

INFLUENCE OF RECOMBINATION ON THE THERMAL CONDUCTION IN BIPOLAR SEMICONDUCTORS AND SEMICONDUCTOR STRUCTURES

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ABSTRACT

It is investigated the influence of recombination on the energy flux in bipolar semiconductors. The expression for energy flux in a nondegenerate semiconductor in a linear approximation with respect to perturbation in a quasi-neutral approximation taking into account recombination (the presence of nonequilibrium charge carriers in the semiconductor) has been obtained. In a one-dimension case when the different temperatures from the both sides of the semiconductor have been considered the energy flux density has been calculated in two different cases: the case of weak recombination and the case of strong recombination.

INTRODUCTION

It is generally accepted that the energy transfer in solids is by means of heat conductivity and the energy flux density is set by the Fourier's law, $-\kappa\nabla T$, where κ is the material conductivity, T is the temperature [1].

Nevertheless, the electrical currents of electrons and holes can be presented in bipolar semiconductors when the total electrical current is absent. Therefore, the energy can be transferred not only by means of heat conductivity but also by means of electrons' and holes' transports since they carry the energy. The process of an appearance of these electrical currents is as follows. The temperature gradient that arises because of the different values of the temperature from the both sides of the semiconductor causes the nascency of both the thermoelectric currents and thermal generation of electron-hole pairs. Nonequilibrium electrons and holes that have arisen because of the inhomogeneous thermal generation form the diffusion electrical currents. The redistribution of electrons and holes takes place because of diffusion and thermal diffusion of charge carriers. The latter changes the electrical potential in the semiconductor. As a result of this, the electrical field arises that causes the electrical current too.

The purpose of this paper is to investigate the process of energy transport in nondegenerate bipolar semiconductors taking

into account not only the process of heat conductivity but also the process of an energy transport by means of electrons' and holes' transference (diffusion, thermal diffusion, drift motion in an electrical field), bearing in mind recombination (the presence of nonequilibrium charge carriers).

NOMENCLATURE

T	[J]	Temperature
κ	[W/m J]	Thermal conductivity
ε_g	[J]	Bandgap
w	[W/m ²]	Energy flux density
j	[A/m ²]	Electrical current density
$\tilde{\varphi}$	[V]	Electrochemical potential (Fermi quasi-level)
Π	[V]	Peltier coefficient
x	[m]	Cartesian axis direction
φ	[V]	Electrical potential
μ	[J]	Chemical potential
E	[C]	Hole charge (the magnitude of electron charge)
R	[-]	The exponent in the momentum relaxation time for electrons (holes)
τ^n	[s]	The momentum relaxation time for electrons (holes)
τ	[s]	Lifetime of charge carriers
τ_{bb}	[s]	Lifetime of charge carriers with respect to band-band recombination
τ_i	[s]	Lifetime of charge carriers in extrinsic semiconductor with respect to recombination through the impurities
α	[V/J]	Seebeck coefficient (thermopower, thermoelectric power, and thermoelectric sensitivity)
σ	[$\Omega^{-1} m^{-1}$]	Electrical conductivity
ξ	[-]	Dimensionless coefficient that depend on the exponent in the momentum relaxation time for electrons (holes)
ε_i	[J]	Impurity energy level
n	[m ⁻³]	Electron concentration
p	[m ⁻³]	Hole concentration
R	[m ⁻³ s ⁻¹]	Recombination rate
k	[m ³ /s]	Capture coefficient
N_i	[m ⁻³]	Impurity concentration
d	[m]	Half-length of the semiconductor

Subscripts

n	Electrons
p	Holes
0	Equilibrium besides of j_0 i w_0

ENERGY TRANSPORT IN A BIPOLAR SEMICONDUCTOR: GENERAL EQUATIONS

The classic approach to the energy transport in semiconductors assumes that this transport takes place only by means of heat conductivity [1]. This approach neglects the influence of recombination on the energy transport process. In this case, the heat flux density, \mathbf{q} , is equal to the energy flux density, \mathbf{w} . Moreover, the expression for the energy flux density is set by the Fourier's law:

$$\mathbf{w} = -\kappa \nabla T, \quad (1)$$

where $\kappa = \kappa_n + \kappa_p + \kappa_{ph}$ is the thermal conductivity of the semiconductor (κ_n is the thermal conductivity of electrons in a conduction band, κ_p is the thermal conductivity of holes in a valence band, and κ_{ph} is the thermal conductivity of phonons) and T is the temperature. We assume that the temperature has the energy units (the Boltzmann constant is equal to unity and has no dimension).

