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Development of diode junction nuclear battery using ^{63}Ni

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Abstract The diode junction nuclear battery is a long-lived, high-energy-density, but low electrical current power source with many specialized applications. In this type of battery, nuclear radiation is directly converted to electric power. A model is described and used to design the device configuration. Details of fabrication and testing of a planar geometry battery with ^{63}Ni radiation source are described. The electron beam induced current (EBIC) measurement technique and CASINO Monte Carlo simulation code were employed to analyze the device performance. Finally, an improved design with 3-dimensional surface microstructures that will provide improved performance is presented.

Keywords ^{63}Ni · Betavoltaic battery · Radioisotope battery · P–N junction diode · Nuclear battery

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Introduction

A diode junction nuclear battery is a device that converts nuclear radiation directly to electric power [1]. The physics of this battery is similar to the P–N junction diode used for solar arrays. The photovoltaic effect in which photons are converted to electrical energy in the junction works on the same principle as the betavoltaic effect where beta particles are collected and converted to electrical energy. A low amount of current is generated, generally on the order of nano or micro amps in relatively small devices, at a cell voltage as high as 1.5 V. If a radioisotope with a long half-life (50+ years) is chosen, then a power source with a very long usable life can be constructed. Since the battery derives its energy from a nuclear source, the energy density is extremely high compared to conventional batteries.

Some special applications require long-lived compact power sources. These include space equipment, sensors in remote locations (space, underground, etc.), and implantable medical devices. Conventionally, these sources rely on converting chemical energy to electricity. This means they require a large storage of chemical “fuel” since the amount of energy released per reaction is small. The nuclear battery is a novel solution to solve the power needs of these applications.

The properties of the diode nuclear battery also present a few other interesting applications. A diode nuclear battery can be paired with a conventional rechargeable battery or supercapacitor to accommodate devices that require high power intermittently, such as a remote sensor with RF communication capability for infrequent data transmission. The two power sources can be mated such that the nuclear battery trickle-charges the rechargeable battery in between infrequent high power drain applications. Another application is the battery-on-chip. It is possible to make the nuclear battery on the same piece of silicon wafer as the device it is powering, potentially enabling a new generation of sensors, actuators, and low power processors without the need for external power sources.

In order to choose the right radioisotope to construct a nuclear battery, certain criteria must be met. ^{63}Ni was chosen as the beta emitter because it has a long half-life (100.1 years) and with an average and maximum energy well below the damage threshold of silicon (max. energy ~67 keV). Although this radioisotope suffers from low specific power (0.006 W/g), its long half-life qualifies it for applications that require operation for decades with insignificant decline in performance. The use of ^{63}Ni greatly simplifies safety issues since chemical toxicity is low and shielding can be easily accomplished with only a thin sheet of plastic.

In terms of choosing a substrate on which to construct our nuclear batteries, silicon is an attractive choice due to its large band gap, robustness in the environment, wide availability and relatively low cost. With its wide use in integrated circuit (IC) industry and microelectromechanical systems (MEMS), silicon micromachining processes have been well developed compared to other semiconductors such as GaAs, Ge, and SiC.

The objective of the present work is to develop experimental and analytical tools to properly examine the operation principle of a P–N junction nuclear battery and means to improve its performance. The experience gained from this study enables optimum design of a high surface area to volume ratio battery with maximum energy density on a wafer thickness device. Previous literature has shown a porous battery based on gas phase tritium [2]. Such an approach however has inherent low energy density because of the encapsulation required to contain the gas as well as the low specific power of tritium. Various planar geometry ^{63}Ni devices have also been reported however the small surface area combined with shallow P–N junction has typically limited performance [3, 4].

Model for battery design

A simple model for the operation of the P–N junction nuclear battery starts with the basic principles of the photovoltaic effect. It is assumed that all electron-hole pairs (EHPs) created in the junction are collected as current. Additionally, EHPs created within a minority carrier diffusion length of the depletion region also have a chance to be collected as a function of their distance from the junction edge [4, 5]. There are two major deviations from the photovoltaic theory. The first is that each beta particle produces thousands of EHPs as it inelastically scatters through the silicon substrate. This point leads into the second major deviation. The range of the beta particles, and therefore the location of their deposited energy is deep within the silicon substrate.

One of the primary design considerations in a P–N junction nuclear battery is how the penetration depth of the beta particles relates to the junction depth and depletion region width. The penetration depth of the particles in the silicon device can be found using the Katz–Penfold maximum range equation [6]. This formula is used to compute the range of high energy electrons in materials. The Katz–Penfold range equation (Eq. 1) depends only on the density of the material and the energy of the particles

$$R_{\mathrm{KP}} = (412/\rho_{\mathrm{si}}) \times E_{\mathrm{MeV}} \times \mathrm{e}^{1.265-0.0954\times\log(E_{\mathrm{MeV}})}. \quad (1)$$

The maximum range of the average beta particle energy from ^{63}Ni into silicon is 2.2 μm. This effectively determines the depth of the depletion region required. Since the shape of the beta spectrum is weighted toward the lower energies, we collect the most EHPs by setting the depletion region around the average energy penetration depth. Then the doping levels are selected as to obtain a wide depletion region which primarily extends toward the surface of the device.

