International Journal of Thermal Sciences 48 (2009) 2080–2084

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Non-typical temperature distribution in p–n structure under thermoelectric cooling

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ARTICLE INFO

Article history:
Received 3 October 2008
Received in revised form
15 February 2009
Accepted 7 March 2009
Available online 29 March 2009

PACS:
72.15.Jf
72.20.Pa

Keywords:
Thermoelectric cooling
Temperature distribution
p–n junction
Two-temperature approximation
Thermal transport

ABSTRACT

The physical peculiarities of the thermoelectric cooling phenomenon by an electric current in p–n structures of thermally thick structure in the linear approximation are investigated. It is shown the possibility of the realization of an exotic distribution of the temperatures of electrons, holes, and phonons: the thermoelectric cooling takes place near the p–n interface and in the subsystems of charged quasi-particles only. The phonon subsystem stays in the equilibrium state. The prerequisites to such situation are examined.

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 [1–5].

However, researchers do not discuss the criteria of the applicability of such approximation. Indeed, at first glance, such model might be correct for thermally thick samples, when the layers' lengths of the p–n structure are much longer than the length of electron (hole)–phonon energy interaction (cooling lengths [6]). Under these conditions there is a strong electron–phonon interaction in such samples. The cooling length is of submicron orders [7]. For the justification of one-temperature approach it would seem therefore that the p- and n-layers' lengths should be larger than one micron or more.

However, since the Peltier's effect takes place exactly in subsystems of charged particles [8], and arises up on an interface, the subsystems of charged particles are heated or cooled first of all. Moreover, the temperature of the phonon subsystem changes due to the energy interaction with electrons and holes. Therefore, under small enough power interaction between electrons (holes) and phonons at the interface (the criteria for this are established below) there will be always an area nearby the p–n junction where the temperatures of electrons (holes) and phonons will differ. This area is of the order of the cooling length. This leads to use of a two-temperature approximation, when the temperatures of electrons (holes) and phonons differ. The profiles of temperatures of phonons and electrons (holes) will be identical on the distance, more than the cooling length from the interface, in absence of volume heat sources [7]. Under these circumstances, as will be shown below, an exotic case can arise when the phonon subsystem remains at the equilibrium in all the volume of p–n structure, whereas essential cooling (heating) occurs only in the near-interface layers (over a distance in the order of a cooling length) of the charged particle subsystems (electrons and holes).

The purpose of this work consists in both establishing the temperature distribution in the subsystems of charged particles in a thermally thick p–n structure under a current, when the subsystem of phonons remains in equilibrium, and in establishing prerequisites to such situation.

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1290-0729/$ – see front matter
doi:10.1016/j.ijthermalsci.2009.03.004

Nomenclature

j	Density of electric current, A/m^2
T_e	Temperature of electron subsystem in the n-layer of the structure, K
T_{pe}	Temperature of phonon subsystem in the n-layer of the structure, K
T_h	Temperature of hole subsystem in the p-layer of the structure, K
T_{ph}	Temperature of phonon subsystem in the p-layer of the structure, K
d_n	Thickness of the n-layer of the structure, m
d_p	Thickness of the p-layer of the structure, m
T_0	Ambient temperature, K
κ_e	Thermal conductivity of electron subsystem in the n-layer of the structure, W/m K
κ_{pe}	Thermal conductivity of phonon subsystem in the n-layer of the structure, W/m K
κ_h	Thermal conductivity of hole subsystem in the p-layer of the structure, W/m K
κ_{ph}	Thermal conductivity of phonon subsystem in the p-layer of the structure, W/m K
P_e	Coefficient which defines intensity electron–phonon energy interaction in the volume, W/K m^3
P_h	Coefficient which defines intensity hole–phonon energy interaction in the volume, W/K m^3
η_p	Phonon interface thermal conductivity, W/K m^2
η_{eh}	Electron–hole interface thermal conductivity, W/K m^2
P_{ee}	Coefficient which corresponds to the electron–phonon energy interaction on the interface between the electrons and phonons of the n-layer of the structure, W/K m^2
P_{eh}	Coefficient which corresponds to electron–phonon energy interaction on the interface between the electrons of the n-layer and the phonons of the p-layer, W/K m^2
P_{he}	Coefficient that corresponds to the hole–phonon energy interaction on the interface between the holes of the p-layer and the phonons of the n-layer; W/K m^2
P_{hh}	Coefficient, which corresponds to the hole–phonon energy interaction on the interface between the holes and phonons of the p-layer of the structure, W/K m^2
Π_e	Peltier's coefficient of the n-layer of the structure, W/A
Π_h	Peltier's coefficient of the p-layer of the structure, W/A
Π_s	Peltier's coefficient of the interface, W/A
k_e^{-1}	Electrons cooling length, m
k_h^{-1}	Holes cooling length, m