Nevertheless, if the temperature in a semiconductor is nonuniform so the thermal diffusion of electrons and holes take place. This means that electrical currents of electrons and holes can be presented in a semiconductor, in which the total electrical current is absent. These currents have the same magnitude but opposite directions and take place due to recombination. As a result of these electrical currents the energy can be transferred not only by means of heat conductivity but also by means of electrons' and holes' transport. Thus, the expression for the energy flux density is as follows [2]:

$$\mathbf{w} = -\kappa \nabla T + (\tilde{\varphi}_n + \Pi_n) \mathbf{j}_n + (\tilde{\varphi}_p + \Pi_p) \mathbf{j}_p, \quad (2)$$

where $\tilde{\varphi}_n$ ($\tilde{\varphi}_p$) is an electrochemical potential (Fermi quasi-level) of electrons (holes); \mathbf{j}_n (\mathbf{j}_p) is electrical current density of electrons (holes); and Π_n (Π_p) is the Peltier coefficient of electrons (holes). Let us note that we consider a uniform specimen without a total electrical current. Therefore the Peltier effect is absent.

It is seen from Eq. (2) that, only if the electrical currents of electrons and holes are absent, then the energy flux (2) reduces to Eq. (1).

The expressions for electrochemical potentials of electrons and holes are as follows [3,4]:

$$\tilde{\varphi}_n = \varphi - \frac{1}{e} \mu_n, \quad \tilde{\varphi}_p = \varphi + \frac{1}{e} \mu_p, \quad (3)$$

where φ is the electrical potential and μ_n (μ_p) is the chemical potential of electrons (holes).

Let us consider the case of a nondegenerate semiconductor. In this case the expressions for Peltier coefficients are as follows [5-8]:

$$\Pi_{n,p} = \mp \frac{1}{e} \left(\left[r_{n,p} + \frac{5}{2} \right] T - \mu_{n,p} \right), \quad (4)$$

where r_n (r_p) is the exponent in the momentum relaxation time for electrons (holes) [9]; $\tau_{n,p}^m = \tau_{0,n,p}^m (\varepsilon/T)^{r_{n,p}}$, where ε is the

energy of the carriers (the constant quantities $\tau_{0,n,p}^m$ and $r_{n,p}$ for different relaxation mechanisms can be found in Ref. [9]).

Let us consider a quasi-neutral approximation [3,10-14]. In this approximation the concentration of electrons and holes in equilibrium, n_0 , p_0 , are constant [15]. Hence, the electrical potential in equilibrium, φ_0 , the chemical potential of electrons (holes) in equilibrium, μ_{n0} (μ_{p0}), and the electrochemical potential of electrons (holes) in equilibrium, $\tilde{\varphi}_{n0}$ ($\tilde{\varphi}_{p0}$), are constants.

The expressions for the densities of electrical currents of electrons and holes, which are in expressions for energy flux densities (see Eqs. (2)), are as follows [16,17]:

$$\mathbf{j}_{n,p} = -\sigma_{n,p} (\nabla \delta \tilde{\varphi}_{n,p} + \alpha_{n,p} \nabla \delta T), \dots \dots \dots (5)$$

where σ_n (σ_p) is electrical conductivity of electrons (holes); α_n (α_p) is the Seebeck coefficient of electrons (holes); $\delta \tilde{\varphi}_{n,p} = \tilde{\varphi}_{n,p} - \tilde{\varphi}_{n0,p0}$; and $\delta T = T - T_0$, where T_0 is the equilibrium temperature.

It is seen from Eqs. (2)-(5) that the energy flux density depends not only on the temperature distribution in a semiconductor but also on the distributions of electrochemical potentials of electrons and holes, $\tilde{\varphi}_{n,p}$.

