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REVIEW OF THOMSON HEAT

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Abstract: The review of Thomson heat is presented: the traditional and modern descriptions. It is emphasized that the value of Thomson heat in the newest and traditional descriptions are different. It is presented explanation that the Thomson heat is equal to the product of the Seebeck coefficient, the temperature gradient, and the current density. This is result of the newest theory.

Keywords: Thomson effect, Thomson heat, Thomson coefficient, seebeck coefficient

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1. INTRODUCTION

In 1854, Thomson (Lord Kelvin) rationalized that the Peltier voltage has to be equal to the Seebeck voltage. Moreover, these two voltages must be proportional to the temperature in a linear manner [1]. This conclusion he made from the assumption that the electrical current produces only the Peltier heat, when it passes through two junctions. Nevertheless, the experiment did not prove it. Therefore, Thomson deduced that another reversible thermoelectric process must exist. This process consists in the evolution or absorption of heat, if the electrical current passes through a conductor with a temperature gradient. Mathematically,

$$Q_{\tau} = \tau \vec{j} \nabla T \quad (1)$$

where Q_{τ} is the heat source density of a conductor, τ is the Thomson coefficient, \vec{j} is the electric current density, and ∇T is the temperature gradient. In addition, Thomson has found the relationship between the Thomson, Peltier, and Seebeck coefficients, so cold Kelvin relationships: $\Pi = ST$ and $\tau = -T \frac{dS}{dT}$, where S is the Seebeck coefficient, Π is the Peltier coefficient.

2. TRADITIONAL THEORY OF THE THOMSON HEAT

The rate of heat absorbed or liberated in a unit volume of a conductor, Q , by Seeger is [2]:

$$Q = \vec{j} \vec{E} - \nabla \cdot (\Pi \vec{j} - \kappa \nabla T - \frac{\mu}{e} \vec{j}) \quad (2)$$

where

$$\vec{q} = \Pi \vec{j} - \kappa \nabla T \quad (3)$$

is the thermal (heat) flux density [2-7], κ is the thermal conductivity coefficient, μ is the chemical potential, e is the magnitude of an electron charge, \vec{E} is the electric field strength.

Excluding \vec{E} from Eq. [2] using the electrical current density expression [3,8],

$$\vec{j} = -\sigma(\nabla\psi + S\nabla T) = \sigma\left(\vec{E} + \frac{1}{e}\nabla\mu - S\nabla T\right) \quad (4)$$

we obtain the following

$$Q = \frac{j^2}{\sigma} - T \frac{dS}{dT} \vec{j}\nabla T + \nabla(\kappa\nabla T) \quad (5)$$

Here $\psi = \varphi - \frac{1}{e}\mu$ is the electrochemical potential of electrons [9], φ is the electrical potential. From Eq. [5], Seeger [2] and traditional theory makes decision that the second term, $-T \frac{dS}{dT} \vec{j}\nabla T$, is the Thomson heat and the Thomson coefficient is equal to $-T \frac{dS}{dT}$. In Eqs. [4,5] σ is the electrical conductivity coefficient. The first term in Eq. [5] corresponds to the Joule heat and the third term corresponds to heat transport due to the thermal conductivity transport process.

Let us use the equation from mathematical physics. Let \vec{p} is the flux of a physical quantity P . In this case, in the following equation

$$\nabla \cdot \vec{p} = D \quad (6)$$

D plays a role of a source of the physical quantity P under stationary conditions [10,11]. The last means that, according to the traditional theory of the rate of heat absorbed or liberated in a unit volume, the stationary heat balance equation must be the following (considering the sample does not absorb nor radiate light) [12]

$$\nabla \cdot \vec{q} = -T \frac{dS}{dT} \vec{j}\nabla T + \frac{j^2}{\sigma} \quad (7)$$

Equation [7] must be correct because, according to the traditional theory, the Joule heat is $\frac{j^2}{\sigma}$, and the Thomson heat is $-T \frac{dS}{dT} \vec{j}\nabla T$.

Consequence of a traditional theory: There are two heat sources: the Thomson heat, $-T \frac{dS}{dT} \vec{j}\nabla T$, and the Joule heat, $\frac{j^2}{\sigma}$. Nevertheless, as follows from the modern theory of heat absorbed or liberated in a unit volume of a conductor, Eq. [7] is wrong.

3. MODERN THEORY OF THE THOMSON HEAT

The energy flux density, \vec{w}_n , in an electron subsystem in a monopolar conductor is $\vec{w}_n = -\kappa_n \nabla T + \Pi \vec{j} + \psi \vec{j}$ [13], where κ_n is the heat conductivity coefficient of electrons. If we add the phonon thermal flux density, $-\kappa_{ph} \nabla T$, we obtain the expression for the total energy flux density in a conductor, \vec{w} :

$$\vec{w} = \vec{q} + \psi \vec{j} \quad (8)$$

Here, $\kappa = \kappa_n + \kappa_{ph}$, κ_{ph} is the phonon thermal conductivity coefficient.