Experimental

The experimental work described here was performed to establish experiment techniques needed to eventually construct an improved design with 3-dimensional surface microstructures to achieve an order of magnitude higher power and energy density than in a planar device.

P–N junction formation

To fabricate the P–N junction, a Si wafer ($P\langle 100\rangle$ 160–240 Ω cm) is first degreased in a sequence of acetone, water, and isopropanol, and then dehydrated at a temperature of 110 °C for 2 min. A thermal oxide layer (0.5 μm) is then grown on the entire wafer in a tube furnace at 1,100 °C for approximately 13 h. The oxide layer is removed from one side of the wafer using buffered oxide etch (BOE), and liquid N-type phosphorus dopant (P-8545) is spun-on. The wafer is then placed in a tube furnace at 1,000 °C for 10 min in order to diffuse the phosphorus into the silicon. The undiffused phosphorus (which remains as an unreduced glass layer) as well as the oxide layer on the backside of the wafer is then removed using BOE, yielding a P–N junction. We then used secondary ion mass spectrometer (SIMS) to determine the doping density as well as the P–N junction depth. The result suggests that a doping concentration of 10^{20} cm^{-3} and a junction depth of approximately 0.3 μm has been formed.

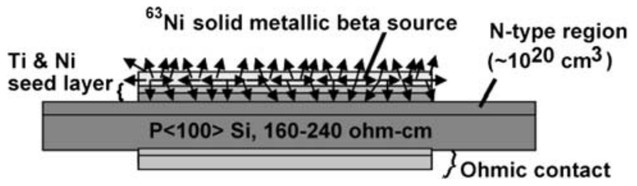

Fig. 1 Cross-sectional schematic of ^{63}Ni P–N junction nuclear battery

In order to turn the P–N junction wafer into a substrate on which ^{63}Ni can be deposited and power output can be measured, metallic contacts have to be fabricated on both sides of the wafer that serve as ohmic and seed layer (for ^{63}Ni electrodeposition) contacts. Standard photolithography and lift-off technique were used to form both contacts. The ohmic contacts were formed on the undoped P-type side of the wafer; 200 Å of sputtered Al, annealed at 450 °C for 30 min under N_2 ambient serves as the ohmic contact, with a 100 Å chromium layer and 1,500 Å gold layer placed over it. On the reverse side, the side of the P–N junction, photolithography and lift-off techniques were used to form the ^{63}Ni deposition seed layers of 500 Å of sputtered Ti and 200 Å of sputtered Ni (Fig. 1).

^{63}Ni deposition

Electrodeposition is performed using a standard three-electrode setup with a titanium counter electrode and an $Ag/AgCl_2$ reference electrode. From calibration experiments, we have determined an approximate deposition rate that will allow us to deposit the desired amount of activity. Typical conditions are −0.78 V at 1 mA/cm^2 for 5–10 min. Faraday's law of electrolysis gives us an approximate mass of material plated from the solution which correlates to an activity of ^{63}Ni deposited on the device.

Results and discussion

The performance characteristic of the planar nuclear battery was tested using a Keithley 6487 picoammeter/voltage source and is shown in Fig. 2. The open circuit voltage was found to be 0.8 mV while the short circuit current was 11 nA. The maximum power output was found to be 2.5 picowatts at a voltage of 0.4 mV for ~4 mCi ^{63}Ni. While this performance is relatively low it demonstrates the validity of the fabrication technique of the battery. The next step is to change the junction depth and doping densities of the N and P regions. Due to the limitations of the diffusion doping technique in producing the desired junction depth and doping density, the next generation device will use epitaxial film growth technique.

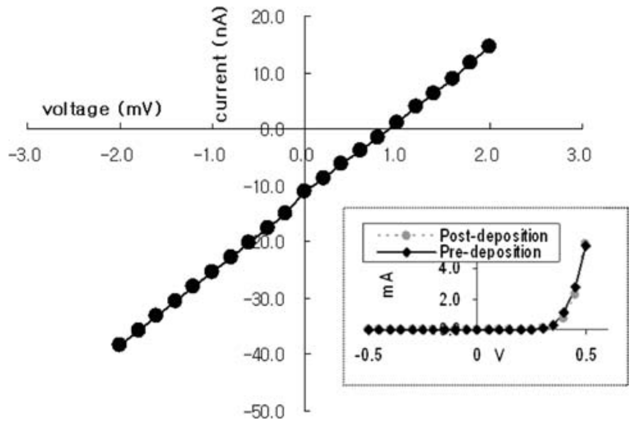

Fig. 2 Planar nuclear battery performance characteristic. The *inset* shows diode rectifying behavior pre- and post-deposition of ^{63}Ni