Substituting Eqs. (5) for the electrical current densities, $\mathbf{j}_{n,p}$, in Eq. (2) for energy flux density in a semiconductor, the following expression for energy flux density can be obtained:

$$\mathbf{w} = - \left[\kappa + \alpha_n \sigma_n (\tilde{\varphi}_n + \Pi_n) + \alpha_p \sigma_p (\tilde{\varphi}_p + \Pi_p) \right] \nabla \delta T - \sigma_n (\tilde{\varphi}_n + \Pi_n) \nabla \delta \tilde{\varphi}_n - \sigma_p (\tilde{\varphi}_p + \Pi_p) \nabla \delta \tilde{\varphi}_p. \quad (6)$$

It is seen from Eq. (6) that the energy flux in a semiconductor depends on the gradient of the temperature, ∇T , and on the gradients of the electrochemical potentials, $\nabla \tilde{\varphi}_n$ and $\nabla \tilde{\varphi}_p$.

It is worth to mention here that the following expression must take place in a semiconductor, in which the total electrical current is equal to zero:

$$\mathbf{j}_n + \mathbf{j}_p = 0. \quad (7)$$

Substituting the expressions for electrical currents (5) into Eq. (7), the following additional equation that connects the temperature with electrochemical potentials can be obtained:

$$\sigma_n (\nabla \delta \tilde{\varphi}_n + \alpha_n \nabla \delta T) + \sigma_p (\nabla \delta \tilde{\varphi}_p + \alpha_p \nabla \delta T) = 0. \quad (8)$$

Hence, the energy flux density in a semiconductor, in which the total electrical current is equal to zero ($\mathbf{j}_0 = 0$, where $\mathbf{j}_0 = \mathbf{j}_n + \mathbf{j}_p$), is expressed by Eq. (6), and in addition, the Eq. (8) must take place too.

Substituting the expressions for electrochemical potentials (3) into the equation for the energy flux density (6) and into the condition of a total electrical current absence (8), taking into account the expressions for Peltier coefficients (4), two following formulas can be obtained:

$$\begin{aligned} \mathbf{w} = & -\left(\sigma\varphi - \sigma_n \left[r_n + \frac{\xi}{2} \right] \frac{1}{e} T + \sigma_p \left[r_p + \frac{\xi}{2} \right] \frac{1}{e} T\right) \nabla \delta\varphi - \\ & \left[\kappa + \alpha_n \sigma_n \left(\varphi - \left[r_n + \frac{\xi}{2} \right] \frac{1}{e} T \right) + \alpha_p \sigma_p \left(\varphi + \left[r_p + \frac{\xi}{2} \right] \frac{1}{e} T \right) \right] \nabla \delta T \\ & + \frac{1}{e} \sigma_n \left(\varphi - \left[r_n + \frac{\xi}{2} \right] \frac{1}{e} T \right) \nabla \delta\mu_n - \frac{1}{e} \sigma_p \left(\varphi + \left[r_p + \frac{\xi}{2} \right] \frac{1}{e} T \right) \nabla \delta\mu_p, \quad (9a) \\ & \sigma \nabla \delta\varphi + \left(\alpha_n \sigma_n + \alpha_p \sigma_p \right) \nabla \delta T - \frac{1}{e} \sigma_n \nabla \delta\mu_n + \frac{1}{e} \sigma_p \nabla \delta\mu_p = 0, \quad (9b) \end{aligned}$$

where $\sigma = \sigma_n + \sigma_p$.

Equation (9a) expresses the energy flux density in a nondegenerate bipolar semiconductor by means of the following functions: φ , T , μ_n , and μ_p .

Expressing $\nabla \delta\varphi$ from Eq. (9b) and substituting in the expression of the energy flux density in a semiconductor (9a), the expression for \mathbf{w} that now depends on the three functions, T , μ_n , and μ_p , can be obtained

$$\begin{aligned} \mathbf{w} = & -\kappa \nabla \delta T - \xi \frac{\sigma_n \sigma_p}{e^2 \sigma} \\ & \times \left\{ \left[\xi T - \mu_p - \mu_n \right] \nabla \delta T + T \nabla \left[\delta\mu_n + \delta\mu_p \right] \right\}, \quad (10) \end{aligned}$$

where $\xi = r_n + r_p + 5$. In Eq. (10) we have taken into account Eqs. (4), and also the expression $\Pi_{n,p} = \alpha_{n,p} T$ [16,18,19] that connects the Peltier coefficient, $\Pi_{n,p}$, with the Seebeck coefficient, $\alpha_{n,p}$.