2. Energy balance equations and boundary conditions

We will examine a cooling case for definiteness: i.e. the drift fluxes of heat [8] are directed away from an interface. The electric current should flow from the n- to the p-region for this purpose.

There will be extraction of minority charge carriers and subsequently their thermal generation when the current passes through the p–n transition interface. The latter will cause the set of a population of non-equilibrium charge carriers [9]. Traditionally, authors [1–5] say nothing about non-equilibrium charge carriers when studying the temperature distributions in a p–n structure. We will examine the case of an infinite speed for the recombination processes [10] for simplicity. Therefore, the non-equilibrium charge carriers will not exist. Thus, the concentrations of electrons (holes) in the whole volume of the structure will be identical and equal to their equilibrium values.

Let T_e and T_{pe} be the temperatures of electron and phonon subsystems respectively in the n-layer ($-d_e \le x < 0$), T_h and T_{ph} be the temperatures of holes and phonons in the p-layer ($0 < x \le d_h$). The current flows normally to the interface along the positive direction of the x axis. We consider the cross-section area of the structure to be equal to unity, the ambient temperature is T_0. Let us assume that the lateral interfaces of the structure are adiabatically isolated and the materials of the structure layers are homogeneous. In this case, the problem becomes one-dimensional, and the energy balance equations in the linear approximation by a current are [7]:

$$P_{e,h}\left(T_{pe,ph} - T_{e,h}\right) + \kappa_{e,h}\frac{d^2T_{e,h}}{dx^2} = 0, \tag{1a}$$

$$-P_{e,h}\left(T_{pe,ph} - T_{e,h}\right) + \kappa_{pe,ph}\frac{d^2T_{pe,ph}}{dx^2} = 0, \tag{1b}$$

In eq. (1) κ_e and κ_{pe} are thermal conductivities of electron and phonon subsystems respectively in the n-layer, κ_h and κ_{ph} are thermal conductivities of hole and phonon subsystems in the p-layer respectively, $P_{e,h}$ is the coefficient which defines intensity electron–phonon (hole–phonon) energy interaction in the volume. The latter is proportional to the energy frequency of the interaction between electrons (holes) and phonons [7].

In order to correctly formulate the problem in terms of the thermoelectric cooling [8], we will consider that at the external interfaces ($x = -d_e$ and $x = d_h$) there are isothermal junctions:

$$T_{e,pe}(-d_e) = T_0, \quad T_{h,ph}(d_h) = T_0. \tag{2}$$

Traditionally, researchers use the approximation of isothermal junction for a p–n junction [2,3] to investigate the thermoelectric cooling. However, Peltier's effect takes place on this interface, the physics of which we investigate. Therefore, it is not correct to simplify the model by making use of an isothermal junction at the p–n transition. We will use the general model, which takes into account all thermal properties of the p–n junction and the possibility of energy interaction at the interface between electrons, holes and phonons.

Following the procedure outlined in [7,11], it is not difficult to obtain the following boundary conditions at the interface:

$$\begin{aligned} &j\Pi_s + \eta_{eh}\left(T_e|_{x=-0} - T_h|_{x=+0}\right) - Q_e|_{x=-0} \\ &\quad = P_{ee}\left(T_{pe}|_{x=-0} - T_e|_{x=-0}\right) + P_{eh}\left(T_{ph}\big|_{x=+0} - T_e|_{x=-0}\right), \end{aligned} \tag{3a}$$

$$\begin{aligned} &Q_h|_{x=+0} - \left(j\Pi_s + \eta_{eh}\left[T_e|_{x=-0} - T_h|_{x=+0}\right]\right) \\ &\quad = P_{he}\left(T_{pe}|_{x=-0} - T_h|_{x=+0}\right) + P_{hh}\left(T_{ph}\big|_{x=+0} - T_h|_{x=+0}\right), \end{aligned} \tag{3b}$$

