Possibilities in Thermoelectric Conversion Using a New Principle: "Spin Seebeck Effect"

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Abstract

A thermoelectric (TE) conversion element is a promising candidate to enable the recovery of a vast amount of waste heat all over the world into useful electricity. There are several types of TE conversion elements being developed in the market, but a particularly promising one is being developed with a TE conversion technology that employs a novel mechanism based on the "spin Seebeck effect." This technology may bring innovation into the field of thermal energy, where mature technologies already exist. This paper describes the possibilities of the spin Seebeck effect: how it solves the issue of waste heat and how it recovers these heat sources into useful electricity.

Keywords

spin Seebeck effect, thermoelectric, waste heat utilization

1. Introduction

Worldwide energy consumption is increasing year after year due to the expanding economic scales of developing countries. If we simply ignore this situation and allow energy consumption to increase in a disorderly manner, we will face resource depletion and drastic climate change, which may lead to unfavorable consequences for our lives.

Therefore, a new technology is expected to be created that can appeal both to the economic efficiency of energy consumption and also to the reduction of environmental influences. This environment is accelerating the study and development of technologies to recover some of the vast amount of waste heat being discarded around the world every day.

2. Waste Heat Recovery with Thermoelectric Conversion Technology

Most of the waste energy in our society is discharged in the form of steam or hot water. It has been shown that the temperature of this discharged steam or water does not exceed 150 ℃ . When converting waste heat into electricity in this temperature range, sufficient conversion efficiency cannot be expected by using the TE conversion technology or no matter what technology is used. This makes it difficult to put waste heat recovery technology to practical use.

However, the practical study of TE conversion technology in the high temperature range, where reasonable conversion efficiency can be expected, is being actively promoted. For example, many countries have launched projects to recover the heat generated from automobile engines to achieve efficient fuel consumption. Such projects also meet the needs for the recent world trend of tightening automobile fuel consumption. Waste heat with a relatively high temperature can be collected from an automobile, so there is more potential to employ it to achieve a practical application of TE conversion technology[1]. It is reported that thermal engines such as the Rankine cycle, the Stirling cycle and a prototype device using the element using the Seebeck effect have achieved around a 10% improvement in fuel consumption efficiency[1].

However, the biggest issue with these technologies is that they are not profitable. In the automobile industry, the maximum cost to improve automobile fuel consumption by 1% is about 10,000 yen. However, none of the aforementioned technologies have achieved a sufficient cost performance to cope with this demand.

Looking at this fact from the other side, however, waste heat recovery technology in the high temperature range has the potential to create a new industry if it achieves economic feasibility and is applied for practical use. From there, it can be expected to lead to R&D of waste heat recovery technology in the low temperature range.

3. Features of Spin Seebeck Elements

Spin-TE conversion is a new TE conversion mechanism using the spin Seebeck effect[2]. It was demonstrated by a member of Saitoh Laboratory at Keio University in 2008 (the laboratory has since moved to Tohoku University). NEC has focused on the innovative aspects of this mechanism and has been promoting R&D with the aim of putting spin Seebeck elements to practical use by optimally employing the TE conversion mechanism[3].

The most prominent feature of a spin Seebeck element is its simple structure. **Fig. 1** shows a photo of an element formed on the surface of a glass substrate along with a schematic structure of the element. As shown in the schematic illustration, the element structure consists of two layers of film: a magnetic insulator and a conductor. The materials employed are bismuth-substituted yttrium iron garnet (Bi:YIG) for the magnetic insulator film and platinum (Pt) for the conductor film. **Fig. 2** illustrates the schematic structure of a Seebeck element using a standard semiconductor with a p-n junction. This clearly shows the differences between it and a spin Seebeck element.

With a Seebeck element, n-type and p-type semiconductor blocks are connected in series inside the element, so that the structure of the element has to be complicated to increase thermoelectric power.

However, with a spin Seebeck element, electromotive force is induced along the conductor film. By setting a distance between the terminals longer, a larger amount of electromotive force can be obtained. Furthermore, the amount of electricity can be increased in proportion to the area of the element surface. Such simple structure and easy scalability provide various advantages for a variety of products.

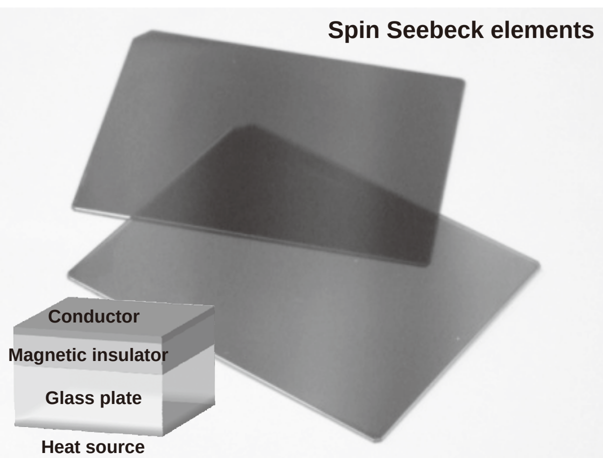

Fig. 1 Spin Seebeck element and its schematic structure.

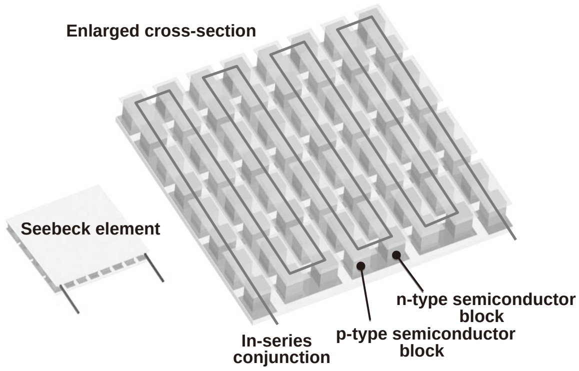

Fig. 2 Schematic illustration of the modular structure of a conventional Seebeck element.