Formula (10) is the equation for the energy flux density in nondegenerate bipolar semiconductor, in which the total electrical current is absent, $\mathbf{j}_0 = 0$.

If the semiconductor does not irradiate and absorb light the energy balance equation in a stationary case is as follows [2]:

$$\operatorname{div} \mathbf{w} = 0. \quad (11)$$

In a one-dimensional case the Eq. (11) means that the energy flux density is constant:

$$\mathbf{w} = \mathbf{w}_0, \quad (12)$$

where $\mathbf{w}_0 = \text{const}$.

Let us consider the case of a linear approximation with respect to perturbation. In this case expression (10) for the energy flux density reduces to the following:

$$\mathbf{w} = -\kappa_0 \nabla \delta T - \frac{\xi \sigma_{n0} \sigma_{p0}}{e^2 \sigma_0} \left\{ \left[\xi T_0 + \varepsilon_{g0} \right] \nabla \delta T + T_0 \nabla \left[\delta\mu_n + \delta\mu_p \right] \right\}, \quad (13)$$

where κ_0 is the thermal conductivity of a semiconductor in equilibrium; σ_{n0} (σ_{p0}) is the electrical conductivity of electrons (holes) in equilibrium; $\sigma_0 = \sigma_{n0} + \sigma_{p0}$; and ε_{g0} is the energy bandgap in a semiconductor in equilibrium. The equation $\mu_{n0} + \mu_{p0} = -\varepsilon_0$ [16,18,19] has been utilized for obtaining expression (13).

The chemical potentials of electrons and holes in a linear approximation with respect to perturbation are [17,18]:

$$\delta\mu_n = \left(-\frac{3}{2} + \frac{\mu_{n0}}{T_0} \right) \delta T + \frac{T_0}{n_0} \delta n, \quad (14a)$$

$$\delta\mu_p = \left(-\frac{3}{2} + \frac{\mu_{p0}}{T_0} \right) \delta T + \frac{T_0}{p_0} \delta p, \quad (14b)$$

where $\delta\mu_n = \mu_n - \mu_{n0}$; $\delta\mu_p = \mu_p - \mu_{p0}$; $\delta n = n - n_0$; $\delta p = p - p_0$; and n (p) is the concentration of electrons (holes). Equations (14a) and (14b) do not take into account the dependences of effective masses of electrons and holes on the temperature [17].

Substituting expressions (14a) and (14b) for chemical potentials into Eq. (13), we obtain:

$$\mathbf{w} = -\kappa_0 \nabla \delta T - \frac{\xi \sigma_{n0} \sigma_{p0}}{e^2 \sigma_0} \left\{ (\xi - 3) T_0 \nabla \delta T + T_0^2 \nabla \left(\frac{\delta n}{n_0} + \frac{\delta p}{p_0} \right) \right\}. \quad (15)$$

This equation expresses the energy flux density, \mathbf{w} , by means of the temperature gradient, $\nabla \delta T$, and the gradient of concentrations' combination, $\nabla \left(\frac{\delta n}{n_0} + \frac{\delta p}{p_0} \right)$.

In Ref [2] the balance equation for the diffusion heat flux, $\mathbf{q}_{\text{diff}} = -\kappa \nabla \delta T$, is obtained in a linear approximation with respect to perturbation for a nondegenerate semiconductor in a quasi-neutral approximation:

$$\operatorname{div} \mathbf{q}_{\text{diff}} = \xi T_0 R. \quad (16)$$

where R is the rate of recombination, which is set by such expression [20,21]:

$$R = \frac{1}{\tau_0} \frac{n_0 p_0}{n_0 + p_0} \left(\frac{\delta n}{n_0} + \frac{\delta p}{p_0} - \left[3 + \frac{\varepsilon_{g0}}{T_0} \right] \frac{\delta T}{T_0} \right), \quad (17)$$

where τ_0 is the time that characterizes the lifetime of electrons and holes. If the semiconductor is intrinsic, then $\tau_0 = \tau_{\text{bb}}$, where

