# Chapter 11
# Influence of Magnetic Field on Thermoelectric Coefficient Value and Peltier Factor in InSb

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The original setup for measuring effect of magnetic field on thermo EMF and the Peltier factor in InSb has been developed and fabricated. It has been shown that the magnetic field changes 7 times thermo EMF in InSb, and the Peltier factor at 5 %. It is also shown that in the circuit consisting of an electromagnet and a capacitor in the presence of the temperature gradient could be created continuous waves.

It is well known, that thermo EMF under the influence of magnetic fields may increase [1]. The paper [2–5] show, that thermo EMF in the InSb monotonically increases with increase of the magnetic field induction, does not depend on the sign, and at the fields of about 1 T it is observed saturation. Moreover, thermo EMF $\alpha(B)$ differs from the thermo EMF in zero field ($\alpha_0$) on 20–40 μV/K at $\alpha_0 = 440$ μV/K. By creating a temperature gradient in the transverse magnetic field, in addition to a longitudinal electric field (thermal EMF), the transverse electric field (Nernst–Ettingshausen effect) and transverse gradient of temperatures (Righi-Leduc effect) arise. The electric field and temperature gradient are parallel one to other and perpendicular to the vector of the magnetic induction. As shown in [9], the transverse electric field is equal to 3 μV/cm at the room temperature and $B = 0.1$ T, and the transverse gradient of temperatures does not exceed of $10^{-3}$ K/cm.

For studies of this phenomenon, we have chosen the crystal of InSb. For the measurement of thermo EMF, the InSb sample was fabricated in the disc shape with diameter of 3 mm and thickness of 0.5 mm. It had gold–nickel electrodes, sprayed on the upper and lower surfaces of the disk. The sample was fixed between two copper rods, so that between the rods and the disc was a good thermal contact. One of the rods was connected to the heater, representing the spiral coiled on the

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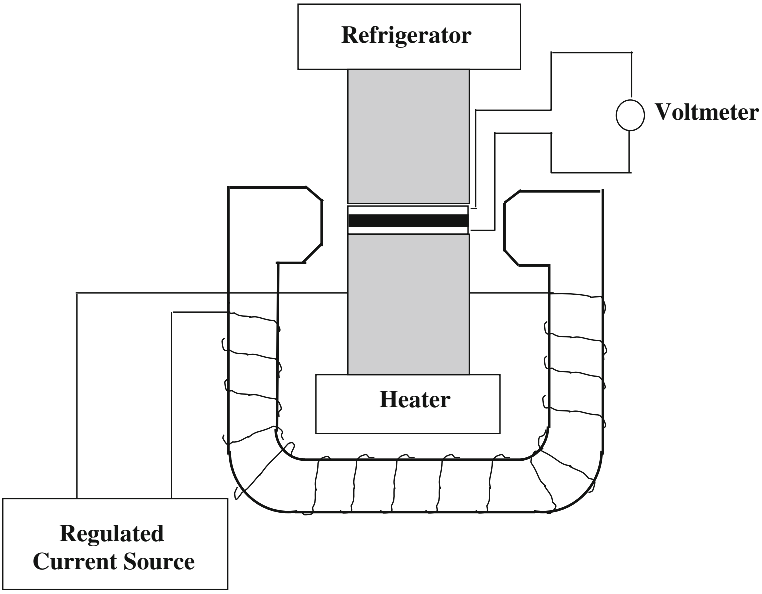


**Fig. 11.1** Scheme of the experimental setup for measuring of the magnetic field influence on thermo EMF

rod through isolator, and other rod was connected to the Peltier cooler. In the gap between the rods, besides the InSb disc, the resistance thermometer was attached to measure the temperature and its changes. The rods together with the InSb disk were placed in the gap of the electromagnet, representing itself a coil with steel core. The electromagnet could rotate so that the orientation of the magnetic field changed relative to the crystallographic axes, remaining perpendicular to the gradient of temperature all the time as shown in Fig. 11.1.

The gradients of the electric field and the temperature were negligibly small in the gold–nickel electrodes because of low mobility of electrons and good thermal conductivity in metals. Due to this the gradients of the electric field and the temperature were shorted in the contact area of electrodes and they can be neglected. Thus, the longitudinal thermo EMF was only measured in this setup.

The following measurements were conducted:

(i) the dependence of thermo EMF from the orientation of the magnetic field relative to the crystallographic axes in the InSb specimen at constant magnitude of the magnetic field induction,
(ii) the dependence of thermo EMF on the magnetic field at which was observed maximal change of thermo EMF.

