NOVEL APPROACH FOR THERMOELECTRICITY

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A new point of view on the thermoelectric phenomena as a transport of non-equilibrium charge carriers is presented. The role of recombination in the forming of transport phenomena is discussed. It is shown that in the presence of thermal fields a new term in the expression for recombination processes, appears. This term depends on temperature inhomogeneity.

1. Introduction

Traditionally the temperature distribution in a p-n structure, when a current passes through, has been examined under quasi-equilibrium conditions, when temperatures of all quasi-particles (electrons, holes, phonons) in each point coincide and the concentrations of electrons and holes are equal to equilibrium concentrations[1-5].

However, researchers' do not discuss the criteria of the applicability of such approximation.

As known [6], the Peltier effect which underlies thermoelectric cooling is a contact phenomenon. Traditionally a p-n structure is used in thermoelectric refrigerators (coolers) [1-5], because at a corresponding current direction, from the n-region to the p-region, the thermoelectric drift fluxes of majority charge carriers are both directed from the p-n interface of the structure, which intensifies the cooling phenomenon [6]. The thermal generation and extraction of minority carriers must take place near the interface for electric current pass [7]. As a consequence the non-equilibrium carriers current arises [8]. But the researchers' study of the Peltier effect tells nothing about non-equilibrium carriers. If it means that they neglect the generation-recombination processes, it is wrong. As it was shown in [8], without this process instead of cooling, we have heating. Moreover, in this situation the concentration of non-equilibrium carriers is maximum [9].

Only when the recombination is very strong and we have no non-equilibrium carriers, the conventional theory of cooling is correct. Really, in this situation we can neglect the current of minority carriers near the p-n contact (the hole current j_p^n in n-region and the electron current j_n^p in p-region) and take into account only the electron current j_n^n in n-region and the hole current j_p^p in p-region. In this situation $j_n^n = j_p^p = j_0$, where j_0 is the total current. This is the convention theory [1-6].

Actually the recombination intensity has a finite (or small) value. In this situation the current of minority carriers near the p-n junction is the same order that the current of majority carriers and the conventional theory is wrong.

In this article we present a new point of view on this problem.

2. Conventional theory

The recent results [6, 10] have shown that the variation in temperature associated with the Peltier effect is not related to the presence of heat sources and sinks: $\left(\Pi_1 - \Pi_2\right)\boldsymbol{j}$, Π is the Peltier coefficient (the subscripts are for two media, 1 and 2), which can be written as $\Pi = \alpha T$, α is the Seebeck coefficient and T is temperature. In contrast, this variation is related to the appearance of a diffusion heat flux, $\boldsymbol{q}_{diff} = -\kappa \nabla T$, which, following the Le Chatelier–Braun principle, compensates the change in the drift component of the heat flux, $\boldsymbol{q}_{dr} = \Pi \boldsymbol{j}$ where κ is the thermal conductivity.

Thus the heat balance equation can be written as

$$\mathrm{div}\boldsymbol{q} = 0 \qquad (1)$$

where $\boldsymbol{q} = \boldsymbol{q}_{dr} + \boldsymbol{q}_{diff}$ is the total heat flux.

In the absence of nonequilibrium carriers (strong recombination) in n- and p- regions we must write $\boldsymbol{j}$ and Π for majority carriers (see the distribution of current in p-n-structure in Fig. 1). In this case $\boldsymbol{j} = \mathrm{const}$ in all the structure.

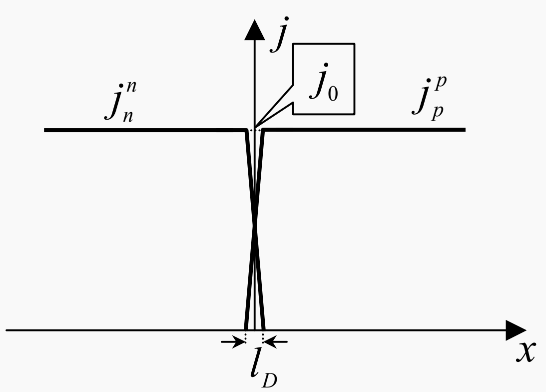

Fig. 1. Distribution of current when recombination is infinite.

But near the interface within the distance r_d (the Debye length) the concentration of majority carriers changes (space charge layers) and the chemical potential depends on coordinate. It means that Π depends on coordinate too. Only if we use the quasineutrality approximation ($r_d \to 0$) [11] the Peltier coefficient is constant in n- (and p-) layers. The energy diagram for this case is presented in Fig. 2.

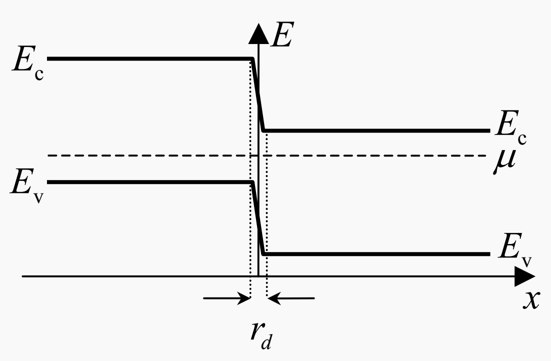

Fig. 2. Energy band diagramme.

