Abstract
Generation of electric power by the Nernst effect is a new application of a semiconductor. A key point of this proposal is to find materials with a high thermomagnetic figure-of-merit, which are called Nernst elements. In order to find candidates of the Nernst element, a physical model to describe its transport phenomena is needed. As the first model, we began with a parabolic two-band model in classical statistics. According to this model, we selected InSb as candidates of the Nernst element and measured their transport coefficients in magnetic fields up to 4 Tesla within a temperature region from 270 K to 330 K. In this region, we calculated transport coefficients numerically by our physical model. For InSb, experimental data are coincident with theoretical values in strong magnetic field.

1 Introduction
One of the authors, S. Y., proposed [1] the direct electric energy conversion of the heat from plasma by the Nernst effect in a fusion reactor, where a strong magnetic field is used to confine a high temperature fusion plasma. He called [1, 2] the element which induces the electric field in the presence of temperature gradient and magnetic field, as Nernst element. In his papers [1, 2], he also estimated the figure of merit of the Nernst element in a semiconductor model. In his results [1, 2], the Nernst element has high performance in low temperature region. To calculate transport coefficients in a magnetic field, we use the two-band model, In

2 Theoretical calculations
As the physical model to describe transport phenomena of the material in the Nernst element, we use a parabolic two-band model in the classical statistics. We have the following parameters of this model;

\begin{itemize}
\item \( m_n \) (\( m_p \)): effective mass of electron (hole),
\item \( \varepsilon_D \) (\( \varepsilon_A \)): energy level of a donor (an acceptor),
\item \( N_D \) (\( N_A \)): concentration of donors (acceptors),
\item \( \mu_n \) (\( \mu_p \)): mobility of an electron (a hole),
\item \( \varepsilon_F \): energy gap, \( \varepsilon_F \): fermi energy.
\end{itemize}

Using these parameters, we obtain concentrations of carriers as follows:

\begin{align}
n(T) & = N_C(T) \exp \left( \frac{-\varepsilon_F - \varepsilon_G}{kT} \right), \quad (1) \\
p(T) & = N_V(T) \exp \left( \frac{-\varepsilon_F}{kT} \right), \quad (2)
\end{align}

where \( n(p) \) is the concentration of free electron (hole). Here \( N_C \) (\( N_V \)), the effective density of state in the conduction (valence) band is given by

\begin{align}
N_C(T) & = 2 \left( \frac{2m_n \pi kT}{\hbar^2} \right)^{\frac{3}{2}}, \quad (3) \\
N_V(T) & = 2 \left( \frac{2m_p \pi kT}{\hbar^2} \right)^{\frac{3}{2}}. \quad (4)
\end{align}

We also obtain the concentration of electrons (holes) in the donor (acceptor) level, \( n_D \) (\( p_A \)) as follows:

\begin{align}
n_D & = N_D \frac{1}{1 + \frac{1}{2} \exp \left( \frac{-\varepsilon_D - \varepsilon_F}{kT} \right)}, \quad (5) \\
p_A & = N_A \frac{1}{1 + 2 \exp \left( -\frac{-\varepsilon_A + \varepsilon_F}{kT} \right)}. \quad (6)
\end{align}

We suppose the charge neutrality as

\begin{equation}
N_D - n_D + p(T) = N_A - p_A(T) + n(T). \quad (7)
\end{equation}

Substituting the concentrations of carriers with eqs. (1)-(6) in eq. (7), we obtain the following algebraic equation in value \( x = \exp(\varepsilon_F/kT) \) as

\begin{align}
sux^4 + (u + N_A s + stu) x^3 + (N_A - N_D + ut - N_V s) x^2 - (N_D t + N_V + N_D st) x - N_V t & = 0, \quad (8)
\end{align}
where
\[ s = 2 \exp \left( \frac{\varepsilon_D - \varepsilon_G}{kT} \right), \]
\[ t = \frac{1}{2} \exp \left( \frac{\varepsilon_A}{kT} \right), \]
\[ u = N_c \exp \left( -\frac{\varepsilon_G}{kT} \right). \] (9)

Using the fermi energy which is given from eqs. [8] and [9], we can solve the Boltzmann equation of this model in a magnetic field with a perturbation theory and the relaxation time approximation. See Ref. [1] for details. Here we define the following parameters to simplify formulation as
\[ \eta \equiv \frac{\varepsilon_A}{kT}, \gamma = \frac{2m_n kT}{\hbar^2}, \beta_0 = \frac{\sqrt{\pi} \mu_n B}{4z}, \beta = \frac{\beta_0}{4} \sqrt[4]{\frac{kT}{\varepsilon_G}}. \] (10)

We also define the following integrals as
\[ I_i (\beta_0) = 4 \gamma^{-1} \int_0^\infty x^i \exp \left( \eta - x \right) \frac{1}{1 + \frac{x}{2\sqrt{\pi}}} \] (11)
\[ J_i (\beta_0) = 16 \gamma^{-\frac{3}{2}} \int_0^\infty x^{j} \frac{1}{1 + \frac{x}{2\sqrt{\pi}}} \exp \left( \eta - x \right). \] (12)