$\tau_{\text{bb}} = (k_0 [n_0 + p_0])^{-1}$ is the time that characterizes the lifetime of electrons and holes with respect to band-band recombination [20] (k_0 is the capture coefficient of electrons by holes in equilibrium); if the semiconductor is extrinsic, then $\tau_0^{-1} = \tau_{\text{bb}}^{-1} + \tau_t^{-1}$, where $\tau_t = (k_{n0} k_{p0} N_t [n_0 + p_0])^{-1}$

$\times (k_{n0} [n_0 + n_{i0}] + k_{p0} [p_0 + p_{i0}])$ [21] is the lifetime of charge carriers in an extrinsic semiconductor with respect to recombination through the impurity energy level, where k_{n0} (k_{p0}) is the capture coefficient of electrons (holes) by impurities in equilibrium; N_t is the impurity concentration;

$n_{i0} = \nu_{n0} \exp(-\varepsilon_{i0}/T_0)$; $p_{i0} = \nu_{p0} \exp(-[\varepsilon_{g0} - \varepsilon_{i0}]/T_0)$;

$\nu_{n0,p0} = \frac{1}{4} (2m_{n0,p0} T_0 / \pi \hbar^2)^{3/2}$ are the electron and hole densities of states at the bottom of the conduction band and at the top of the valence band, $m_{n0,p0}$ are the electron and hole effective masses in equilibrium; ε_{i0} is the impurity energy level in equilibrium. Here the Shockley-Read model is used for recombination [22].

From Eqs. (16) and (17) the following relationship between the function of concentrations, $\frac{\delta n}{n_0} + \frac{\delta p}{p_0}$, and the temperature, δT , in a linear approximation with respect to perturbation can be obtained:

$$\frac{\delta n}{n_0} + \frac{\delta p}{p_0} = \left(3 + \frac{\varepsilon_{g0}}{T_0} \right) \frac{\delta T}{T_0} - \frac{n_0 + p_0}{n_0 p_0} \frac{\tau_0 \kappa_0}{\xi T_0} \Delta \delta T. \quad (18)$$

Substituting the expression for concentration's combination, $\frac{\delta n}{n_0} + \frac{\delta p}{p_0}$, from Eq. (18) into Eq. (15), the following expression for the energy flux density can be obtained:

$$\mathbf{w} = -\kappa_0 \nabla \delta T - \xi \frac{\sigma_{n0} \sigma_{p0}}{e^2 \sigma_0} \times \left(\left[\xi + \frac{\varepsilon_{g0}}{T_0} \right] T_0 \nabla \delta T - \frac{n_0 + p_0}{\xi n_0 p_0} \tau_0 \kappa_0 T_0 \nabla (\Delta \delta T) \right). \quad (19)$$

Comparing Eq. (19) for the energy flux density with the Fourier's law (see Eq. (1)), we see that they are different. In contrast to the Fourier's law the energy flux density in a semiconductor (see Eq. (19)) depends not only on the thermal conductivity, κ_0 , but also on many other its parameters such as the lifetime of charge carriers, τ_0 , the bandgap, ε_{g0} , and the electrical conductivities of electrons and holes, $\sigma_{n0, p0}$. Moreover, the energy flux density depends not only on the temperature gradient, ∇T , but also on the third derivative of the temperature with a coordinate, $\nabla (\Delta \delta T)$. Just the term, which is proportional to the third derivative of the temperature, $\frac{\sigma_{n0} \sigma_{p0}}{e^2 \sigma_0} \frac{n_0 + p_0}{n_0 p_0} \tau_0 \kappa_0 T_0 \nabla (\Delta \delta T)$, depends on recombination (on the lifetime of charge carriers, τ_0). Due to that the heat dissipates by means of recombination [2] then the temperature is not a linear function with a coordinate [15,23] because of nonuniform recombination. Therefore the third derivative of the temperature is nonzero ($\nabla (\Delta \delta T) \neq 0$).