Let us use the energy conservation law. Using this law we can write the following equation, $\frac{\partial u}{\partial t} = -\nabla \cdot \vec{w}$. This equation is correct, when radiation or absorption of light is absent. Here u is the energy density. The term, $-\nabla \cdot \vec{w}$, describes energy transport. Let us consider the stationary process. In this case, $\frac{\partial u}{\partial t} = 0$. Therefore, we obtain the following equation under stationary conditions:

$$\nabla \cdot \vec{w} = 0 \quad (9)$$

This is the stationary energy balance equation, when light radiation or absorption is absent. It follows from comparison of Eq. [9] with Eq. [6] that the energy sources are absent.

Using the expression for the energy flux density, \vec{w} , Eq. [8], the equation [9] transforms to:

$$\nabla \cdot \vec{q} = -\vec{j} \nabla \psi \quad (10)$$

Obtaining this equation, we have used $\nabla \cdot \vec{j} = 0$ [13]. This is the consequence of the charge conservation law under stationary conditions [13].

Expressing $\nabla \psi$, using Eq. 4, Eq. 10 can be rewritten as follows [14]:

$$\nabla \cdot \vec{q} = \frac{j^2}{\sigma} + S\vec{j}\nabla T \quad (11)$$

This is the *stationary heat balance equation, when light radiation or absorption is absent*. Comparing Eq. [11] with Eq. [6], we can conclude that there are only two heat sources: the Joule heat, $\frac{j^2}{\sigma}$, and the Thomson heat [14]:

$$Q_\tau = S\vec{j}\nabla T \quad (12)$$

It follows from Eq. [1] and Eq. [12] that the Thomson coefficient, τ , is equal to the Seebeck coefficient, S :

$$\tau = S \quad (13)$$

Important. The equation [11] is the consequence of the energy conservation law. Therefore, we can trust this equation more, than Eq. [7]. Thus, we must conclude that Eq. [7] is wrong. Hence, as Eq. [11] is correct, whereas, Eq. [7] is wrong, we must conclude that the correct Thomson heat is $S\vec{j}\nabla T$, but not $-T \frac{dS}{dT} \vec{j}\nabla T$ [12, 14] and we must accept that the Thomson coefficient, τ , is equal to the Seebeck coefficient, S : $\tau = S$.

4. COMPARISON OF THE TRADITIONAL THEORY WITH THE MODERN ONE

Substituting expression for the heat flux, Eq. [3], into the stationary heat balance equation, Eq. [11], we obtain the following:

$$\frac{j^2}{\sigma} - T \frac{dS}{dT} \vec{j}\nabla T + \nabla \cdot (\kappa \nabla T) = 0 \quad (14)$$

Comparing this equation with Eq. [5] we deduce that the value of the rate of heat absorbed or liberated in a unit volume of a conductor, Q , by Seeger is always equal to zero. This is the consequence of the energy conservation law. This means that the definition, Eq. [2] of the rate of heat absorbed or liberated in a unit volume of a conductor, Q , by Seeger, that is used by traditional theory, is wrong. Moreover, the following equation must be accepted as the correct definition of the rate of heat absorbed or liberated in a unit volume of a conductor, Q , under stationary conditions:

$$\nabla \cdot \vec{q} = Q \quad (15)$$

Thus, comparing this equation with Eq. [11] we obtain for Q :

$$Q = \frac{j^2}{\sigma} + S\vec{j}\nabla T \quad (16)$$

It means that only two heat sources for the heat flux, \vec{q} , exist: the Joule heat, $\frac{j^2}{\sigma}$, and the Thomson heat, $S\vec{j}\nabla T$.

5. THOMSON HEAT IN A BIPOLAR SEMICONDUCTOR

The expression for the energy flux density, \vec{w}_b , in a bipolar semiconductor can be written as follows [15]

$$\vec{w}_b = \vec{q}_b + \psi_n \vec{j}_n + \psi_p \vec{j}_p \quad (17)$$

where

$$\vec{q}_b = \Pi_n \vec{j}_n + \Pi_p \vec{j}_p - \kappa_b \nabla T \quad (18)$$

is the thermal (heat) flux density in a bipolar semiconductor; Π_n (Π_p) is the Peltier coefficient of conduction electrons (holes); \vec{j}_n (\vec{j}_p) is the electrical current density of conduction electrons (holes); $\kappa_b = \kappa_n + \kappa_p + \kappa_{ph}$ is the thermal conductivity coefficient of a bipolar semiconductor; κ_p is the thermal conductivity coefficient of holes; $\psi_n = \varphi - \frac{1}{e}\mu_n$ is the electrochemical potential of conduction electrons; $\psi_p = \varphi + \frac{1}{e}\mu_p$ is the electrochemical potential of holes [9]; μ_n (μ_p) is the chemical potential of conduction electrons (holes). Substituting the expression for the energy flux density in a bipolar semiconductor, Eq. [17], into the stationary energy balance, Eq. [9], we obtain [15]

$$\nabla \cdot \vec{q}_b = (\mu_n + \mu_p)R + \frac{j_n^2}{\sigma_n} + \frac{j_p^2}{\sigma_p} + S_n \vec{j}_n \nabla T + S_p \vec{j}_p \nabla T \quad (19)$$

According to Eq. 15 it follows from Eq. 19 that there are two Thomson heat sources in a bipolar semiconductor: Thomson heat of conduction electrons, $S_n \vec{j}_n \nabla T$, and Thomson heat of holes, $S_p \vec{j}_p \nabla T$. Here S_n (S_p) is the Seebeck coefficient of conduction electrons (holes), R is the recombination rate.

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