$$\begin{aligned} &\eta_p\left(T_{pe}|_{x=-0} - T_{ph}\big|_{x=+0}\right) - Q_p|_{x=-0} \\ &\quad = P_{ee}\left(T_e|_{x=-0} - T_{pe}|_{x=-0}\right) + P_{he}\left(T_h|_{x=+0} - T_{pe}|_{x=-0}\right), \end{aligned} \tag{3c}$$

$$\begin{aligned} &Q_p|_{x=+0} - \eta_p\left(T_{pe}|_{x=-0} - T_{ph}\big|_{x=+0}\right) \\ &\quad = P_{eh}\left(T_e|_{x=-0} - T_{ph}\big|_{x=+0}\right) + P_{hh}\left(T_h|_{x=+0} - T_{ph}\big|_{x=+0}\right). \end{aligned} \tag{3d}$$

Here

$$Q_e|_{x=-0} = j\Pi_e - \kappa_e \frac{dT_e}{dx}\bigg|_{x=-0} \tag{4a}$$

is the heat flux in the electron subsystem at $x = -0$;

$$Q_h|_{x=+0} = j\Pi_h - \kappa_h \frac{dT_h}{dx}\bigg|_{x=+0} \tag{4b}$$

is the heat flux in the hole subsystem at $x = +0$;

$$Q_p|_{x=-0} = -\kappa_{pe} \frac{dT_{pe}}{dx}\bigg|_{x=-0} \tag{4c}$$

is the heat flux in the phonon subsystem at $x = -0$; and finally,

$$Q_p|_{x=+0} = -\kappa_{ph} \frac{dT_{ph}}{dx}\bigg|_{x=+0} \tag{4d}$$

is the heat flux in the phonon subsystem at $x = +0$.

In eqs. (3) and (4) j is the density of electric current, η_p is the phonon interface thermal conductivity, η_{eh} is the electron–hole interface thermal conductivity, P_{ee} is the coefficient which corresponds to the electron–phonon energy interaction on the interface between the electrons and phonons of the n-layer of the structure, P_{eh} is the coefficient that corresponds to electron–phonon energy interaction on the interface between the electrons of the n-layer and the phonons of the p-layer, P_{he} is the coefficient that corresponds to the hole–phonon energy interaction on the interface between the holes of the p-layer and the phonons of the n-layer; P_{hh} is the coefficient, which corresponds to the hole–phonon energy interaction on the interface between the holes and phonons of the p-layer of the structure, Π_e is the Peltier's coefficient of the n-layer ($\Pi_e < 0$), Π_h is the Peltier's coefficient of the p-layer ($\Pi_h > 0$), Π_s is the Peltier's coefficient of the interface [12,13]. The latter coefficient, according to its definition ($\Pi_s = \lim_{\delta \to 0}\{(\int_{-\delta}^{\delta} dx/\kappa(x))^{-1} \cdot \int_{-\delta}^{\delta} \Pi(x)/\kappa(x) dx\}$, where $\kappa(x)$ is the thermal conductivity of charge carriers, $\Pi(x)$ is the Peltier's coefficient, δ is the width of transition layer (see Fig. 1)), can be positive or negative on the p–n junction.

We will investigate the case of nondegenerated semiconductors. Then, the phonon thermal conductivity is much greater than the electron (holes) thermal conductivity [7]:

$$\kappa_{pe,ph} \gg \kappa_{e,h}. \tag{5}$$

This condition causes the cooling length to be equal to the electrons (holes) cooling length $k_{e,h}^{-1} = \sqrt{\kappa_{e,h}/P_{e,h}}$ [7]. Since we investigate

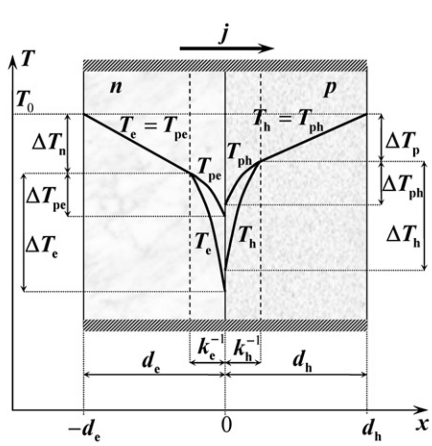

Fig. 1. Schematic image of the temperature at thermal cooling in the p–n diode in the case of thermal thick layers.

