East European Journal of Physics. 3. 359-363 (2024)
DOI:10.26565/2312-4334-2024-3-42 ISSN 2312-4334

EFFECT OF HEATING OF CHARGE CARRIERS AND PHONONS ON THE CONTACT RESISTANCE OF RECTIFYING METAL-SEMICONDUCTOR STRUCTURES

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Received May 27, 2024; revised July 27, 2024; accepted August 7, 2024

The dependence of the temperature of charge carriers and phonons on the contact resistance of the Schottky diode is calculated. It is shown that the increase in contact resistance depends on the current passing through the diode, the surface and volume heat transfer coefficients of electrons and phonons, barrier height, the dimensions of the diode, as well as scattering mechanisms, relaxation time of energy and momentum.

Keywords: *Potential barrier; Contact resistance; Temperature distributions of electrons and phonons; Electronic and phonon thermal conductivities; Nonideality coefficient; Peltier effect; Thermal size effects (TSE)*
PACS: 73.40.Cg

INTRODUCTION

A semiconductor compound with a Schottky potential barrier is one of the key elements of semiconductor electronics. The development of modern semiconductor electronics is largely determined by fundamental research in the field of semiconductor physics. In semiconductor structures, one of the main characteristics is specific contact resistance, which significantly affects their current-voltage characteristics (I-V characteristics) [1-3].

A semiconductor composition with a Schottky potential barrier is a basic element of semiconductor electronics. The development of modern semiconductor electronics is largely determined by fundamental research in the field of semiconductor physics. Among such studies, an important place is occupied by the study of the properties of semiconductors in electric fields, when the average energy of charge carriers significantly exceeds the equilibrium energy determined by the temperature of the crystal lattice [4].

In [5-10], the influence of heating of current carriers (assuming that the temperature of the phonon gas is equal to the ambient temperature) on the current-voltage characteristics of rectifying structures was studied. In [10], contact resistance was studied and it was found that contact resistance strongly depends on the temperature of charge carriers and on the magnitude of the current flowing through the barrier.

In many works [11-15], it has been experimentally established that in the high-temperature region the resistivity of the contact increases with increasing temperature, but this has not been studied theoretically.

The main goal of this work is to study the dependence of the temperature of charge carriers and phonons on the resistance of the Schottky barrier metal-semiconductor contact.

THE INFLUENCE OF HEATING ELECTRONS AND PHONONS ON CURRENT RECTIFYING METAL-SEMICONDUCTOR STRUCTURES

Theoretically calculated the current in rectifying metal-semiconductor diodes as a result of heating of charge carriers and phonons, it is necessary to calculate the carrier and phonon temperature distribution around the diode contact. To do this, we assume that the Schottky contact is located at point $x = 0$, metal-semiconductor boundary, barrier height φ_0, the thickness of the contact charge region δ. We assume that the conditions of the diode theory are met. We assume that the conditions of the diode theory studied earlier are correct [16]. If the current passes through the barrier, the electrons or holes are considered to be heated by the barrier field and the externally applied field. 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 $T_e \neq T_p$, is approximately $l_\varepsilon \gg l_i$ (l_ε, l_i are the relaxation lengths of electron energy and momentum) and in this region the temperature approximation is valid [17]. In the temperature approximation, kinetic coefficients (conductivity, thermal conductivity, and others) depend on T_e and T_p In the calculations, we will assume that T_e and $T_e$differ slightly from the equilibrium temperature ($\left|T_{e,p} - T_0\right| \ll T_0$) [17].

In [8], the temperature distributions of electrons and phonons in thin ($k_a \ll 1$) and massive ($k_a \gg 1$) diodes are given. The temperature distributions of carriers and phonons in the diode contact region are determined from solving the system equation and taking into account the boundary conditions and give the following expressions:

Cite as: G. Gulyamov, K.B. Umarov, A.Z. Soliyev, East Eur. J. Phys. 3, 359 (2024), https://doi.org/10.26565/2312-4334-2024-3-42
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$$T_{e,p}(x) = T - \Phi_{e,p}(x) J\varphi \tag{1}$$

where $\Phi_{e,p}(x)$ are the parameters depending on the coefficients of surface and volume thermal conductivity of electrons and phonons, barrier height, the size of the diode, as well as the mechanisms of pulse scattering, relaxation time of energy and momentum.