Using the above eqs. [10] - [12], we obtain transport coefficients in a magnetic field \( B \), as follows:
\[ \sigma (B) = \sigma (0) \frac{I_2^2 + (\beta J_1)^2}{I_1 (0) I_1}, \] (13)
\[ R_{H} (B) = \frac{3\pi^2}{2e^2} \frac{n J_1}{I_1 (0) I_1 + (\beta J_1)^2}, \] (14)
\[ \alpha (B) = \frac{k}{ze} \left\{ \frac{I_1 I_2 + \beta^2 J_1 J_2}{I_1^2 + (\beta J_1)^2} \right\}, \] (15)
\[ \beta (B) = N (B) B = \frac{k\beta}{ze} \left\{ \frac{J_1 J_2 - I_1 J_2}{I_1^2 + (\beta J_1)^2} \right\}, \] (16)

where is the conductivity, \( R_{H} \) the Hall coefficient, \( \alpha \) the thermoelectric power, and \( N \) the Nernst coefficient for electron \((z = -1)\). For hole \((z = 1)\), we must use \( p, \eta + \varepsilon_G \), and \( \mu_p \) instead of \( n, \mu_n \) and \( \eta \). Relations between these one-band transport coefficients and the two-band ones are written as [1]
\[ \sigma = \frac{D}{\sigma_1 (1 + B^2 R_{H1}^2 \sigma_2^2) + \sigma_2 (1 + B^2 R_{H2}^2 \sigma_1^2)}, \] (17)
\[ R_{H} = \frac{1}{B^2} \times \left\{ R_{H1} \sigma_1^2 + R_{H2} \sigma_2^2 + B^2 R_{H1} R_{H2} \sigma_1^2 \sigma_2^2 (R_{H1} + R_{H2}) \right\}, \] (18)
\[ \alpha = \frac{1}{B^2} \times \left\{ \sigma_1 (\sigma_1 + \sigma_2 + \sigma_1^2 \sigma_2^2 R_{H2} (R_{H1} + R_{H2}) B^2) \right\}, \] (19)
\[ \times \left\{ \sigma_2 (\sigma_1 + \sigma_2 + \sigma_1^2 \sigma_2^2 R_{H1} (R_{H1} + R_{H2}) B^2) \right\} \] (20)
\[ + \sigma_1 \sigma_2 (N_1 - N_2) (R_{H1} \sigma_1 - R_{H2} \sigma_2) B^2 \]

where the subscripts 1 and 2 denote the contribution from conduction and balance bands, respectively. The parameter \( D \) is described as
\[ D \equiv (\sigma_1 + \sigma_2)^2 + B^2 \sigma_1 \sigma_2 (R_{H1} + R_{H2})^2. \] (21)

By the above algorithm, we calculate the transport coefficients in a magnetic field. In this calculations, we must prepare physical quantities i.e. effective masses, energy levels, concentrations of impurities, mobilities, energy gap. From the previous works [8], we can get the following parameters:
\[ m_n = 0.0152 m_0, \]
\[ m_p = 1.1140 m_0, \]
\[ \varepsilon_G = 0.210 eV, \]
\[ \varepsilon_D = 0.0007 eV, \]
\[ \varepsilon_A = 0.002 eV, \]
\[ \mu_n = 38000 T^{-1.5} m^2/V/s, \]
\[ \mu_p = 1056.8 T^{-1.5} m^2/V/s, \]
\[ N_D = 2.1 \times 10^{22} m^{-3}, \]
\[ N_A = 0, \] (22)

where \( m_0 \) is the bare electron mass. Using eq. [22], we calculate transport coefficients.

3 Comparison between experimental and theoretical results

We measured transport coefficients of indium antimonide in a magnetic field. The sample \( X \) has the electron carrier concentration \( n = 6.6 \times 10^{20} m^{-3} \) and mobility \( \mu_n = 21 m^2/V/s \) at 77K. The sample \( B \) has \( n = 2.1 \times 10^{22} m^{-3} \) at 77K.

The conductivity and the Hall coefficient are measured by the van der Pauw method. The thermoelectric power and the Nernst coefficient are also measured for the bridge shaped sample [8]. In Fig. 1, we plot the thermoelectric power of \( \text{InSb} \) as a function of magnetic field. The Nernst coefficient of \( \text{InSb} \) is plotted in Fig. 3. These figures show that these transport coefficients can be calculated by the two-band model. For InSb, we also measured the conductivity, the Hall coefficient the thermoelectric power and the Nernst coefficient. These results are plotted in Figs. 4-6. These transport coefficients given by the theoretical calculations are coincident with the experimental values.

4 Discussion and conclusions

From comparison the experimental and the theoretical values, we conclude that the two-band model is enough good model to estimate the transport coefficient. We need to measure thermal conductivity to estimate the thermomagnetic (i.e. Nernst) figure-of-merit \( Z_N = \sigma (NB)^2 / \kappa \). The thermal conductivity has phonon scattering mechanism. We, therefore, improve the physical model to include the phonon scattering
Figure 1: Thermoelectric power versus magnetic field of InSb_X at 308K

Figure 2: Nernst Coefficient multiplied by magnetic field $NB$ versus magnetic field of InSb_X at 308K

Figure 3: Electrical conductivity versus magnetic field of InSb_B at 273K and 353K

Figure 4: Hall coefficient versus magnetic field of InSb_B at 273K and 353K
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