over 4 times. The thinned-down device has a conversion efficiency of 11.2%, due to damages to the device layers in the wafer thinning process. However, it still gives a power density improvement of 10 times over the best SiC betavoltaics reported so far. With device layers protected in the wafer thinning process, the efficiency can be increased to 23.6%, while the device thickness can be decreased to below 30µm. Therefore, an overall power density improvement of 30-40X can be achieved, with further increases possible with thinner SiC diodes.

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