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Potential of thermoelectric power generation using anomalous Nernst effect in magnetic materials

Yuya Sakuraba

National Institute for Materials Science, Sengen 1-2-1, Tsukuba, Japan

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ABSTRACT

This article introduces the concept and advantage of thermoelectric power generation (TEG) using anomalous Nernst effect (ANE). The three-dimensionality of ANE can largely simplify a thermopile structure and realize TEG systems using heat sources with a non-flat surface. The improvement of *ZT* can be expected because of the orthogonal relationship between thermal and electric conductivities. The calculations of an achievable electric power predicted that an improvement of thermopower by one order of magnitude would open up a usage of practical applications.

1. Introduction

Seebeck effect (SE), which originates from a diffusion of charged carrier excited by applying a temperature gradient to conductive materials, is a representative thermoelectric phenomenon. Thermoelectric power generation (TEG) using SE has been expected as an ecological technique to generate electricity from waste/environmental heat because it can directly convert thermal energy to electric energy without any mechanical and chemical mediations. However, it is still a challenging task to find/synthesize new materials having a large dimensionless figure of merit *ZT* to improve energy conversion efficiency. On the other hand, another thermoelectric phenomenon called Nernst effect (NE) arises when we also apply an external magnetic filed ($\vec{B}_{ex}$) together with a temperature gradient ∇T to the conductive material. The electric filed from Nernst effect ($\vec{E}_{NE}$) appears to the outer product direction of $\vec{B}_{ex}$ and ∇ as expressed below using Nernst coefficient Q_0.

$$\vec{E}_{NE} = Q_0(\vec{B}_{ex} \times \nabla T) \tag{1}$$

Here NE will be compared with SE about the magnitude and the geometrical relationship of heat and electric transports. In SE there is a one-dimensional relationship between the heat and carrier transports, i.e., the electric field from SE ($\vec{E}_{SE}$) always generates to the same axis direction of ∇T as expressed in $\vec{E}_{SE} = S_{SE} \cdot \nabla T$. Here S_{SE} represents Seebeck coefficient, which is a sole parameter that determines the magnitude and the direction of $\vec{E}_{SE}$. In contrast, Nernst effect is a three-dimensional effect where the electric field occurs to the perpendicular direction to both $\vec{B}_{ex}$ and ∇T. Since the magnitude of Nernst effect can be enlarged by increasing magnetic field B_{ex}, Nernst effect has been studied to enhance thermoelectric power generation and cooling effects by applying strong magnetic field [1–5]. Wolfe et al. have successfully showed that the figure of merit of a single-crystal Bi-Sb becomes 2.8 times larger by applying 1.7 T than that without magnetic field [4]. However, the usage of Nernst effect for practical applications is not easy because of the necessity of strong external magnetic field from an electrical magnet or permanent magnet.

2. Advantages in thermoelectric power generation using anomalous Nernst effect

In ferromagnetic materials such as Fe, spontaneous magnetization $\vec{M}$ gives rise to strong Nernst effect without applying external magnetic field, which is called anomalous Nernst effect (ANE). The electric field generating from ANE ($\vec{E}_{\mathrm{ANE}}$) is written in the following formula by changing Q_0 and $\vec{B}_{ex}$ in Eq. (1) to Q_S and $\mu_0\vec{M}$, respectively.

$$\vec{E}_{\mathrm{ANE}} = Q_S(\mu_0\vec{M} \times \nabla T) \tag{2}$$

Here Q_S is anomalous Nernst coefficient that determines the sign and magnitude of ANE. There is a geometrical analogy between anomalous Hall effect(AHE) and ANE; the electric field $\vec{E}$ arises from the spontaneous magnetization $\vec{M}$ to its perpendicular direction but excited by electric current in the former and heat

E-mail address: Sakuraba.Yuya@nims.go.jp

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currents in the latter. In contrast to above-mentioned Nernst effect induced by an external magnetic field, ANE arises without applying magnetic field. Therefore, Sakuraba et al. proposed that there are several technological benefits to use ANE for a practical TEG by utilizing its three-dimensionality [6,7]. Since the direction of $\vec{E}_{ANE}$ is always perpendicular to ∇T, we can increase a serial electric voltage by making laterally connecting ferromagnetic wires as shown in Fig. 1(a). $\vec{E}_{ANE}$ appears to the direction along the wires (x-direction) by giving ∇T to the z-direction and align $\vec{M}$ to the y-direction, thus anomalous Nernst voltage V_{ANE} can be proportionally increased with the total length of the wires. As suggested in Ref. [6], this simple lateral connection of thermopiles has several unique advantages in comparison with general TEG using the Seebeck effect;

(i) ANE-based TEG can be applied to large size (over square-meter) heat sources because the fabrication process to make a lateral thermopile structure is easier than for conventional SE-based perpendicular thermopile. ANE-based TEG does not require a flatness of the heat source, thus can be applied to a heat source with a round/rough surface. It is also expected that a flexible thermoelectric device is easily fabricated by ANE because of their simple structure. In addition, if we use a tube/cylinder-shaped heat source as shown in Fig. 1(b), it is not necessary to make a thermopile structure anymore to increase V_{ANE}. Because $\vec{E}_{ANE}$ is always generated to the tangent direction in the wound ferromagnetic wire, V_{ANE} can be increased by rolling one ferromagnetic wire spirally.

