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On the Electromagnetic Properties of Single Crystals of Tellurium. II
Ettingshausen-Nernst Effect*

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Synopsis

The Ettingshausen-Nernst effect of a single crystal of highly purified tellurium has been measured over the temperatures ranging from −160 to +300°C. In the intrinsic semiconductor range of temperature, it was found that the value of coefficient of this effect is roughly in agreement with that evaluated theoretically from the values of the electron and hole mobilities and the width of the forbidden region, which were deduced by analysing the experimental values of the conductivity, the Hall coefficient and the magneto-resistance coefficient measured on the same specimen.

I. Introduction

In the preceding paper(1), we have reported the measurements of the electrical conductivity, the Hall effect and the magneto-resistance effect of the single crystals of highly purified tellurium over the temperatures ranging from −190 to +300°C. By analysing these data, it became evinced that tellurium crystal is normally a P-type extrinsic semiconductor at low temperatures and transmutes into an intrinsic semiconductor as the temperature rises; and also could estimate the width of the forbidden region, the concentrations, the mobilities, the mean free paths and the effective masses of electrons and holes in the intrinsic semiconductor range of temperature. The thermoelectric power calculated from these quantities were in conformity with the observed values qualitatively.

In the present paper, we shall describe the Ettingshausen-Nernst effect of the same crystal measured concurrently with the four quantities mentioned above and show that this effect can also be explained by utilizing the knowledge of the width of forbidden region and the mobilities of electrons and holes obtained in the paper I.

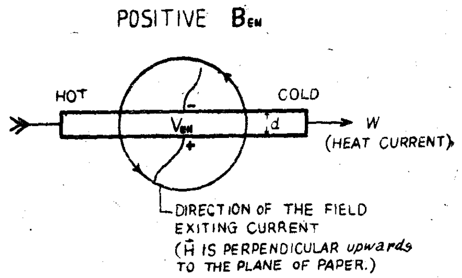

Fig. 1. The sign convention for the Ettingshausen-Nernst effect.

When there is a temperature gradient or a thermal current along the length of a specimen and a magnetic field is applied normal to the temperature gradient, a

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* The 562nd report of the Research Institute for Iron, Steel and Other metals.

(1) The present writers: Sci. Rep. RITU, 1 (1949), 373/86; this will be referred to as "Paper I" hereafter.

potential difference is brought forth in the direction perpendicular both to the temperature gradient and to the magnetic field, as shown in Fig. 1; this phenomenon is called Ettingshausen-Nernst effect(2)* after the names of the discoverers. The said potential difference, V_{EN}, satisfies the next relation with a proviso that the temperature gradient, $-dt/dl$, and the magnetic field strength, H, are not very large.

$$V_{EN} = B_{EN} \cdot H \cdot \left(-\frac{dt}{dl}\right) \cdot D . \qquad (1)$$

in which D stands for the diameter of the specimen. The constant B_{EN}, the Ettingshausen-Nernst coefficient, has either a positive or a negative sign corresponding to the polarity of the transverse potential gradient in relation to the directions of the temperature gradient and the magnetic field. That is, B_{EN} is ordinarily defined to be positive in the case of Fig. 1 and to be negative when the potential set in towards the opposite direction(2).

I. Experimental method

(i) Specimen

The Kahlbaum tellurium was distilled fractionally in high vacuum repeating three times, though still it was shown to contain $10^{-2} \sim 10^{-3}$ per cent of tin and a smaller trace of copper by means of the spectroscopic analysis. This highly purified tellurium was cast in vacuo in a pyrex glass tube and solidified in a single crystal by cooling from one end with a suitable rate. The specimen has a circular section 0.16 cm in diameter and is about 2.2 cm long, whose length making an angle 6.0° with the principal [0001] axis and has been named "specimen I" in the paper I.

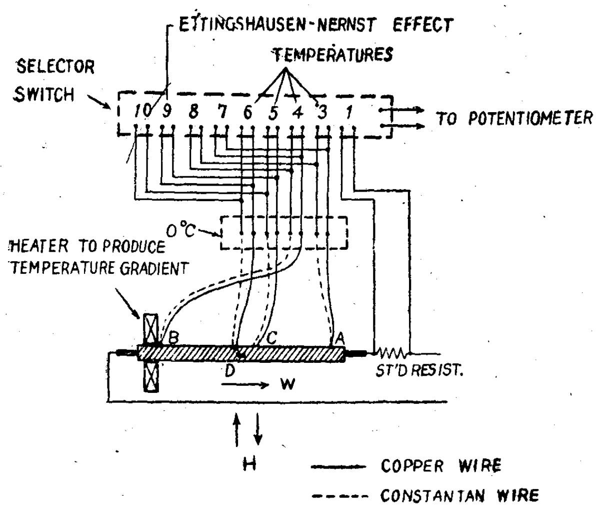

Fig. 2. Schematic diagram of experimenting arrangement.