In the volume of the sample, the temperatures of electrons and phonons coincide due to the cooling length k^{-1} and depend linearly on the *x* coordinate.

To approximate the diode theory, we present the I-V characteristics of a Schottky diode in dimensionless form [16]:

$$I = exp\left(\frac{Y}{\theta_p} - \frac{Y-U}{\theta_e}\right) - 1 \tag{2}$$

$$\theta_e = 1 - B_e I(Y - U)$$

$$\theta_p = 1 - B_p I(Y - U)$$

$I = \frac{j}{j_s}$ is a current without dimension, $Y = \frac{e\varphi_0}{kT}$ - potential barrier dimensionless height, $U = \frac{eV}{kT}$ dimensionless voltage, $\theta_e = \frac{T_e}{T}$ and $\theta_e = \frac{T_p}{T}$ the dimensionless temperatures of electrons and phonons respectively.

$$B_{e,p} = \frac{j_s \frac{k}{e}}{\chi_e k} \Phi_{e,p}(\delta) \text{ or } B_{e,p} = \Phi_{e,p} \sqrt{\frac{1}{3\pi(r+5/2)}} \sqrt{\frac{\tau_e}{\tau_p}} e^{-Y} \tag{3}$$

where τ_e is the energy relaxation time, τ_p is the pulse relaxation time, and *r* is the number that determines the mechanisms of pulse dissipation. It contains as a parameter the surface and volume thermal conductivity of electrons and phonons ($\chi_{e,p}$ and $\eta_{e,p}$).

Transforming (2) the system of equations we obtain the following quadratic equation for ψ:

$$B_p I(1 - B_e I ln(I + 1)\psi^2 + ((1 + B_e I \left(Y_0 - ln\left((I + 1)\right) + B_p I ln(I + 1)\right)\psi - (Y_0 - ln(I + 1)) = 0, \tag{4}$$

where $\psi = Y_0 - U$. (4) to the quadratic equation is given by the I-V characteristics of the Schottky diode.

If $B_p = 0$, then the diode's current-voltage characteristics has the following form:

$$U = \frac{Y_0 - (Y_0 - \ln(I+1))(1 - Y_0 I B_e)}{1 + B_e I(Y_0 - \ln(I+1))}. \tag{5}$$

When $B_p = B_e$, then the I-V characteristics of the diode:

$$U = \frac{(1 - I Y_0 B_e)\ln(I+1)}{1 + B_e I \ln(I+1)}. \tag{6}$$

From (3) it is clear that the values of the parameters B_e and B_p change the appearance of the diode's current-voltage characteristic. The parameters B_e and B_p are determined through the parameters of the diode: the coefficients of surface and volume thermal conductivity of electrons and phonons, barrier height, the size of the diode, the mechanisms of pulse scattering, energy and momentum relaxation time.

CONTACT RESISTANCE OF A SCHOTTKY DIODE DURING HEATING OF ELECTRONS AND PHONONS

Experimental studies of the electrical properties of metal-semiconductor contacts have shown that the direct branch of the current-voltage characteristic often differs somewhat from the theoretical one and is usually approximated in dimensionless form by the following expression [16]:

$$I = exp\frac{U}{m} - 1, \tag{7}$$

m is the nonideality coefficient, characterizing the difference between the properties of a real contact and an ideal.

We put expression (5) into (7) and obtain for the nonideality coefficient m at [15]:

$$m = \frac{1 + \frac{B_e I(Y - ln(I+1))}{ln\,(I+1)} Y}{1 + B_e I(Y - ln(I+1))}. \tag{8}$$

This formula is valid for currents when the Joule heating of the diode base is less than the heating of the barrier region [16].

Contact resistance is the value of the derivative of voltage with respect to current. According to [16], the contact resistance is equal to:

$$R_c = \left(\frac{dI}{dU}\right)^{-1}. \tag{9}$$

Then from expression (7) we can depict the contact resistance in the following dimensionless form:

$$R_c = \left(\frac{dI}{dU}\right)^{-1} = \frac{m}{I+1}. \tag{10}$$

where $R_c = \frac{R_c(U)}{R_c(U_0)}$ is the dimensionless contact resistance.

