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論 文 内 容 の 要 旨
Abstract of Dissertation

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In 2016, 72% of the world's energy corresponding to approximately 341 PJ, was reported to be lost during conversion and exhaust to the surrounding environment as a form of waste heat. Quickly, multiple countries and areas realize the enormous potential of waste heat and the technology start to see contribution is many countries and areas like United State, European and Japan.

Although waste heat recovery shows multiple successes and is taking measures against the global energy crisis, most of the recovered waste heat was in the medium to high-grade (>200 ^oC), leaving behind more than 63% of medium low-grade heat (<150 ^oC). Therefore, recent research is taking an attempt on recycling these high-potential low-grade heat, making them a promising sustainable power source for modern technologies like the Internet of Things, and Robotics. Pyroelectricity which can convert fluctuating heat to electricity shows its flexibility towards the nature characteristic of low-grade waste heat, can operate without additional cooling devices, making the technologies the most suitable ones for the sugested applications.

In this research, our group faces two big problems in conventional pyroelectric materials: 1) lack of materials for medium low-grade heat, and 2) being toxicity with lead usage. So far the lowest temperature for a conventional pyroelectric material to exhibit its best potential was above 130 ^oC. Furthermore, the materials use lead, which is a pure toxic substance and therefore, is one of many concerns in 17 Sustainable Development Goals (SDGs). As consequence, our group aims the development of a lead-free pyroelectric material that can convert waste heat at temperatures lower than 130 ^oC. The objective is to fulfill Goals 7 and 12 of SDGs, provide a sustainable renewable energy source from unused waste heat.

Lead-free $Ba(Zr_{0.1}Ti_{0.9})O_3$-BZT10 with a phase transition temperature of 93 ^oC, exhibits a high polarization was a promissing target in this research. The material undergoes a mix of ferroelectric-relaxor phases, which helps maintain the low phase transition temperature while enabling a large pyroelectric energy against the variation of temperature.

As a result, the BZT10 sample under a single heat source (no cooling assist) configuration exhibit a maximum power density of 8.9 mW/cm^3 at a temperature range of 70-90 ^oC. Efficiently utilizing the pyroelectric effect with the novel Kim cycle was the main reason for the significant increase in power generation ability. Furtherly taking the advantage of the novel Kim cycle, the power density of the BZT10 sample was enhanced, achieving 15 mW/cm^3 when increasing the temperature difference ΔT to 40 ^oC. Therefore, BZT10 has potential for an actual application; for instance, supplying power to a Bluetooth Low Energy in Internet of Things.

In addition, the BZT10 under a cooling assist configuration also shows a comparatively high energy density. The BZT10 sample exhibit the maximum potential of 504 mJ/cm^3 in the temperature range of 20-120 ^oC. This value is higher than any reported bulk-type lead-free

pyroelectric materials. Therefore, BZT10 composition is a potential and novel discovery for soft-type lead-free bulk ferroelectric materials used in energy harvesting applications.