a thermally thick p–n structure, then the cooling lengths are less than the lengths d_e, d_h of the structure:

$$k_{e,h} d_{e,h} \gg 1 \tag{6}$$

3. Non-typical temperature distributions

In general, the temperatures of electrons, holes and phonons in the p–n structure with thermally thick layers are distributed as represented on Fig. 1. The electrons (holes) do not interact with the phonons in the areas close to the interface ($|x| \lesssim k_{e,h}^{-1}$) [7]. The energy interaction between electrons (holes) and phonons is very strong in areas far from the interface ($|x| \gg k_{e,h}^{-1}$).Therefore, the temperatures of electrons (holes) and phonons near the p–n interface on the distance of cooling length will be different if the interface energy interaction between electrons (holes) and phonons will be weak enough (a criterion to determine when the level is "weak enough" is given below). The energy interaction between electrons (holes) and phonons is very strong in areas far from the interface ($|x| \gg k_{e,h}^{-1}$). Therefore, the temperatures of electrons (holes) and phonons are identical in these areas, and are linear functions of the coordinate x in the one-dimensional case.

The phonon temperature is the equilibrium one, and the cooling takes place only in the subsystems of electrons and holes if the next inequalities are correct, as follows from Fig. 1:

$$\Delta T_e \gg \Delta T_{pe}, \tag{7a}$$

$$\Delta T_e \gg \Delta T_n, \tag{7b}$$

$$\Delta T_h \gg \Delta T_{ph}, \tag{7c}$$

$$\Delta T_h \gg \Delta T_p. \tag{7d}$$

We assume for the estimation that:

$$P_{ee} \sim P_{eh} \sim P_{he} \sim P_{hh} \sim P_{ij}, \tag{8a}$$

$$P_e \sim P_h, \quad \kappa_e \sim \kappa_h \sim \kappa_{eh},$$

$$(k_e \sim k_h \sim k_{eh}) \tag{8b}$$

$$\kappa_{pe} \sim \kappa_{ph} \sim \kappa_p, \tag{8c}$$

$$d_e \sim d_h \sim d. \tag{8d}$$

From the boundary condition (3c) we can see:

$$\eta_p\left(\Delta T_{ph} - \Delta T_{pe}\right) + \kappa_{pe}\frac{dT_{pe}}{dx}\bigg|_{x=-0} = P_{ee}(\Delta T_{pe} - \Delta T_e) + P_{he}(\Delta T_{pe} - \Delta T_h). \tag{9}$$

From Fig. 1 it follows that

$$\frac{dT_{pe}}{dx}\bigg|_{x=-0} \sim -k_e \Delta T_{pe}. \tag{10}$$

From eqs. (10), (9), (7a) and (7c) we obtain:

$$\eta_p\left(\Delta T_{pe} - \Delta T_{ph}\right) + \kappa_{pe} k_e \Delta T_{pe} \sim P_{ee}\Delta T_e + P_{he}\Delta T_h, \tag{11}$$

From eq. (8) it follows, that

$$\Delta T_e \sim \Delta T_h \sim \Delta T_{eh}, \quad (12a)$$

$$\Delta T_{pe} \sim \Delta T_{ph} \sim \Delta T_{peh}, \quad (12b)$$

$$\Delta T_n \sim \Delta T_p \sim \Delta T. \quad (12c)$$

From eqs. (11), (12) and (8), we obtain:

$$\frac{\Delta T_{peh}}{\Delta T_{eh}} \sim \frac{P_{ij}}{k_{eh}\kappa_p}, \quad (13)$$

We can see from eq. (13) that for the fulfillment of criteria (7a) and (7c), it is necessary that

$$P_{ij} \ll k_{eh}\kappa_p. \quad (14)$$

The physics of the inequality in eq. (14) will be discussed below.

