Nanostructured Bulk Thermoelectric Generator for Efficient Power Harvesting for Self-powered Sensor Networks

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NEET2

October 18-19, 2017
Goal, and Objectives
• Develop high-efficiency and reliable thermoelectric generators (TEGs)
• Demonstrate self-powered wireless sensor nodes (WSNs)

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Schedule 01/2015 - 12/2017

| Year 1 | • Determine and profile WSN power consumption  
|        | • Select thermoelectric materials with optimal performance  
|        | • Study irradiation effect on thermoelectric materials |
| Year 2 | • Develop a TEG and WSN simulator  
|        | • Design TEG of sufficient power output  
|        | • Complete analysis of irradiation effect |
| Year 3 | • Fabricate the TEG and test the TEG under irradiation effect  
|        | • Demonstrate the TEG-powered WSN prototype |
Background and motivation

- TEG is very compact and reliable
- Heat sources are very abundant in nuclear power plant and fuel cycles
- The nanostructured bulk thermoelectric materials have significantly higher efficiency and potentially improved radiation resistances over commercial bulk materials.
Thermoelectric Figure of Merit ZT

Device efficiency increases with ZT and ΔT

\[ ZT = \frac{\alpha^2 \sigma}{\kappa_E + \kappa_L} \]

Power factor: \( \alpha^2 \sigma \)

Seebeck coefficient

Electrical conductivity

Electronic thermal conductivity

Lattice thermal conductivity

\[ \eta_{\text{max}} = \frac{T_H - T_C}{T_H} \left( \frac{\sqrt{1 + ZT^2} - 1}{\sqrt{1 + ZT^2} + \frac{T_C}{T_H}} \right) \]
Accomplishments

The team achieved the following milestones for FY17

• Fabricated high-temperature and high-power-density thermoelectric generators (TEGs)

• Developed flexible TEGs by screen printing

• Performed comprehensive study of irradiation effect on thermoelectric materials and devices

• Demonstrated self-powered wireless sensor system
High-temperature Nanobulk TEG Fabrication Process

- TE Legs
- Unicouple
- TE module

Nanobulk Half-Heusler

- Nano Powder

Integrated TEG System
- Ultrahigh power density of 8.6 W/cm² at 600 °C and 0.75 W/cm² at 200 °C.

![Graphs showing TEG Device Testing Results](image)
Developed a novel additive printing process to fabricate flexible TE materials and devices.

A flexible thermoelectric device produces a power density of 16 mW/cm² with 80 ºC ΔT.
Irradiation Effect on Thermoelectric Materials

- Ion irradiation to simulate neutron damage:
  - 2.5 MeV Protons at 100 nA current and $2 \times 10^{16}$ ions/cm² fluence

- Two approaches to characterize property changes:

**Approach 1: SThM on Bulk Bar**
- Masks to block ions in select regions
- Incident Surface Scan
- Cross-Section Scan
- Irradiated Regions

**Approach 2: Thin Film Property Measurement**
- Entire depth is irradiated
- Bulk properties compared before and after irradiation
Irradiation Effect on Nanostructured Thermoelectric Materials

- 14% decrease in thermal conductivity
- No measurable change in Seebeck coefficient
- Maximum thermal conductivity reduction corresponds to the peak damage location;
- The average thermal conductivity reduces by 25% in the damaged region.
Standard Measurement on Irradiated Film

- 25% decrease in both electrical and thermal conductivities at room temperature;
- No change in Seebeck coefficient;
- Room-temperature ZT remains unchanged.
In-situ TEG Device Test During Gamma Irradiation

Gamma source: Co\textsuperscript{60}
In-situ Test of TEG Devices Under Gamma Irradiation

- Average dose rate: 6.14 kGy/hour
- Total received dose: 2360 kGy
- No measureable change in any nanostructured bulk half-Heusler device
- ~3.5% increase in resistivity of commercial BiTe module
• Four Main Design Portions:
  • **Power Management System**
    • DC/DC Converter
    • Battery Backup/Charger
  • **Embedded and Data Storage**
    • Microcontroller
    • USB/FTDI Programming
    • Micro SD Storage
  • **Wireless Transmission**
    • XBee Transceiver
  • **Sensing Inputs**
    • Thermocouple Input
    • Amplifier/Biasing
    • Additional sensor input
• The entire WSN consumes less than 0.4 W, which requires a TEG with <1 cm² with 200 °C heat source
• More input power is required when frequency of transmission is increased
Technology Impact

Impact on overall NE mission and the nuclear industry

- Address critical technology gaps in monitoring nuclear reactors and fuel cycle.
- Enable self-powered WSNs in multiple nuclear reactor designs as well as spent fuel storage facilities.
- Cost savings by eliminating cable installation and maintenance.
- Significant expansion in remote monitoring of nuclear facilities.
- Significantly improve sensor power reliability and thus safety in nuclear power plants and spent fuel storage facilities.
Conclusion and Future Work

- Developed high-temperature and high-power density TEGs;
- Developed flexible TEGs for power harvesting near ambient temperature;
- Performed comprehensive study on irradiation effect on thermoelectric materials. The nanostructured TE materials showed robust performances under proton and gamma irradiation;
- Built a WSN and tested the power consumption based on Zigbee protocol, and demonstrated a self-powered WSN prototype;
- The high-temperature TEGs we developed showed promises for in-pile power harvesting;
- Future work will focus on in-pile testing of the nanobulk TEGs.