As it follows directly from Eq. (1), in this approximation $\mathrm{div}\boldsymbol{q}_{dr} = 0$ and for the heat balance equations we obtain:

$$\Delta T = 0. \qquad (2)$$

In this situation the Peltier coefficient appears only in the boundary conditions [6, 10].

3. Nonequilibrium carriers

It is that the intensity of recombination is finite. For simplicity assume that the quasineutral approximation take place. As shown in [11] the bulk space charge established at the distance of the order of the Debye length cannot influence the macroscopic parameters such as temperature distribution. It means that the last approximation cannot change the result.

The distribution of currents of majority and minority carriers in a p-n contact is captured in Fig. 3.

In the quasineutral region $-l_D^p < x < l_D^n$

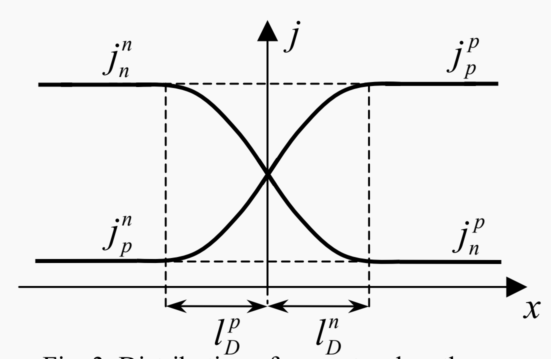

Fig. 3. Distribution of currents when the recombination is finite.

where $l_D^{n,p}$ is the diffusion length ($r_d << l_D^{n,p}$), the current of minority carriers has the same order as the current of majority carriers (see Fig. 3). It means that heat balance equation (1) must be rewritten as:

$$-\kappa_1 \Delta T + \Pi_n^n \nabla \boldsymbol{j}_n^n + \Pi_p^n \nabla \boldsymbol{j}_p^n = \varepsilon_g R_1 \quad x<0 \quad (3a)$$

$$-\kappa_2 \Delta T + \Pi_p^p \nabla \boldsymbol{j}_p^p + \Pi_n^p \nabla \boldsymbol{j}_n^p = \varepsilon_g R_2 \quad x>0 \quad (3b)$$

Here ε_g is the band-gap, $R_{1,2}$ is the recombination rates. The last term in Eq.(3)

is a new source of heat in the theory of thermoelectric cooling (see. [12]).

It should be stressed that beyond the fact that the term $j_{n,p}^{n,p}$ depends on coordinate, the heat balance equations (3) contain $\nabla \boldsymbol{j}_{n,p}^{n,p}$ (it depends on the drift heat fluxes).

The current densities can be calculated as [13]:

$$\boldsymbol{j}_n^n = -\sigma_n^n \left(\nabla\varphi - \nabla\mu_n^n / e + \alpha_n^n \nabla T \right)$$

$$\boldsymbol{j}_p^n = -\sigma_p^n \left(\nabla\varphi - \nabla\mu_p^n / e + \alpha_p^n \nabla T \right)$$

$$\boldsymbol{j}_p^p = -\sigma_p^p \left(\nabla\varphi - \nabla\mu_p^p / e + \alpha_p^p \nabla T \right)$$

$$\boldsymbol{j}_n^p = -\sigma_n^p \left(\nabla\varphi - \nabla\mu_n^p / e + \alpha_n^p \nabla T \right)$$

Here φ is electrical potential, μ is chemical potential, σ is electrical conductivity.

It means that Eqs. (3) contain the concentrations of nonequilibrium carriers.

The macroscopic description of the transport of nonequilibrium charge carriers is performed with the continuity equations for the electron and hole current densities and the Poisson equation [11]

$$\nabla \boldsymbol{j}_n^n = eR_1 \quad (4a)$$

$$\nabla \boldsymbol{j}_p^n = -eR_1 \quad (4b)$$

$$\nabla \boldsymbol{j}_n^p = eR_2 \quad (4c)$$

$$\nabla \boldsymbol{j}_p^p = -eR_2 \quad (4d)$$

$$\Delta\varphi = 4\pi\rho / \varepsilon_0 \quad (5)$$

where ρ is space charge, ε_0 is permittivity.

The recombination rate in the presence of temperature gradient was obtained in [13]:

$$R = [n(x) - n_0]/\tau_1 + [p(x) - p_0]/\tau_2 + \beta[T(x) - T_0] \quad (6)$$

Here n_0 and p_0 are equilibrium concentrations of electrons and holes, T_0 is equilibrium temperature.

Under the quasineutral condition instead of Eq. (5) we obtain $\rho = 0$ [11].

Taking into account Eqs. (4) we can rewrite Eqs. (3) as

$$-\kappa_1 \Delta T = (\varepsilon_g - \Pi_n^n + \Pi_p^n) R_1 \quad (7a)$$

$$-\kappa_2 \Delta T = (\varepsilon_g - \Pi_n^p + \Pi_p^p) R_2 \quad (7b)$$

Eqs. (7) and its solutions differ dramatically from Eq. (2) and it solution.

It should be stressed that only the set of equations (3)-(5) can determine cooling in a p-n structure.

The boundary conditions for this system were obtained in [10, 14].

4. Conclusions

In the present work the Peltier effect in a p-n structure was consistently studied taking into account the existence of the nonequilibrium carriers.

It was shown, that the existence of the nonequilibrum carriers is the indispensable condition for a thermoelectric cooling process.

Acknowledgments

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