In order to obtain the criteria for the realization of conditions (7b) and (7d), let us consider the boundary conditions for the heat flux at $x = -k_e^{-1}$:

$$-(\kappa_{pe} + \kappa_e)\frac{dT_e}{dx}\bigg|_{x=-k_e^{-1}-0} = -\kappa_{pe}\frac{dT_{pe}}{dx}\bigg|_{x=-k_e^{-1}+0} - \kappa_e\frac{dT_e}{dx}\bigg|_{x=-k_e^{-1}+0} \quad (15)$$

As in nondegenerated semiconductors the electron thermal conductivity is more less than the phonon thermal conductivity [7] (see eq. (5)) then the electron thermal conductivity in the left side of the equation (15) can be neglected. Taking into account eqs. (5), (6) and (8), we can rewrite this boundary condition by an order of magnitude as follows:

$$\kappa_p\frac{\Delta T}{d} \sim \kappa_p k_{eh}\Delta T_{peh} + \kappa_{eh}k_{eh}\Delta T_{eh}. \quad (16)$$

Taking into account eq. (13), we obtain from eq. (16):

$$\kappa_p\frac{\Delta T}{d} \sim (k_{eh}\kappa_{eh} + P_{ij})\Delta T_{eh}. \quad (17)$$

Now, using eqs. (7b) and (7d), from eq. (17) follows the criterion

$$\kappa_p \gg (k_{eh}\kappa_{eh} + P_{ij})d. \quad (18)$$

From condition (6) follows that the fulfillment of the criterion (18) guarantees the fulfillment of the criterion (14). Consequently, the criterion in eq. (18) provides the implementation not only of the conditions (7b) and (7d), but also of all the conditions in eq. (7a), (7b), (7c) and (7d). Thus, in thermally thick samples (condition (6)) to ensure that a substantial cooling exists in the interface neighborhood in both the subsystems of electrons and holes (the subsystem of phonons remains in the equilibrium state), it is sufficient that the criterion (18) is fulfilled. The criterion (18) has a clear meaning: Obviously, in order to ensure that the phonon temperature remains equal to its equilibrium value, it is necessary a value of the phonon thermal conductivity be much larger than both the electron and hole thermal conductivities. In addition, it is also clear that in order to prevent that the phonon subsystem will undergo a cooling process at an interface, it is necessary a weak energy interaction between phonons and electrons (holes) at the interface.

Now let us find the temperature distribution in the electron and hole subsystems under the criterion (18). In this case, the phonon subsystem is at thermal equilibrium:

$$T_{pe}(x) = T_{ph}(x) = T_0. \quad (19)$$

From eq. (1), the boundary conditions (2) and (3), and also taking into account the condition (6) and eq. (19), we obtain for the temperatures of electrons and holes:

$$T_{e,h}(x) = T_0 + e^{\pm k_{eh}x}\left\{j(\Pi_e - \Pi_h)\eta_{eh} \pm j(\Pi_{e,h} - \Pi_s)(k_{eh}\kappa_{eh} + P_{ij})\right\} \times \left\{k_{eh}^2\kappa_{eh}^2 + (k_{eh}\kappa_{eh} + P_{ij})(\eta_{eh} + P_{ij})\right\}^{-1}. \quad (20)$$

We can see from eq. (20) that both heating and cooling of the charge carriers can take place. The latter depends on the magnitude and the sign of Π_s.

In the case of the fulfillment of the inequality

$$|\Pi_s| \ll |\Pi_{e,h}|\frac{\eta_{eh}}{k_{eh}\kappa_{eh} + P_{ij}} \quad (21)$$

we have only carrier cooling, which does not depend on the interface Peltier's coefficient Π_s.

Let us consider some partial cases for a more detailed analysis of the temperature distribution in eq. (20).

1) The interface electron–phonon thermal conductivity η_{eh} is sufficiently large:

$$\eta_{eh} \gg P_{ij},\ k_{eh}\kappa_{eh},\ (k_{eh}\kappa_{eh} + P_{ij})\frac{|\Pi_s|}{|\Pi_{e,h}|}. \quad (22)$$

Under these circumstances, the temperature distribution (20) simplifies as follows (see Fig. 2):

$$T_{e,h}(x) = T_0 + \frac{j(\Pi_e - \Pi_h)}{k_{eh}\kappa_{eh} + P_{ij}}e^{\pm k_{eh}x}. \quad (23)$$

We can see from eq. (23) that the temperature of electrons equals to the temperature of holes at the interface in this case. Only cooling takes place at the interface which is enhanced when the values of the parameters k_{eh}, κ_{eh} and P_{ij} become smaller.