First of all, since a simple coating process is used to form the element layer, it can be applied over a large area at low cost.

Secondly, the element can be applied to various shapes of materials.

It has actually been confirmed that sufficient TE conversion performance can be acquired with an element formed by the coating process and also with an element formed on a flexible surface substrate.

4. Opportunities for Spin Seebeck Elements

Another significant feature of the spin Seebeck element is its potential conversion efficiency, which is expected to be superior to that of a conventional Seebeck element. **Fig. 3** explains the differences in mechanism between a Seebeck element and a spin Seebeck element.

First, when applying a temperature difference (temperature gradient) to both ends of the element, heat flow (thermal current) is generated.

With a Seebeck element, when heat flow is generated in the element, some of the heat flow is converted into a certain amount of electrical current and it all flows in the same direction. The efficiency of the conversion from heat flow to electrical current can be improved by applying either of the following countermeasures: reducing the heat conductance in the element, or employing an element material with superior electrical conductance. However, the heat conductance is limited by the number of electrons in the conductor or semiconductor, so these countermeasures cannot be applied independently. This physical restriction, known as the Wiedemann-Franz law,

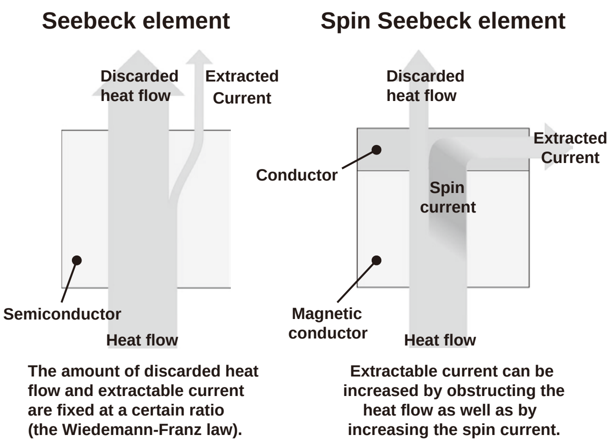

Fig. 3 Differences in the mechanism of semiconductor-type and spin current TE conversion elements.

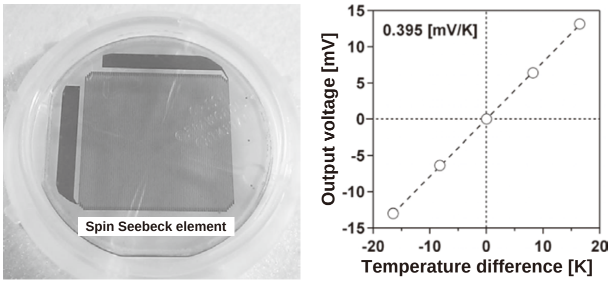

Fig. 4 Electromotive force accumulation experiment using a spin Seebeck element.

is a major obstacle to improving the properties of Seebeck elements.

Spin-TE conversion demonstrates a TE conversion mechanism that is free from the Wiedemann-Franz law. This is the key advantage of spin-TE conversion. The heat flow applied to a spin Seebeck element generates a flow of spin angular momentum via localized spins in the magnetic insulator. This is the so-called "spin Seebeck effect" that generates spin current. The spin current is then induced in the paramagnetic transition metal (TM), and converted into an electrical current by means of the inverse spin Hall effect (ISHE). The ISHE converts spin current into electrical current that flows in directions orthogonal to the directions of heat flow and spin current and this electricity can then be extracted.

Due to the above principles, the TE conversion efficiency of a spin Seebeck element can be improved by independently controlling the heat conductance of the magnetic insulator to be depleted and the electrical conductance of the conductor to be increased on each material. This is a feature that the conventional Seebeck element cannot achieve, and the reason why the spin Seebeck element is expected to be significantly superior in its performance.

As described before, the device uses a simple two-layer element structure. This simple structure enables a simple coating-based process and results in the advantage of producing an element with a large area at low cost.

Finally, the features of the spin Seebeck element are explained below. **Fig. 4** shows a photo of the element and the measurement results of its output voltage power. The elements are connected in series by patterning the conductor film to accumulate the electromotive force of each spin Seebeck element. A TE conversion coefficient of 0.395 mV/K is achieved, as shown in the plot of the temperature dependency of thermoelectric power. As described so far, efficient accumulation of electromotive force is available through the spin Seebeck element by employing the same procedure employed for the conventional Seebeck element. In comparison with properties of the conventional semiconductor-type Seebeck element, those of the spin Seebeck element currently fabricated are still inferior; the conversion coefficient is small and the element's internal resistance is large. This means that it needs to be improved further to achieve practical performance as a power source.

The output power of the element can be increased by modifying the thickness of the element to some mm size and by improving its material properties, so that the performance of the element can be improved to a level that is superior to conventional semiconductor-type elements.

5. Conclusion

Thermoelectric (TE) conversion elements are expected to be a significant technology for recovering the waste heat discarded by society. Current study and development in this area is mainly concerned with semiconductor-type Seebeck elements. However, if the spin Seebeck element can demonstrate its superiority in conversion efficiency, low-cost feasibility and long-durability performance over conventional Seebeck elements, it may change the market drastically and expand the potential market even further. NEC will continue its challenge to promptly develop the spin Seebeck element for practical use, so that we can establish a society that can optimally use more waste heat.

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