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THERMAL SIZE EFFECTS IN CONTACT METAL SEMICONDUCTOR

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Abstract: *The heating of electrons and phonons, as well as thermal size effects in the Schottky barrier, are investigated. The dependence of the electron and phonon temperature is analyzed depending on the thermal boundary conditions and the sample size. It was found that in thin (ka << 1) diodes at the contacts, the electron temperature is much higher than the phonon temperature. When the condition of ideal heat transfer is satisfied in an ohmic contact, the temperatures of electrons and phonons coincide with the ambient temperature. In massive (ka >> 1) diodes in the volume, the temperatures of electrons and phonons coincide, and in an ohmic contact, the temperatures coincide with the ambient temperature.*

Key words: *thermal dimensional effects, Schottky barrier, cooling length, thermal conductivity, heat transfer.*

Introduction

At present, the dimensions of semiconductor diodes in microcircuits are of the same order of magnitude as the cooling length of charge carriers on phonons. When the dimensions of the sample coincide in order of magnitude with the cooling length of carriers on phonons, the average energy of charge carriers changes. In this case, carriers at all points in space "feel" thermal boundary conditions, and we are dealing with the so-called thermal size effects (TRE). In the works, the influence of heating of current carriers and phonons, as well as ERE in bounded homogeneous semiconductors. The study of FRE in semiconductors opens up broad prospects for use in semiconductor microelectronics.

To study the process of current passing through an inhomogeneous semiconductor, we will consider the sample as a limited system consisting of subsystems of charge carriers and phonons. The charge carrier subsystem interacts with the phonon subsystem and with the environment. At the sample boundary, it is necessary to formulate thermal and current boundary conditions. Taking into account the boundary will lead to the fact that each subsystem will establish its own distribution of the field and temperatures. However, at present, the effect of ERE on the operation of inhomogeneous semiconductor structures has hardly been studied.

Thus, the study of the heating of current carriers and phonons, as well as ERE in Schottky barriers used to create semiconductor devices, is relevant and has a clear scientific and practical perspective.

The purpose of this work is to study the heating of charge carriers and phonons, as well as the ERE in Schottky barriers.

2. Equations of thermal conductivity in the electron and phonon subsystems and boundary conditions

Consider a thin Schottky diode in the form of a parallelopiped with dimensions x = a, z = b, y = c. We will assume that the dimensions of the samples in the y and z directions significantly exceed the characteristic lengths of temperature variation and all quantities will depend on only one coordinate x, at the point x = 0 there is a metal-semiconductor contact and its temperature T2, and at the point x = a the temperature of the thermostat T1 . Let us assume that the main mechanism of charge transfer through the contact is thermionic emission and the Bethe diode approximation is fulfilled Te,p = T.When the current passes through the potential barrier, the carriers are heated (cooled) by the field of the barrier and the field applied from outside, and in the metal the energy received by electrons from the field is transferred to phonons. The phonon and electronic subsystems transfer energy to the contacts due to thermal conductivity. We will assume that the scattering of electrons by phonons in a semiconductor is quasi-elastic, and the electron-electron interaction is quite effective. Then the thickness of the region near the contact, where applied Ie << Ii (Ie,Ii -the relaxation lengths of the energy and momentum of electrons) and in this region, the temperature approximation is valid. In the temperature approximation, the kinetic coefficients (conductivity, thermal conductivity and other coefficients) depend on Te and Tp . In the calculations, we will assume that Te and Tp slightly differ from the equilibrium temperature . (|Te,p - T0| << T0) Then the energy balance equations for electrons and phonons have the following form:

Where

$$\frac{dQ_e}{dx} + P\left(T_e - T_p\right) = j\Delta\varphi, \qquad (1)$$

$$\frac{dQ_p}{dx} + P\left(T_e - T_p\right) = 0. \qquad (2)$$

$$Q_e = -\varkappa_e \frac{dT_e}{dx} + \left[\Pi\left(T_e\right) + \frac{1}{e}\,\mu\left(T_e\right)\right]\cdot j, \qquad (3)$$

$$Q_p = -\varkappa_p \frac{dT_p}{dx}. \qquad (4)$$

Here, $\varkappa_e$ и $\varkappa_p$ - the electronic and phonon thermal conductivity (let's assume for simplicity иe = const, иp= const), the rate of energy transfer from electrons to phonons, chemical potential, П(Te)= a Te Pelte coefficient, thermoelectric coefficient, current density passing through the contact.