(ii) Method of measurement

In the paper I, the method of simultaneous measurement of the electrical conductivity, the Hall effect, the magneto-resistance effect and the thermoelectric power was given in detail, but we did not give a description on the Ettingshausen-Nernst effect which has also been measured together with the aforesaid properties. So the measurement of the last effect will be described here. Fig. 2 is the schematic diagram of the measuring circuit which was already given in the paper I. Junction points of the four pairs of copper

(2) W. Meissner, Handb. d. exp. Phys. XI 2 teil (1935), 311.
L. L. Campbell, *Galvanomagnetic and Thermomagnetic effects*, (1923), 211.

* This effect is also called the Nernst effect, but this nomenclature is apt to be confused with the effect producing a longitudinal temperature difference which set in under a longitudinal electric current and a transverse magnetic field.

(BS#35)-constantan(BS#40) thermocouple have been welded respectively to the points A, B, C, and D on the specimen by dint of a condenser discharge method. In order to establish a temperature gradient along the specimen, a discal ring-shaped heater, which was made by winding constantan wire (BS#40) on a brass bobbin so as to afford the power of 0.1 watt at the highest, was put on an end of the specimen and fixed with phosphoric acid cement. When a suitable temperature gradient is being maintained (the temperature difference between A and B is 2°~13°) by the aid of this heater, temperature readings at A, B, C, and D, viz. t_3, t_4, t_5, and t_6, were taken and then applying the magnetic field H, the change of potential difference between C and D, i. e. V_{EN}, was measured. On reversing the polarity of the magnetic field, V_{EN} also changes its sign. With a view to eliminating the parasitic thermoelectric effects, we used to adopt the mean value of the absolute magnitudes of two V_{EN}'s of different signs.

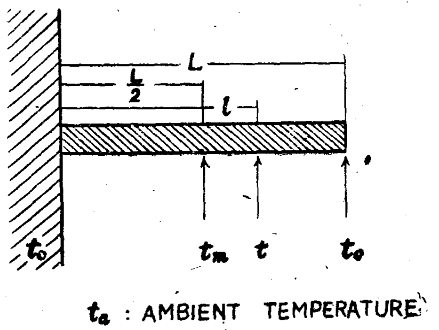

Fig. 3. The idealized schema of the temperature distribution along the specimen.

The temperature gradient $-dt/dl$ was estimated as follows. When a rod juts out from an infinitely spread plane wall as illustrated in Fig. 3, the temperature distribution along the rod is expressed by the next equation.

$$t-t_a=(t_o-t_a)\cdot\exp\left(-\sqrt{\frac{\alpha p}{\kappa s}}\,l\right). \tag{2}$$

where α represents the coefficient of heat transfer, κ the heat conductivity, s the sectional area of rod and p the peripheral length of the section. From this equation, the temperature gradient at the mid point of rod is given by

$$\left(-\frac{dt}{dl}\right)_{l=\frac{L}{2}}=\frac{2}{L}\left(\frac{1}{t_m-t_e}-\frac{1}{t_o-t_m}\right)^{-1}\log\frac{t_o-t_m}{t_m-t_e}. \tag{3}$$

The actual boundary conditions surrounding the specimen are not reconciled perfectly with those which are displayed in Fig. 3, for instance, the heater is not sufficiently large in dimension, current leads are welded at both ends of the specimen and so forth; but to make the actual estimation of $-dt/dl$, Eq. (3) appears to be available most approximately for our case. Hence by substituting $t_e=t_3$, $t_o=t_4$, $t_m=\overline{t_{5,6}}\equiv\frac{1}{2}(t_5+t_6)$, $L=l_{AB}$ we can evaluate $-dt/dl$ from Eq. (3). Thus V_{EN}, H, $-dt/dl$, and D having become known in Eq. (1), the Ettingshausen-Nernst coefficient B_{EN} is now obtained.