Additional experimental studies have been performed on a pre-electroplated P–N junction substrate to examine some of the sources of the device deficiencies. The electron beam induced current (EBIC) technique has been employed to experimentally simulate the beta emission of ^{63}Ni and to estimate the total device current. The technique allows determining the P–N junction current multiplication at different incident electron energies. A scanning electron microscope was used as a high energy electron gun with an incident beam voltage range of 1–30 kV. Figure 3 shows the EBIC result of the P–N junction die. The responsivity data is a measurement of the amperes of device current generated per watt of incident beam current. It can be thought of as a measurement of the efficiency of the junction at converting incident beta particles into collected electron-hole pairs. The essentially zero response for energies less than 10 keV indicates that these low energy particles are being completely absorbed in the nickel and titanium seed layers. Further modeling has been performed

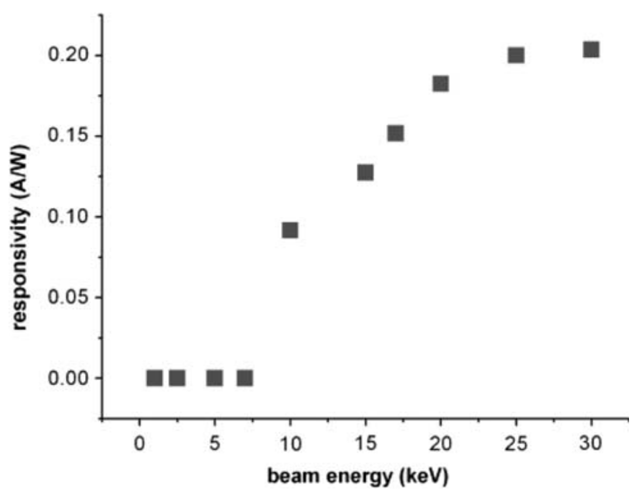

Fig. 3 Electron beam induced current (EBIC) study of planar device

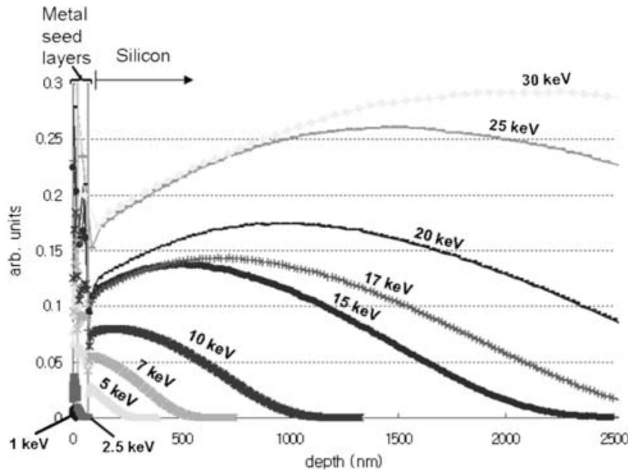

Fig. 4 Monte Carlo model of the energy deposition by depth in silicon for incident beta particles of increasing energy

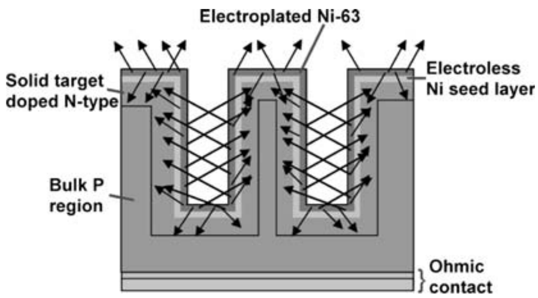

Fig. 5 Cross sectional schematic of 3-D nuclear battery

using the CASINO Monte Carlo code to determine the effect of seed layer absorption loss on device performance [7]. We have modeled the energy deposition as a function of the depth in the silicon. Results presented in Fig. 4 suggest that the energy deposition in the silicon is negligible for energies less than 10 keV. The Monte Carlo simulation results agree with the EBIC data conclusion that the seed layer thickness strongly attenuates the low energy beta particles.

We believe that adjusting the P–N junction and depletion regions depths are keys to higher device performance. Once a parametric study on effect of these parameters on performance of the planar P–N device is conducted, we will design a device with deep trenches spaced at optimum distance. The addition of deep trenches etched into the silicon wafer has the effect of greatly increasing the surface area per unit volume. A schematic of the device is shown in Fig. 5. Considering that the location of the deposited energy is a few microns deep within the substrate, we believe the optimum spacing between the trenches is on the order of several microns. This design allows a greater amount of ^{63}Ni to be deposited per device volume. The additional benefit is the reduction in the number of beta particles being emitted in the “wrong direction”, that is in the opposite direction of the junction. In this design, the beta particles can penetrate into an adjacent junction and still be collected.

Conclusion

We have presented the model of the conversion of beta energy to electrical energy in a P–N junction nuclear battery. This model has been utilized to calculate junction parameters required for an efficient ^{63}Ni based battery. A fabrication recipe has been described to produce a P–N junction nuclear battery with ^{63}Ni source deposited on the surface, constituting a self-contained device. Testing of this battery has identified areas of improvement needed in next units including deeper P–N junction with a wide depletion region within the right polarity (i.e. N or P) region to maximize collection efficiency. Optimizing the planar battery would then allow us to design an efficient device with high aspect ratio surface trenches for higher energy density. The high performance of this device provides a unique new type of battery which can greatly expand applications of this emerging technology.

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