From expressions (8) and (10) we obtain the contact resistance of the Schottky diode

$$R_c = \frac{1+\frac{B_e I(Y-ln(I+1))}{ln(I+1)}Y}{(I+1)\left(1+B_e I(Y-ln(I+1))\right)}. \tag{11}$$

From there it can be seen that the contact resistance determines the parameters of the coefficients of surface and volume thermal conductivity of electrons and phonons, barrier height, the size of the diode, as well as the mechanisms of pulse scattering, relaxation time of energy and momentum.

For each value of B_e and Y, the dependence of contact resistance on current is shown in Fig. 1.

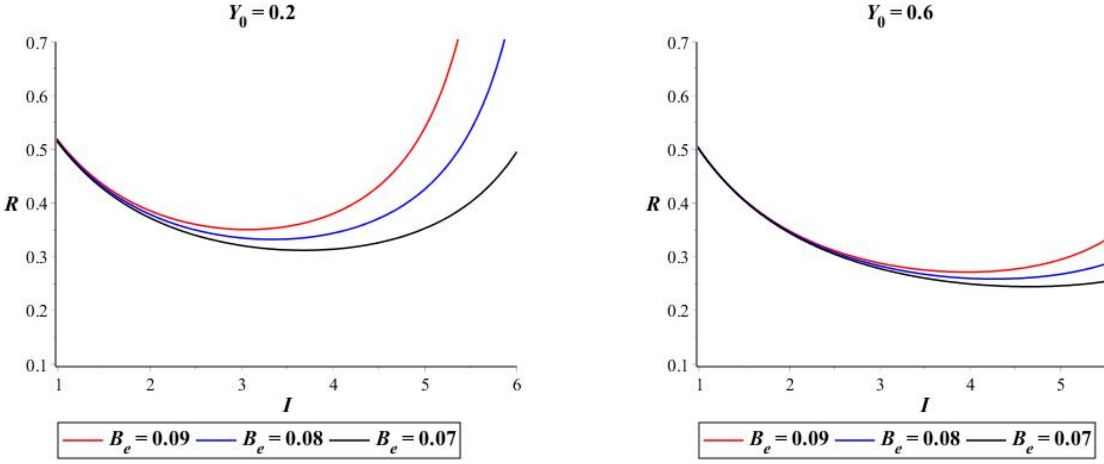

Figure 1. Dependences of $R_c(I)$ for different values of B_e and Y at $B_p=0$.

We put expression (6) into (7) and put the resulting expression for the nonideality coefficient m into (10) expressions for contact resistance at $B_e=B_p$.

$$R_c = \frac{1-B_e Y I}{(I+1)(1+IB_e ln(I+1))}. \tag{12}$$

Figure 2 shows the dependences of $R_c(I)$ for different values of B_e and Y.

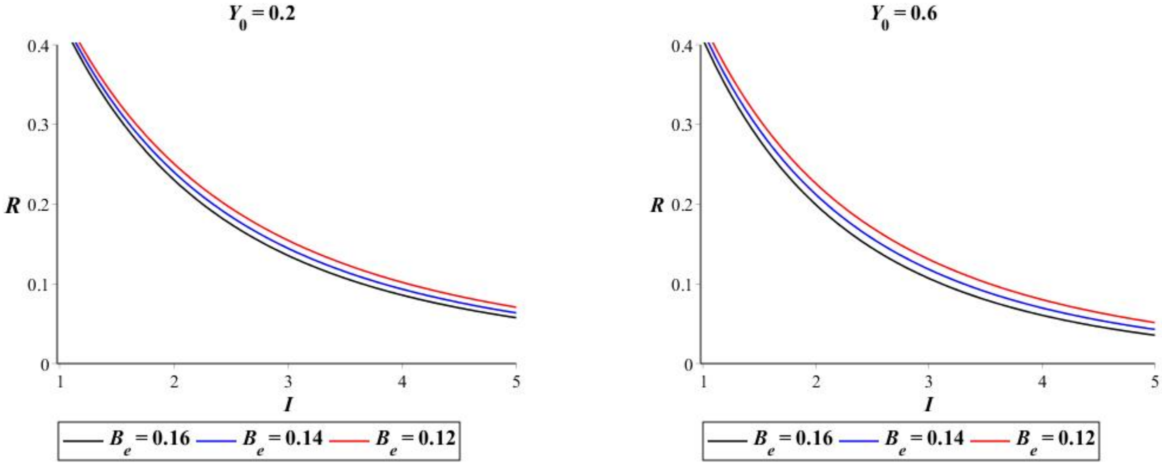

Figure 2. Dependences of $R_c(I)$ for different values of B_e and Y at $B_p = B_e$.