III. Experimental results and theoretical consideration

Fig. 4 proves the existence of the linear relationship between V_{EN} and H. Two sorts of points (○, +) stand for the magnitudes of $|V_{EN}|$ corresponding to the opposite polarities of the magnetic field. In Fig. 5 the Ettingshausen-Nernst coefficients B_{EN}* is plotted as a function of temperatures, of which the potentials

* $B_{EN}^{\text{emu}}=\left(V_{EN}^{\text{volt}}\right)\left(H^{\text{oersted}}\right)^{-1}\left(-\frac{dt}{dl}\ \text{deg}\cdot\text{cm}^{-1}\right)^{-1}\left(D\ \text{cm}\right)^{-1}\times10^{8}.$

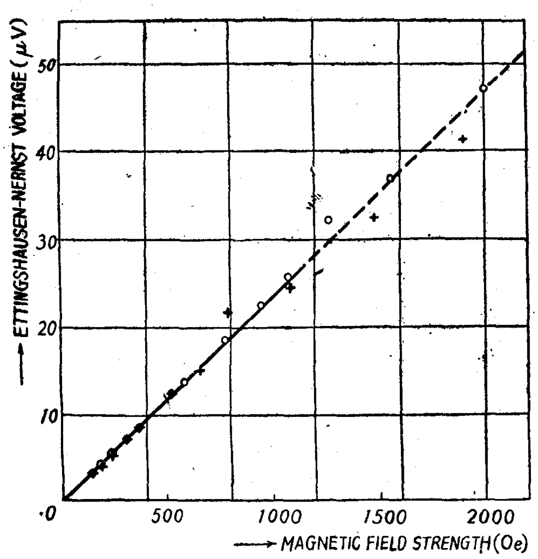

Fig. 4. Relationship between the Ettingshausen-Nernst voltage and the magnetic field strength. Two sorts of points (○, +) correspond to the reversed field directions. $t_3=25.1$°C, $t_4=11.1$°C, $\bar{t}_{5,6}=13.5$°C, $-\frac{dt}{dl}=5.53$ deg·cm^{-1}, $L=1.70$ cm, $d=0.163$ cm, $B_{EN}=2.64$ emu.

in concern have been measured simultaneously with the other data illustrated by the I 2 curves in the paper I. In this figure, $\bar{t}_{5,6}$'s are taken as the temperature scale on the abscissa. Wold[(3)] found a similar characteristic on the Ettingshausen-Nernst coefficients of a pure tellurium crystal above room temperature, but the magnitudes of his values are smaller than ours by a factor of about 2/5.

Johnson and Lark-Horovitz[(4)] deduced the following expression representing the Ettingshausen-Nernst coefficient of a composite semiconductor as a function of the several attributes concerning both electrons and holes.

$$B_{EN}=\frac{-3\pi}{8c|e|}(n_e\mu_e+n_h\mu_h)^{-1}\times\left[\frac{3k}{2}(n_e\mu_e^2+n_h\mu_h^2)+T\left\{n_e\mu_e^2\frac{d}{dT}\left(\frac{\zeta_e}{T}\right)+n_h\mu_h^2\frac{d}{dT}\left(\frac{\zeta_h}{T}\right)\right\}\right]. \quad (4)$$

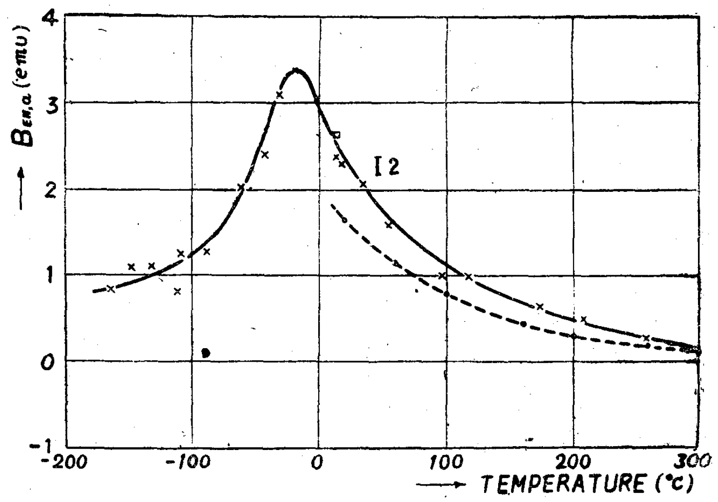

Fig. 5. Relation between the Ettingshausen-Nernst coefficient and the temperature. The square at 13.5°C corresponds to the value of Fig. 4. The dashed line is calculated from Eqs. (5) and (6).

where n_e is the number of electrons per unit volume, μ_e electronic mobility, ζ_e chemical potential for electrons, with subscript h pertaining to holes. In the intrinsic semiconductor range, we can take $n_e \fallingdotseq n_h$, $\zeta_e=\zeta_h=\frac{\Delta E}{2}$, in which $\Delta E=\Delta E(o)+\beta T$ is the width of forbidden region. Then Eq. (4) can be written in a simpler form as next.