If we neglect the voltage drop across the resistance UR of the base layer, then the Joule heating of electrons in the base layer can be ignored. Suppose that in the plane of the diode z = b and y = c adiabatic boundary conditions are satisfied, i.e. n e,p 0= (ne,p - coefficients of surface heat exchanges of electrons and phonons). Then, to solve equations (1) and (2), we can write the following boundary conditions:

$$\left.\frac{dT_{e,p}}{dx}\right|_{x=a} = -\xi^{a}_{e,p} k\left(T_{e,p} - T_1\right)\Big|_{x=a} \qquad (5)$$

$$\left.\frac{dT_{e,p}}{dx}\right|_{x=\delta} = \frac{j\varphi}{\varkappa_e} - \xi^{\delta}_{e,p} k\left(T_{e,p} - T_1\right)\Big|_{x=\delta} \qquad (6)$$

$$\xi^{a}_{e,p} = \frac{\eta_{e,p}}{\varkappa_{e,p} k}, \quad k^2_{e,p} = \frac{P}{\varkappa_{e,p}}, \quad k^2 = k^2_e + k^2_p.$$

the cooling length of electrons and phonons. When solving equations (1) and (2) with boundary conditions (5) and (6), it is possible to find the temperature distributions of electrons and phonons on Schottky diodes.

3. Temperature distributions of electrons and phonons.

When solving equations (1) and (2) with boundary conditions (5) and (6), we assume that in the planes of the diode the heat transfer is adiabatic (Ee,p) and only when the current passes through the diode the carriers are heated (cooled). Then we learn the following equations for the temperature of electrons and phonons:

$$T_{e,p}(x) = T_0 - \frac{j\varphi}{\varkappa_e k}\,\Phi_{e,p}(x) \qquad (7)$$

where the value depends on the diode size and boundary conditions.

$$\Phi_{e,p}(x) = \left(S_4 + S_3 x \pm \frac{k^2_{e,p}}{k^2}\left(S_1 \mathrm{sh}kx + S_2 \mathrm{ch}kx\right)\right)\cdot S^{-1},$$

$$S_1 = -\left(1 - \frac{\xi_e}{\xi_p}\right)\frac{k^2_p}{k^2} k\,\mathrm{sh}k\delta - \xi_e k\,\mathrm{ch}ka + \left(\frac{k^2_e}{k^2} + \frac{\xi_e}{\xi_p}\frac{k^2_p}{k^2}\right)k\,\mathrm{sh}ka,$$

$$S_2 = \left(1 - \frac{\xi_e}{\xi_p}\right)\frac{k^2_p}{k^2} k\,\mathrm{ch}k\delta - \xi_e k\,\mathrm{sh}ka + \left(\frac{k^2_e}{k^2} + \frac{\xi_e}{\xi_p}\frac{k^2_p}{k^2}\right)k\,\mathrm{ch}ka,$$

$$S_3 = \left(\xi_e k\,\mathrm{sh}ka + \left(\frac{k^2_e}{k^2} + \frac{\xi_e}{\xi_p}\frac{k^2_p}{k^2}\right)k\,\mathrm{ch}ka\right)\frac{k^2_p}{k^2} k\,\mathrm{sh}k\delta - \left(\xi_e k\,\mathrm{ch}ka + \left(\frac{k^2_e}{k^2} + \frac{\xi_e}{\xi_p}\frac{k^2_p}{k^2}\right)k\,\mathrm{sh}ka\right)\frac{k^2_p}{k^2} k\,\mathrm{ch}k\delta,$$

$$S_4 = S_1\frac{k^2_p}{k^2}\left(\frac{1}{\xi_p k}k\,\mathrm{ch}ka + \mathrm{sh}ka\right) - S_3\left(\frac{1}{\xi_p k} + a\right) + S_2\frac{k^2_p}{k^2}\left(\frac{1}{\xi_p k}k\,\mathrm{sh}ka + \mathrm{ch}ka\right)$$

$$S = \left(\xi_e k\,\mathrm{ch}ka + \left(\frac{k^2_e}{k^2} + \frac{\xi_e}{\xi_p}\frac{k^2_p}{k^2}\right)k\,\mathrm{sh}ka\right)k\,\mathrm{ch}k\delta - \left(\xi_e k\,\mathrm{sh}ka + \left(\frac{k^2_e}{k^2} + \frac{\xi_e}{\xi_p}\frac{k^2_p}{k^2}\right)k\,\mathrm{ch}ka\right)k\,\mathrm{sh}k\delta .$$

