Tolerance of spin-Seebeck thermoelectricity against swift heavy-ion irradiation

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Thermoelectric (TE) elements, which transduce heat to electricity, attract growing attention since it exhibits a promising pathway to address demands for energy harvesting technologies that would reutilize waste heat energy at factories and cars. The potential of the TE devices in combination with radioisotope elements may be beyond such commoditized uses to more harsh environments as the isotope batteries for spacecraft in deep space. The elemental structure of the TE device is a junction consisting of two different semiconducting, or metallic materials, a thermocouple. Applying temperature gradient on the TE element, electrical voltage is generated on the junction. The TE device is a series of junctions and these junctions can be affected by high energy radiation. Therefore, the options of the radioactive isotopes for a nuclear battery are limited to some special nuclear species which emit an alpha ray only due to the shielding problem.

After recent discovery of the spin- driven thermoelectric (STE) generation, the notable advantage of the STE generation stems from the availability of arranging heat and charge conduction paths in the direction orthogonal to each path, allowing simple and flexible device structures, low-cost fabrication processes, and the unique scaling characteristics of output signals to device dimensions [1][2]. Furthermore, the STE devices are expected to be tolerant against radiations, and their application fields expand to aerospace usage as magnetic memories. If we combine the STE devices to the nuclear batteries, it is possible to develop the next-generation nuclear battery. The long-term performance of the STE device, however, under radioactive conditions is unconfirmed. We contrived a new method to avoid the weakness in the TE junctions via the radiations by replacement to STE devices. In this study, we investigated the performance of STE devices under heavy-ion beam irradiation with varying the dose level.

The STE sample for this study consists of metallic (Pt) and magnetic insulator ($Y_3Fe_5O_{12}$, YIG) films formed on a substrate ($Gd_3Ga_5O_{12}$, GGG) based on spin Seebeck effect (SSE). Swift heavy ion irradiation on samples was performed at the Tandem accelerator in JAEA Tokai Lab with 320 MeV gold ions at room temperature. As is well known, when a high energy heavy ion passes through the samples, high-density electric excitations occur in semi-conducting or insulating materials, and nanoscale amorphous columnar defects are formed along the ion tracks. Since amorphous YIG becomes paramagnetic and does not contribute to the spin transport, the irradiated regions become ineffective for thermoelectric energy conversion via the SSE. The SSE signal becomes smaller with increase the irradiation dose (Fig. 1-(a)). The linearity of the SSE voltages with ΔT is maintained for all as-irradiated samples suggesting that the decrease of the SSE voltage is a result of an increase of the damaged area of the sample (Fig. 1-(b)).

The SSE voltage in Fig. 1-(c) completely disappears above the dose of $\Phi = 1\times10^{12}$ ions/cm^2, where the entire sample surface is covered by the columnar defects, and the limitation of heavy ion irradiation on the SSE devices is obtained. Using the limitation, we evaluated lifetime of the SSE devices on the surface of a spent nuclear fuel (SNF). The fission fragments with ~100 MeV energies can escape from a vitrified waste surface, and the SSE devices may be affected by the fragments. According to the measured dose of neutrons at the surface of the SNF ~1.5×10^{10} n/s, we estimate the maximum flux of the fission fragments ~ 10^8 ions/cm^2/y. This crude estimate assures that the STE devices work for more than 100 years around SNFs without degradation.

Tolerance of thermoelectric devices based on SSE against swift heavy ion irradiation has been investigated [3]. It becomes clear that the spin thermoelectricity devices may work more than hundreds of years with radioactive thermal sources. The present study demonstrates that SSE-based devices are applicable to TE generation even in harsh environments for a long time period.

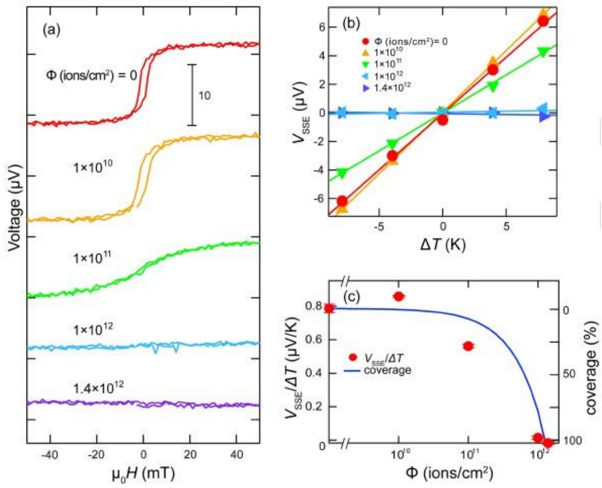

Fig.1-(a) Measured SSE voltage for the ion-irradiated samples with the fluence, Φ =0, $1\text{x}10^{10}$, $1\text{x}10^{11}$,$1\text{x}10^{12}$, and $1.4\text{x}10^{12}$ ions/cm^2 (from top to bottom). The output signals as a function of applied magnetic fields. The temperature difference ΔT between Pt and the substrate is fixed as 8 K.

-(b) The ΔT dependence of the SSE voltages with the different as-irradiated samples.

-(c) The fluence dependence of the SSE voltages and the calculated coverage ratio of the sample surface by the ion tracks (solid curve).

References

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