In particular, in the case of strong recombination ($\tau_0 \rightarrow 0$) expression for the energy flux density (19) reduces to the following:

$$\mathbf{w} = - \left[\kappa_0 + \frac{\sigma_{n0} \sigma_{p0}}{e^2 \sigma_0} \xi \left(\xi + \frac{\varepsilon_{g0}}{T_0} \right) T_0 \right] \nabla \delta T. \quad (20)$$

It is seen from Eq. (20) that the energy flux density does not depend on the third derivative of the temperature, $\nabla (\Delta \delta T)$, in this partial case ($\tau_0 \rightarrow 0$) but depends only on the temperature gradient, ∇T . Moreover, we can see that the expression for the energy flux density is not the same as in the Fourier's law (see Eq. (1)), and differs from it because Eq. (20) has additional term, $\frac{\sigma_{n0} \sigma_{p0}}{e^2 \sigma_0} \xi \left(\xi + \frac{\varepsilon_{g0}}{T_0} \right) T_0 \nabla \delta T$. Since this term is proportional to the electrical conductivities of electrons and holes, $\sigma_{n0} \sigma_{p0}$, so this means that it is connected with the drift motion of charge carriers.

One-Dimensional Case

In a one-dimensional case the general Eq. (19) for the energy flux density is (taking into account Eq. (12)):

$$w_0 = -\kappa_0 \frac{d\delta T}{dx} - \frac{\xi \sigma_{n0} \sigma_{p0}}{e^2 \sigma_0} \left(\left[\xi + \frac{\varepsilon_{g0}}{T_0} \right] T_0 \frac{d\delta T}{dx} - \frac{n_0 + p_0}{\xi n_0 p_0} \tau_0 \kappa_0 T_0 \frac{d^3 \delta T}{dx^3} \right) \quad (21)$$

It is shown in Ref. [15,23] that for any stationary processes of the energy and charge propagation the temperature is:

$$\delta T = C_1 + C_2 x + C_3 \exp \frac{x}{L_0} + C_4 \exp \left(-\frac{x}{L_0} \right), \quad (22)$$

where C_1 , C_2 , C_3 , and C_4 are unknown constants, the values of which depend on the boundary conditions;

$$L_0 = \frac{1}{e} \sqrt{\frac{\tau_0 T_0 \frac{n_0 + p_0}{n_0 p_0}}{\frac{\sigma_0}{\sigma_{n0} \sigma_{p0}} + \frac{\xi \varepsilon_{g0}}{e^2 \kappa_0}}} \quad (23)$$

is the generalized diffusion length [15,23] for the temperatures $T_0 \ll \varepsilon_{g0}$. Equation (22) is correct for nondegenerate bipolar semiconductors in a quasi-neutral case in a linear approximation with respect to perturbation.

Substituting expression for the temperature (22) into the expression for the energy flux density (21) and taking into account the expression for the generalized diffusion length (23), we obtain the following equation for w_0 for $T_0 \ll \varepsilon_{g0}$:

$$w_0 = - \left(\kappa_0 + \varepsilon_{g0} \frac{\xi \sigma_{n0} \sigma_{p0}}{e^2 \sigma_0} \right) C_2. \quad (26)$$

Equation (26) confirms that the energy flux density in a one-dimensional case does not depend on coordinate, i. e., is a constant.

As it seen from Eq. (26), the energy flux density, w_0 , depends on the thermal conductivity, κ_0 , a bandgap, ε_{g0} , the electrical conductivities of electrons and holes, $\sigma_{n0, p0}$, and the boundary conditions because of a constant C_2 that is presented in the temperature (22).

Let us consider two partial cases: strong ($\tau_0 \rightarrow 0$) and weak ($\tau_0 \rightarrow \infty$) recombination. In these two partial cases the temperature is a linear function with respect to coordinate [23]. Therefore, the expression for the temperature (22) reduces to the following:

$$\delta T = C_1 + C_2 x. \quad (27)$$

Here it is worth to mention that the surface recombination on the ends of the semiconductor must take place in the case of the absence of bulk recombination ($\tau_0 \rightarrow \infty$) because the electrical currents of electrons and holes in an isolated semiconductor can exist only by means of recombination.