In thin (ka << 1) diodes, the temperature distributions of electrons and phonons have the following form:

$$T_{e,p}(x) = T_0 - \frac{j\varphi}{\varkappa_e k}\frac{k_p^2}{k^2}ka\left(1-\frac{x}{a}+\frac{1}{a/L}\pm\frac{k_{e,p}^2}{k^2}\cdot\frac{chkx}{a/L}\right), \qquad (8)$$

$$L = \frac{1}{\xi_p k} = \frac{\varkappa_e k}{\eta_e k} = \frac{\varkappa_e}{\eta_e}$$

Here, the electron temperature is much higher than the phonon temperature, and energy is transferred to the environment due to electronic surface heat conduction.

If the condition of ideal heat transfer (Ee >>1) is a >> L satisfied in the ohmic contact x = a, then, as a result, the temperatures of electrons and phonons coincide:

$$T_e = T_p = T_0 - \frac{j\varphi}{\varkappa_e k}\frac{k_p^2}{k^2}ka\left(1-\frac{x}{a}\right) \qquad (9)$$

At the ohmic contact (x = a), Te = Tp= T0 and in the contact, electrons and phonons are weakly heated:

$$T_e = T_p = T_0 - \frac{j\varphi}{\varkappa_e k}\frac{k_p^2}{k^2}ka$$

If conditions (Ee << 1) are a<< L satisfied, then, as a result of this, the electrons and phonons are strongly heated in the plane:

$$T_e = T_0 - \frac{j\varphi}{\varkappa_e k}\frac{1}{\xi_e}ka \qquad (11)$$

$$T_p = T_0 - \frac{j\varphi}{\varkappa_e k}\frac{k_p^2}{k^2}ka. \qquad (12)$$

In massive (ka>> 1) diodes, the temperature distributions of electrons and phonons are as follows:

$$T_{e,p}(x) = T_0 - \frac{j\varphi}{\varkappa_e k}\frac{k_p^2}{k^2}ka\left(1-\frac{x}{a}+\frac{1}{a/L^*}\pm\frac{k_{e,p}^2}{k^2}\cdot\frac{1}{a/L^*}\frac{chkx}{chka}\right), \qquad (13)$$

$$L^* = \frac{\xi_p-\xi_e}{\frac{k^2}{k_p^2}k\xi_e\xi_p+\frac{k_e^2}{k_p^2}k\xi_p+k\xi_e} \qquad (14)$$

Where

the characteristic length is the velocity-dependent surface relaxation of energy, thermal conductivity of electrons and phonons in the bulk of the semiconductor, as well as the cooling length.

If the conditions are satisfied, then for the temperature of electrons and phonons are depicted as (9). At the ohmic contact Te =Tp =T0 (x = a), and in the contact, the temperatures of electrons and phonons are depicted as (10).

If the conditions L* << a are satisfied, then on the ohmic contact (x = a) but in ontact

$$T_e = T_0 - \frac{j\varphi}{\varkappa_e k}\frac{k_p^2}{k^2}ka\left(1+\frac{k^2}{k_p^2}\cdot\frac{1}{a/L^*}\right)$$

$$T_p = T_0 - \frac{j\varphi}{\varkappa_e k}\frac{k_p^2}{k^2}ka$$

x = δ

$$T_e = T_p = T_0 - \frac{j\varphi}{\varkappa_e k}\frac{k_p^2}{k^2}ka\left(1+\frac{1}{a/L^*}\right)$$

4. Conclusion.

When current passes through the diode, temperature separation occurs due to the internal field in the near-contact areas, near the barrier and the current contact. At distances of the order of the cooling length from the barrier and current contacts, the temperatures of electrons and phonons equalize. The electron and phonon temperatures depend on the thermal boundary conditions and the sample size. In thin (ka << 1) diodes at the contacts, the electron temperature is much higher than the phonon temperature, and energy is transferred to the environment due to electronic surface thermal conductivity. When the condition of ideal heat transfer is satisfied in an ohmic contact, then electrons and phonons in it strongly interact with the thermostat and, as a result, the temperatures of electrons and phonons coincide with the ambient temperature. In massive (ka >> 1) diodes in the volume, the temperatures of electrons and phonons coincide, and in an ohmic contact, the temperatures coincide with the ambient temperature.

From there it can be seen that the temperature of electrons and phonons depends on the thermal boundary conditions and the size of the sample. Thermal size effects are more pronounced in barrier structures than in homogeneous samples.

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