Upper and lower surfaces of InSb disc coincided with InSb planes (111). The disc cut was perpendicular to the *x*-axis. The dependence of thermo EMF from the magnetic field orientation is shown in Fig. 11.2 at $B = 0.1$ T. The measurements were carried out at the different signs of magnetic induction $B$, i.e. the orientation

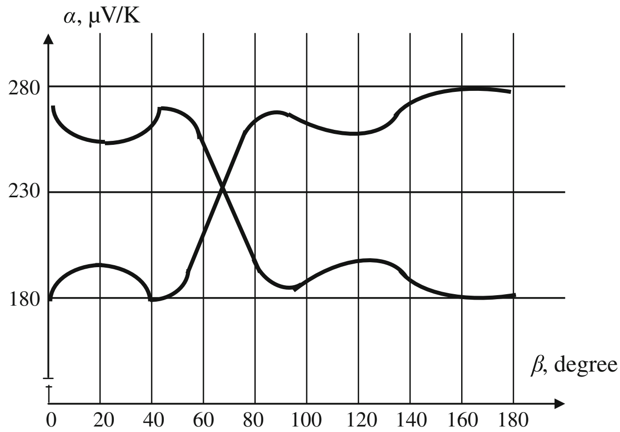


**Fig. 11.2** Dependence of thermo EMF on orientation of the magnetic field at $B = 0.1$ T

of $B$ changed by 180° at each angle considered between the direction $B$ and crystallographic axes.

It was stated that thermo EMF depends significantly on the sign of $B$. Maximal change of thermo EMF was obtained when the vector of $B$ was perpendicular to the cut on the InSb disc.

Figure 11.3 shows the dependence of thermo EMF on the magnetic field at the fixed orientation. As it can be seen from this dependence, $\alpha$ depends not only on magnitude, but also on the sign of $B$ and is almost linear. The $\alpha_{\text{min}} = 50$ μV/K (at $B = -0.25$ T), $\alpha_{\text{max}} = 380$ μV/K (at $B = 0.25$ T), $\alpha(0) = 200$ μV/K.

Thus, under influence of the magnetic field, thermo EMF changed more than 7 times and increased almost 2 times compared to the thermo EMF at $B = 0$.

The experimental data, confirmed in the works [1, 7], differ significantly from the results obtained in the papers [2–5], which indicate that $\alpha$ does not depend on the sign of the field and changes in the fields of lesser than 2 T not more than 10–20 % (significant change of $\alpha$ occurs only in strong magnetic fields more than 5 T).

This fact can be explained, apparently, by the fact that in these works the measurements were carried out at temperatures below 160 K, while our measurements were carried out at the room temperature.

As it follows from the kinetic equations [6] under the assumption: $\nabla T_z = 0$, where $\nabla T_z$ is the temperature gradient, which is perpendicular to the electric field intensity $E_x$.

$$E_x = \nabla T_x \frac{\alpha'(1 + \mu^H B) + \beta' \mu^H B}{1 + (\mu^H B)^2}. \tag{11.1}$$

Then

$$\alpha = \frac{\alpha'(1 + \mu^H B) + \beta' \mu^H B}{1 + (\mu^H B)^2}, \tag{11.2}$$

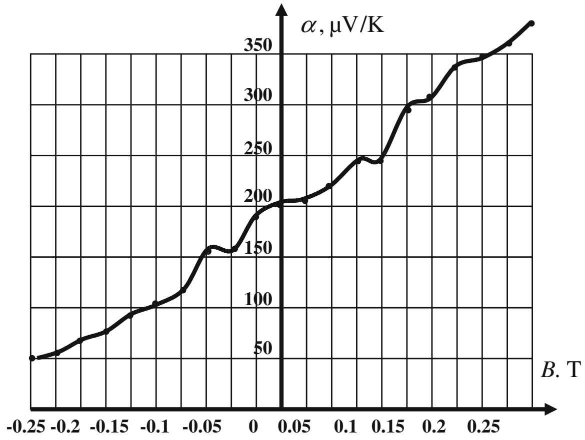


**Fig. 11.3** Dependence of thermo EMF on the induction of magnetic field

where $\mu^H$ is the mobility of electrons in the presence of magnetic field, $\alpha'$ is the thermo EMF without magnetic field, $\nabla T_x$ is the temperature gradient parallel to the electric field intensity $E_x$. From (11.2), it follows that $\alpha(B)$ depends on the sign of the magnetic induction $B$, i.e. the dependence of $B$ follows from solution of the kinetic equations.