(ii) The controllability of an internal resistance is high in ANE-based TEG because the internal resistance can be changed by the thickness and width of ferromagnetic wires. Additionally, the number of contact can be small, which leads to low contact resistance and high mechanical endurance. It should be mentioned here that, to control an internal resistance is impossible in the TEG using spin-Seebeck effect [8] because an electric voltage from spin-Seebeck effect inevitably decreases with increasing thickness of the non-magnetic metal which generates an electric voltage inverse spin-Hall effect.

(iii) Another interesting feature demonstrated in Ref. [6] was the thermopiles using only one ferromagnetic material. Because the direction of $\vec{E}_{ANE}$ can be controlled by the direction of $\vec{E}_{ANE}$ as expected from Eq. (2), a thermopile consisting of two ferromagnetic wires having different coercive field (H_C) can increase V_{ANE} by reversing $\vec{M}$ only in one wire having smaller H_C as shown in **Fig. 2**. It is not difficult to obtain a difference of H_C even in the same ferromagnetic material by changing the number of defects and impurities, thus ANE-based TEG does not require to find two materials having high negative and positive $|Q_S|$ practically.

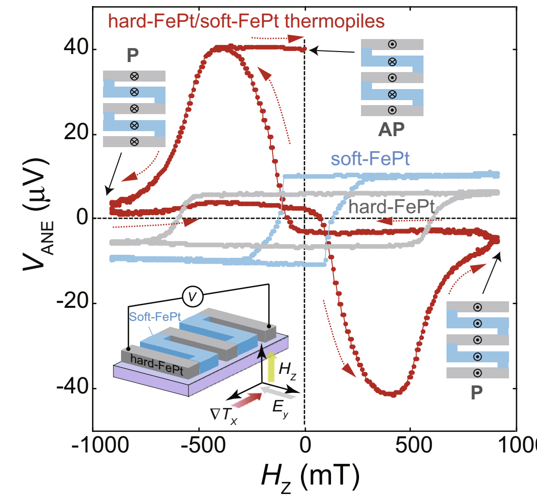

Fig. 2. Magnetic field H_Z dependence of V_{ANE} in the thermopiles consisting of only FePt having different coercive fields in neighboring FePt wires. The thermopiles have two soft-FePt and three hard-FePt wires. The serial V_{ANE} can be increased by realizing anti-parallel (AP) magnetization configuration in neighboring FePt wires even at zero magnetic field [6].

3. Previous studies on anomalous Nernst effect in ferromagnetic materials

As mentioned in the former section, many unique advantages are obtainable if we are able to utilize ANE for practical TEG applications. However, it is just pie-in-the-sky if we cannot improve a thermopower of ANE ($S_{ANE} = \mu_0 M_S Q_S$) because the reported values for S_{ANE} are still limited and not large so far due to a limited number of studies for ANE. Small S_{ANE} has been reported in several ferromagnetic metallic materials because of small S_{SE}, 1–2 μV/K in ferromagnetic amorphous alloys such as $Fe_{77}Ni_1Si_9B_{13}$ [9,10], −1.8 μV/K in $CuCr_2Se_{4-x}Br_x$ [11], about 1 μV/K in FePt with a high uniaxial magnetic anisotropy [6,12] at around 300 K. In the magnetic semiconductor $Ga_{1-x}Mn_xAs$, relatively high S_{ANE} of about 10 μV/K was reported only at low temperature because of low Curie temperature below 150 K [13]. Thus, it must be mentioned that the research for an ANE-based thermoelectric application is still in fundamental and exploratory stage. In other words, however, there are a lot of new materials to be explored for making practical applications more realistic.

The strategy to obtain a higher S_{ANE} can refer to the previous plenty of the experimental and theoretical studies on AHE and spin-Hall effect (SHE) because an asymmetric deflection/scattering of up and down-spin electrons is basically the origin of all these phenomena. It has been almost established that there are intrinsic and extrinsic origins for AHE and SHE; the former originates from an anomalous velocity of the carrier depending on

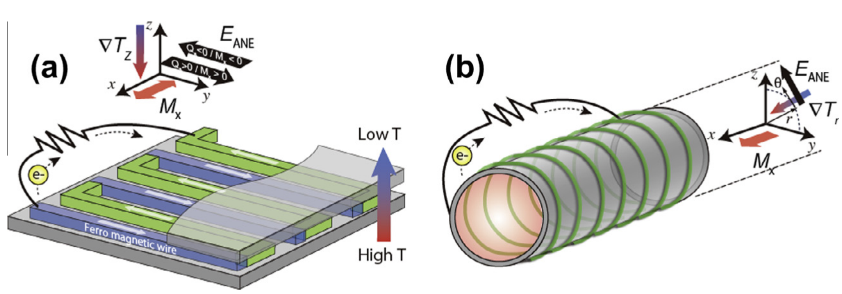

Fig. 1. Examples of TEG based on ANE using the plane-shaped (a) and tube-shaped (b) heat sources. M_x represents the magnetization of ferromagnetic wires [6,7].