2) The electron–hole thermal conductivity η_{eh} is sufficiently small:

$$\eta_{eh} \ll P_{ij},\ k_{eh}\kappa_{eh},\ (k_{eh}\kappa_{eh} + P_{ij})\frac{|\Pi_s|}{|\Pi_{e,h}|}. \quad (24)$$

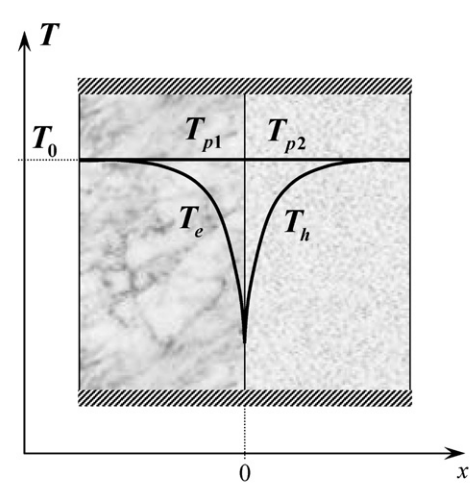

Fig. 2. Temperature's profile at thermal cooling in a p–n diode under the conditions in eqs. (18) and (22).

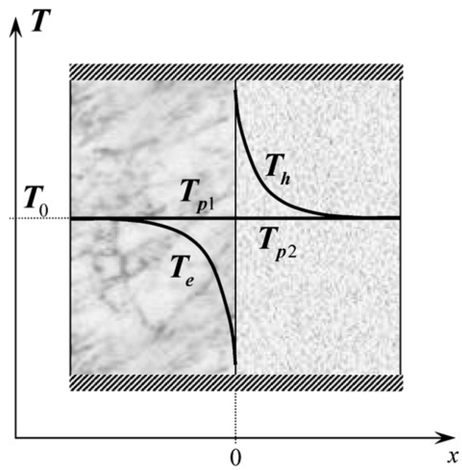

Fig. 3. Temperature profile in a p–n diode under the conditions in eqs. (18) and (24), when $|\Pi_s| \gg |\Pi_{e,h}|$ and $\Pi_s > 0$.

Under these conditions, the temperature distribution (20) simplifies as follows:

$$T_{e,h}(x) = T_0 \pm \frac{j(\Pi_{e,h} - \Pi_s)}{k_{eh}\kappa_{eh} + P_{ij} - \frac{k_{eh}\kappa_{eh}P_{ij}}{k_{eh}\kappa_{eh}+P_{ij}}} e^{\pm k_{eh}x}. \tag{25}$$

As can be seen from eq. (25) in this case, the temperature of electrons is not already equal to the temperature of holes at the interface. Moreover, there both cooling and heating may take place. Thus we see that cooling or heating are becoming greater when the values of the parameters k_{eh}, κ_{eh} and P_{ij} are becoming smaller. This is the same as in the previous case.

If $|\Pi_s| \gg |\Pi_{e,h}|$, then the distribution takes the form:

$$T_{e,h}(x) = T_0 \mp \frac{j\Pi_s(k_{eh}\kappa_{eh} + P_{ij})}{k_{eh}^2\kappa_{eh}^2 + k_{eh}\kappa_{eh}P_{ij} + P_{ij}^2} e^{\pm k_{eh}x}. \tag{26}$$

In the case of $\Pi_s > 0$ ($\Pi_s < 0$), the electron subsystem is cooled (heated), whereas the hole one is, conversely, heated (cooled) (see Fig. 3).

If we have the opposite situation ($|\Pi_s| \ll |\Pi_{e,h}|$), then the temperature distribution is the following:

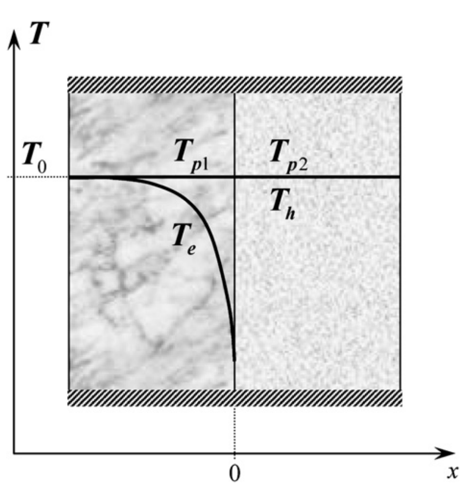

Fig. 4. Temperature profile at thermal cooling in a p–n diode under conditions in eqs. (18) and (24), when $|\Pi_e| \gg \Pi_h, |\Pi_s|$.