Let the semiconductor has isothermal contacts with a thermostats at $x = -d$ and $x = d$, and the temperatures of the thermostats are equal to T_1 at $x = -d$ and T_2 at $x = d$. Let the lateral sides are adiabatically insulated. Then the boundary conditions at $x = \pm d$ are as follows:

$$\delta T(-d) = T_1 - T_0, \quad \delta T(d) = T_2 - T_0. \quad (28)$$

Substituting formula for the temperature (27) into boundary conditions (28), we find the constant C_2 :

$$C_2 = \frac{T_2 - T_1}{2d}. \quad (29)$$

Substituting the expression for the constant C_2 (see Eq. (29)) into Eq. (26), we obtain the following expression for the energy flux density:

$$w_0 = \left(\kappa_0 + \varepsilon_{g0} \frac{\xi \sigma_{n0} \sigma_{p0}}{e^2 \sigma_0} \right) \frac{T_1 - T_2}{2d}. \quad (30)$$

As it is seen from this equation the energy flux density differs from the Fourier's law, $\kappa_0 \frac{T_1 - T_2}{2d}$ (see Eq. (1)), because Eq. (30) has an additional term, $\varepsilon_{g0} \frac{\xi \sigma_{n0} \sigma_{p0}}{e^2 \sigma_0} \frac{T_1 - T_2}{2d}$. This term is the energy flux density by means of a drift motion of electrons and holes. We can see from this expression that the energy flux density by means of a drift motion of charge carriers increases with increasing both electrical conductivities of charge carriers and the bandgap.

It is seen from Eq. (30) that the energy flux density depends not only on the thermal conductivity, κ_0 , the length of the semiconductor, $2d$, and the difference of the temperature, $T_1 - T_2$, on the ends of the semiconductor, as it is in classic result, $\kappa_0 \frac{T_1 - T_2}{2d}$, but also on the bandgap, ε_{g0} , the electrical conductivities of electrons and holes, $\sigma_{n0, p0}$, and the mechanisms of momentum relaxation of charge carriers, ξ . Also, it is seen from Eq. (30) that the energy flux increases with increasing the bandgap. Nevertheless, if the semiconductor tends to monopolar hole (electron) semiconductor, i. e., when $\sigma_{n0} \ll \sigma_{p0}$ ($\sigma_{p0} \ll \sigma_{n0}$), then the expression for the energy flux density (30) reduces to the following: $w_0 = \left(\kappa_0 + \varepsilon_{g0} \frac{\xi \sigma_{n0}}{e^2} \right) \frac{T_1 - T_2}{2d}$ ($w_0 = \left(\kappa_0 + \varepsilon_{g0} \frac{\xi \sigma_{p0}}{e^2} \right) \frac{T_1 - T_2}{2d}$). It means that the energy flux density does not depend on the electrical conductivity of majority carriers but depends on the electrical conductivity of minority carriers: with increasing the electrical conductivity of minority carriers the energy flux density increases. If the semiconductor is monopolar ($\sigma_{n0} \rightarrow 0$ or $\sigma_{p0} \rightarrow 0$), then, as it is seen from two previous equations, the energy flux density has classic expression, $w_0 = \kappa_0 \frac{T_1 - T_2}{2d}$.

CONCLUSIONS

The expression for the energy flux density in nondegenerate bipolar semiconductor is obtained. We have used the following statements: 1) a linear approximation with respect to perturbation; 2) a quasi-neutral approximation; 3) an absence of a total electrical current (the electrical currents of electrons and holes can exist). This flux depends on many parameters of the semiconductor: the thermal conductivities of electrons, holes, and phonons; the electrical conductivities of electrons and holes; the bandgap; the mechanisms of momentum relaxation of charge carriers; the lifetime of charge carriers; the electron and hole concentrations.

The expressions for the energy flux densities are obtained in a one-dimension case under infinitely large and infinitely small recombination rates when there are different temperatures on the ends of the specimen. In these cases the energy flux density depends on the thermal conductivity of the semiconductor, the electrical conductivities of electrons and holes, the bandgap, and the mechanisms of momentum relaxation of charge carriers. It is shown that, when the semiconductor tends to a monopolar one, then the energy flux density leaves the dependence on the

electrical conductivity of majority carriers but maintains the dependence on the electrical conductivity of minority carriers. If the semiconductor is monopolar, then the expression for the energy flux density is classic.

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