As it follows from (11.2), in the presence of temperature gradient, the specific thermo EMF $\alpha$ depended on the magnetic field significantly, but it did not subject to the expression of $\Pi = \alpha T$. This equation was valid for the thermo EMF with $B = 0$ ($\Pi = \alpha'/T$). Thus, the thermal EMF under influence of the magnetic field changed very strongly (almost 7 times), and the Peltier changed only slightly (as shown in [2] not more than 37 μV/K, i.e. not more than 10 %).

Therefore, in the case of a thermoelectric generator, the transmission of heat from the hot end to the cold due to the Peltier effect does not correspond to the maximum coefficient of thermo EMF. One is equal to coefficient of thermo EMF at the absence of magnetic field (Fig. 11.3), which is almost two times smaller, that lead to increased efficiency of the generator. Indeed, the useful electric power $W_{el} = \alpha \Delta T I$, where $I$ is the current in the circuit, and the thermal power transferred is $W_{transmit} = \alpha'/(T_h - T_c)I = \alpha'/\Delta T I$. Then the ratio of these powers (excluding losses on heat conductivity) is equal to $\alpha/\alpha' = 1.75 > 1$, while in the absence of magnetic field, this ratio is equal to 1, that means increase of efficiency (at the absence of the losses caused by the thermal conductivity, the coefficient of efficiency would increase 1.75 times). In the case of a refrigerator arises a parasitic thermo EMF because of the temperature difference due to cooling. Therefore, it is necessary to select the value and sign of the magnetic field in such a way that thermo EMF would be minimal. Then the parasitic thermo EMF will decrease, that leads to reduction of power consumption. So for example, if magnetic field of 0.1 T is applied, thermal EMF decreases to 50 μV/K, while the Peltier effect, which responsible for the cooling, almost does not change. So the power, required to overcome the parasitic thermo EMF, reduces almost 5 times, that lead to a considerable increase in the efficiency of the refrigerator, as the power, required to overcome the parasitic thermo EMF, is one of the main factors determining the refrigerator power consumption.

Thus, the application of a permanent magnetic field allows us to significantly improve the performance of thermoelectric devices, if semiconductor with high electron mobility is used, that leads to a strong dependence of thermo EMF on magnetic field.

Obviously, if the magnetic field is variable $B = B(t)$, then $\alpha(B)$ also depends on time. Since the time of electron scattering on the thermal phonons is the order of $10^{-11}$ s [8], then with every change of the magnetic field the new equilibrium distribution of electrons is also stated during this time. This means that change of thermo EMF with $B$ will occur with a delay of $10^{-11}$ s. Therefore, at times of change of the magnetic field $\tau \gg 10^{-11}$ s, this delay can be neglected and consider changes of $\alpha(B)$ occurring synchronously with the changing magnetic field.

This assumption was checked by using setup, shown in Fig. 11.1, at supplying the sinusoidal voltage alternating with frequency of 50 Hz in electromagnet. In this case, the losses of hysteresis in the core of the electromagnet can be neglected.

Change of thermo EMF was observed in the screen of two-channel oscilloscope with high-impedance input. Change $B(t)$ was observed in the second channel. As expected, dependence $\alpha[B(t)]$ almost coincided with the form of the dependence $B(t)$. This confirmed a synchronization between $\alpha[B(t)]$ and $B(t)$. Some insignificant deviations are explained by the fact, that the dependence $\alpha(B)$ is slightly different from linear.

We further assume that the magnetic coil (see Fig. 11.1) connects in series with a thermocouple through the capacitor $C$. Thus, in series $LC$ circuit arises. In this circuit, magnetic field changes total thermo EMF synchronously with current $i(t)$, flowing through the circuit, because $B(t) \sim i(t)$. The voltage on the thermal element is defined as $U_T = \alpha[B(t)]\Delta T$. Because the dependence $\alpha(B)$ is close to linear (see Fig. 11.3, solid line), then we can write $U_T = \alpha[B(t)]\Delta T = \gamma i(t)\Delta T + U_{T0}$.

Then the differential equation describing fluctuations in the circuit is

$$L\frac{d^2q}{dt^2} + R\frac{dq}{dt} + \frac{q}{C} = U_T(t) = U_{T\sim} + U_{T0}, \tag{11.3}$$

where $q$ is the charge on the capacitor, therefore, $i(t) = \dfrac{dq}{dt}$ and (11.3) takes the form:

$$L\frac{d^2q}{dt^2} + R\frac{dq}{dt} + \frac{q}{C} = \gamma i(t)\Delta T + U_{T0}, \tag{11.4}$$

or

$$L\frac{d^2q}{dt^2} + (R - \gamma\Delta T)\frac{dq}{dt} + \frac{q}{C} = U_{T0}. \tag{11.5}$$

Obviously, the continuous oscillations will arise in the circuit at $R - \gamma\Delta T < 0$. Thus, by using thermocouples disposed in a magnetic field, we can directly obtain