(3) P. I. Wold, Phys. Rev., 7 (1916), 188
(4) V. A. Johnson, K.Lark-Horovitz, Phys. Rev., 73 (1948), 1257.
They calculated the quantity $Q'=\frac{E}{HW}$, in which W is the thermal current density and E is the transverse Ettingshausen-Nernst electric field. Hence, κ being the heat conductivity, $W=-\frac{dt}{dl}\kappa$ and $E=\frac{V_{EN}}{D}$, thereby $B_{EN}=\kappa Q'$.

$$B_{\text{EN}} = \frac{-3\pi k}{8c\,|e|}\left(\frac{3}{2} - \frac{\Delta E(o)}{2kT}\right)\left(\frac{\mu_e^2+\mu_h^2}{\mu_e+\mu_h}\right) \tag{5}$$

$$\doteqdot 1.12\times10^{-17}\left(-1.50 + \frac{\Delta E(o)}{1.72\cdot10^{-4}T}\right)\left(\frac{\mu_e^2+\mu_h^2}{\mu_e+\mu_h}\right). \tag{5'}$$

As is evident from the paper I, the specimen under study becomes an intrinsic semiconductor above 20°C, and the values of μ_e and μ_h have been inferred as listed in Table 1, by analysing the experimental values of the electrical conductivity, the Hall effect and the magneto-resistance effect.

Table 1.

t°C	μ_e esu *	μ_h esu *	$B_{\text{EN},i}$ emu	$B_{\text{EN},a}$ emu
20	5.39×10^5	3.55×10^5	0.827	1.65
60	4.44	2.76	0.573	1.15
100	3.63	2.14	0.396	0.79
160	2.37	1.60	0.215	0.43
200	1.79	1.36	0.146	0.29
260	1.12	1.16	0.086	0 17
300	0.88	1.02	0.063	0.13

Substituting these values in Eq. (5′) and $\Delta E(o) = 0.34$ eV, we can obtain B_{EN} expressed in Gaussian unit or $1/c\ B_{\text{EN}}$ in emu. Values of B_{EN} in emu computed as above are enlisted in the fourth column $B_{\text{EN},i}$ of Table 1.

It must be noticed that the theoretical expression of B_{EN} in Eq. (4) corresponds to the isothermal Ettingshausen-Nernst coefficient ($B_{\text{EN},i}$), in which case a potential difference only arises, but a temprature gradient is prevented from being established, in the transverse direction of the sample; on the other hand, in the present experiment the transverse temperature gradient due to the magnetic field being left to itself, the observed values are rather to be regarded as the adiabatic Ettingshausen-Nernst coefficients ($B_{\text{EN},a}$). It is expected theoretically that the next relationship holds approximately(5).

$$B_{\text{EN},a} = 2\,B_{\text{EN},i} \tag{6}$$

From this equation $B_{\text{EN},a}$ is obtained as enrolled in Table 1, and these values are plotted in Fig. 5 by the dashed curve. In the intrinsic semiconductor range, theoretical and experimental values of $B_{\text{EN},a}$ show similar behaviours as functions of temperature and the ratio of $B_{\text{EN},a}(\text{theor.})/B_{\text{EN},a}(\text{exp.}) \fallingdotseq 0.7$. Considering an appreciable error which might be involved in the estimation of $-dt/dl$, it may be said that the observed Ettingshausen-Nernst effect in the intrinsic semiconductor range can be expressed consistently in terms of other electrical properties which were measured simultaneously on the same specimen.

The similar identification as above in the extrinsic semiconductor range cannot be accomplished at present because of the lack of knowledge of the chemical potential of positive holes at low temperatures.

* μ esu $= 300\cdot\mu\ \text{cm}^2\cdot\text{volt}^{-1}\cdot\text{sec}^{-1}$.

(5) A. Sommerfeld, N. H. Frank, Rev. Mod. Phys., 3 (1931), 28.
Handb. d. exp. Phys. XI 2 teil (1935), 392

Résumé

(1) The Ettingshausen-Nernst effect of a single crystal of highly purified tellurium has been measured at the temperatures ranging from $-160°$ to $+300°C$.
(2) The coefficient ($B_{EN,a}$) of the said effect is found to be positive throughout the temperature range under investigation; in the extrinsic range, the coefficient increases as the temperature rises and then, passing through a maximum value at about $-15°C$, tends to decrease up to the highest temperature.
(3) In the higher temperature range, i.e., in the intrinsic semiconductor range, it can be shown that the coefficient is roughly in accord with that evaluated theoretically from the values of the electron and hole mobilities and the width of the forbidden region, which have been deduced in the paper I.

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