The dependence $\rho_c(T)$ at sufficiently high temperatures can be increasing. In the region of sufficiently low temperatures, the dependences $\rho_c(T)$ are either decreasing or independent of temperature [8].

In [17-20, 22], the temperature dependences of specific contact resistance were studied and a linearly increasing dependence was obtained.

In Figure 3 shows the experimental dependence $\rho c(T)$, taken from [17], as well as the theoretical dependence. This dependence was explained in [21] within the framework of the mechanism of electron scattering by optical phonons, which leads, in particular, to different values of the coefficient of temperature dependence of resistance than in metals [8].

The results we obtained show that the contact resistance is determined by the parameters of the diode, as well as the electron scattering mechanism. As can be seen from Figures 2 and 3, it agrees quite well.

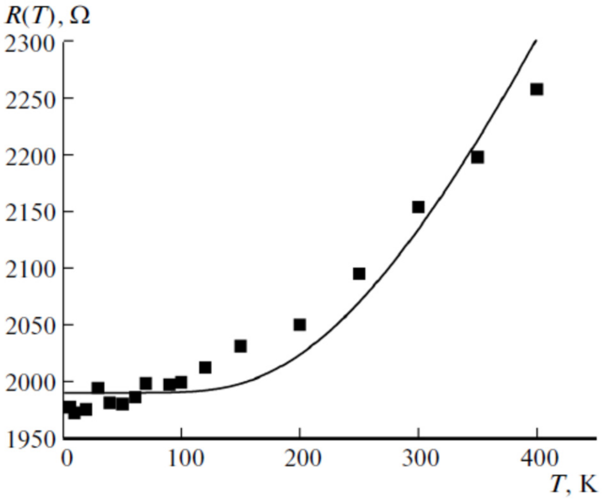

Figure 3. Temperature dependence of resistance *R(T)*: experimental data [21]

CONCLUSIONS

In barrier structures, the contact resistance depends on the parameters: surface and volume thermal conductivity coefficients of electrons and phonons, barrier height, the size of the diode, as well as the mechanisms of pulse scattering, relaxation time of energy and momentum. It is clear from this that stronger thermal dimensional effects are observed in barrier structures than in homogeneous semiconductors. Thermal size effects are due to the Peltier effect. In the volume, electronic and phonon thermal conductivities are infinitely greater, then heating can be neglected.

It is shown that the increase in contact resistance depends on the current passing through the diode, the surface and volume heat transfer coefficients of electrons and phonons, barrier height, the dimensions of the diode, as well as scattering mechanisms, relaxation time of energy and momentum.

Acknowledgments

The work was performed on the basis of the Fundamental Research Grant Programs FZ-20200929243 “The Effect of Hot Electrons and Phonon’s in a Strong Electromagnetic Field on the Characteristics of Semiconductor Solar Photovoltaic Elements and Nanostructures”.

Author Contributions. All the authors contributed equally to the manuscript.

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ВПЛИВ НАГРІВУ НОСІЇВ ЗАРЯДУ ТА ФОНОНІВ НА КОНТАКТНИЙ ОПІР ВИПРЯМЛЯЮЧИХ МЕТАЛ-НАПІВПРОВІДНИКОВИХ СТРУКТУР

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Розраховано залежність температури носіїв заряду та фононів від контактного опору діода Шотткі. Показано, що збільшення контактного опору залежить від струму, що проходить через діод, поверхневого та об’ємного коефіцієнтів тепловіддачі електронів і фононів, висоти бар’єру, розмірів діода, а також механізмів розсіювання, часу релаксації енергії та імпульс.

Ключові слова: *потенційний бар'єр; контактний опір; температурний розподіл електронів і фононів; електронна та фононна теплопровідність; коефіцієнт неідеальності; ефект Пельтьє; тепловий ефект розміру (TSE)*