AC. It is very convenient, because with the secondary winding can get voltage, and its value depends on the number of turns in the coil, i.e. voltage can change in wide limits. The magnetic field in the gap of electromagnet when $\mu \gg 1$ is determined by the formula:

$$B(t) \approx \frac{i(t)N\mu_0}{l}, \tag{11.6}$$

where $N$ is the number of turns, $l$ is the gap width, $\mu_0 = 12.56 \cdot 10^{-7}$ H/m. At $N = 1000$ и $l = 0.5 \cdot 10^{-3}$ m. Then

$$B(t) = i(t)\frac{1000 \cdot 12.56 \cdot 10^{-7}}{5 \cdot 10^{-3}} \approx 0.25 i(t)\,\mathrm{T}. \tag{11.7}$$

As it follows from Fig. 11.3 the dependence $\alpha(B)$ can roughly consider as

$$\alpha(B) = 1520 \cdot B(t) + 200, \mu\mathrm{V/K},$$

then $U(t) = \Delta T(1520 \cdot 0.25 \cdot i(t) + 200) \times 10^{-6}$ V $= \Delta T(380 \cdot i(t) + 200) \times 10^{-6}$ V.

Suppose that $\Delta T = 10$ °C, then

$$U_T = [3800 \cdot i(t) + 2000] \times 10^{-6}\,\mathrm{V} = [3.8 \cdot i(t) + 2] \times 10^{-3}\,\mathrm{V}.$$

Then (11.3) takes the form:

$$L\frac{d^2q}{dt^2} + \left(R - 3.8 \cdot 10^{-3}\right)\frac{dq}{dt} + \frac{q}{C} = 2 \cdot 10^{-3}\,\mathrm{V}.$$

Evaluate the resistance of a circuit, which is composed mostly of resistance of an electromagnet winding, and losses on hysteresis can be neglected.

By using copper wire with cross-section of 0.2 mm$^2$ and $N = 1000$, we obtain resistance $R = 3.4\ \Omega$, i.e. $R \gg 3.8 \times 10^{-3}\ \Omega$. Therefore, in such circuit fluctuations do not arise. In order to the fluctuations appear, it is necessary to increase the temperature difference $\Delta T$ and apply the serial connection of thermocouples.

At $\Delta T = 100$ °C and number of thermocouples $n = 100$, we obtain $U(t) = 3.8 \cdot i(t)$ V, $R - 3.8\ \Omega < 0$, i.e. continuous oscillations arise in the circuit.

The frequency of oscillations is determined from the condition: $\omega_0 = \frac{1}{\sqrt{LC}}$. Due to appropriate selection of capacity $C$, it can be obtained the frequency of oscillation $f_0 = 50$ Hz. Then electromagnet inductance can be defined as

$$L \approx \frac{N^2 S\mu\mu_0}{\mu l_g + l_l},$$

where $l_g$ is the gap width of magnetic circuit, $l_l$ is the length of magnetic circuit.

If $S = 0.5$ cm$^2$ (square of the electromagnet cross-section), $\mu = 2000$, $l_g = 5$ mm, $l_l = 100$ mm, we obtain

$$L = \frac{12.56 \cdot 10^{-7}\mathrm{H/m} \cdot 10^6 \cdot 0.5 \cdot 10^{-4}\mathrm{m}^2 \cdot 2 \cdot 10^3}{2000 \cdot 5 \cdot 10^{-3}\mathrm{m} + 0.1\mathrm{m}} = 1.24 \cdot 10^{-2} H = 12.4 \text{ mH}.$$

Finally, for $f_0 = 50$ Hz we have

$$C = \frac{1}{\omega_0^2 L} = \frac{1}{6.28^2 \cdot 1.24 \cdot 10^{-2} \cdot 2500} \approx 804.1 \mu\mathrm{F}.$$

Since the magnetic field varies in time, it produces a vortex electric field in the disc of InSb, and therefore vortex EMF $E_{vort} = d\,\Phi/dt = \omega_0 B_0 S_{sec}$, where $\Phi$ is the magnetic flux, $S_{sec}$ is the square of disc cross-section in the direction perpendicular to the magnetic field lines. At the frequency of 50 Hz for the disc with thickness of 0.5 mm and diameter of 3 mm, this voltage is approximately of 4 mV, which is much lesser than the thermo EMF at $\Delta T = 100°$, and vortex EMF can be neglected.

Thus, by using an electromagnet with a consistently connected capacity, and forming an oscillatory contour in the gap, which is the thermocouple, we can obtain directly alternating current in thermoelectric converters that is very important for many practical applications.

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