$$T_{e,h}(x) = T_0 \pm \frac{j\Pi_{e,h}(k_{eh}\kappa_{eh} + P_{ij})}{k_{eh}^2\kappa_{eh}^2 + k_{eh}\kappa_{eh}P_{ij} + P_{ij}^2} e^{\pm k_{eh}x}. \tag{27}$$

There is cooling of both electron and hole subsystems. However, in the case of $|\Pi_e| \gg \Pi_h$ ($|\Pi_e| \ll \Pi_h$) there is cooling only in the electron (hole) subsystem (see Fig. 4).

4. Conclusions

As a general conclusion, in our work it is shown the possibility of realization of the exotic temperature distribution in a p–n structure under an electric current. The phonon temperature is at its thermal equilibrium value, whereas the temperatures of electrons and holes undergo essential cooling or heating near the interface over a distance of the order of the cooling length. We have established the prerequisites for these temperature distributions (criterion in eq. (18)).

Moreover, it is shown that there can be cooling (or heating) only in one of the subsystems: either in the electron or in the hole one – whereas the other one stays in the equilibrium state. Such situation takes place, when the interface electron–hole thermal conductivity on the interface is essentially small (the criteria of infinitesimality are established) and the Peltier's coefficient of electron (hole) semiconductor is essentially larger than both the Peltier's coefficient of the hole (electron) one and the interface Peltier's coefficient.

The temperatures of electrons and holes on the interface coincide under some criteria.

Acknowledgements

Authors are grateful to CONACYT (México) for partial finance support. One of the authors (I.L.) is grateful to CINVESTAV-I.P.N. for finance support.

Authors thank Prof. Enrique Velazquez-Perez (Salamanca University, Spain) for useful discussions.

References

[1] A.F. Ioffe, Semiconductor Thermoelements and Thermoelectric Cooling, Infosearch, London, 1957.
[2] J. Tauc, Photo and Thermoelectric Effects in Semiconductors, Pergamon, Oxford, 1962.
[3] L.I. Anatychuk, Physics of Thermoelectricity, Institute of Thermoelectricity, Kyiv and Chernovtsi, 1998.
[4] G.S. Nolas, J. Sharp, H.J. Goldsmid, Thermoelectrics. Basic Principles and New Materials Development, Springer, Berlin and New York, 2001.
[5] D.M. Rowe (Ed.), Thermoelectrics Handbook: Macro to Nano, Taylor & Francis, London/CRC, Boca Raton, FL, 2006.
[6] Z.S. Gribnikov, N.A. Prima, Size dependence of the transverse magnetoresitance of semiconductors, Sov. Phys. Semicond. 5 (1972) 1126–1130.
[7] Yu.G. Gurevich, F. Perez Rodríguez, Fenomenos de transporte en semiconductores, Fondo de cultura economica, Mexico, 2007, (in Spanish).
[8] Yu.G. Gurevich, G.N. Logvinov, Physics of thermoelectric cooling, Semicond. Sci. Technol. 20 (2005) R57–R64.
[9] Yu.G. Gurevich, O.Yu. Titov, G.N. Logvinov, O.I. Lyubimov, Nature of the thermopower in bipolar semiconductor, Phys. Rev. B 51 (1995) 6999–7004.
[10] Yu.G. Gurevich, G.N. Logvinov, I.N. Volovichev, G. Espejo, O.Yu. Titov, A. Meriuts, The role of non-equilibrium carriers in the formation of thermo-e.m.f. in bipolar semiconductors, Phys. Stat. Sol. (b) 231 (2002) 278–293.
[11] O.Yu Titov, J. Giraldo, Yu.G. Gurevich, Boundary conditions in an electric current contact, Appl. Phys. Lett. 80 (2002) 3108–3110.
[12] G.N. Logvinov, J.E. Velásquez, I.M. Lashkevych, Yu.G. Gurevich, Heating and cooling in semiconductor structures by en electric current, Appl. Phys. Lett. 89 (2006) 092118-1–092118-3.
[13] Yu.G. Gurevich, G.N. Logvinov, Theory of thermoelectric cooling in semiconductor structures, Revista Mexicana de Física 53 (5) (2007) 337–349.