INFLUENCE OF THE HEATING OF CHARGE CARRIERS AND PHONONS ON THE CVC AND THE COEFFICIENT OF NON-IDEALITY OF A RECTIFIED CONTACT

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Abstract. In this work, the *I–V* characteristics and the coefficient of non-ideality of the rectifying contact are calculated taking into account the heating of charge carriers and phonons. It was shown that the heating of carriers by the internal field of the rectifying contact linearly depends on the current and leads to the deviation of the *I–V* characteristic from non-ideality, as a result of which the non-ideality coefficient will be different from unity even when $I \to 0$. The nonideality *I–V* characteristic of the Schottky diode depends on the parameters of the semiconductor and the potential barrier.

Key words: Thermal size effects, coefficient of nonideality, potential barrier, heating of carriers and phonons.

1. INTRODUCTION

Semiconductor structures with potential Schottky barriers are the main elements of semiconductor electronics. The microminiaturization of electronics has led to more and more active elements per unit area and unit volume of a semiconductor. Under these conditions, the dimensions of the elements become similar to the characteristic sample lengths such as diffusion length, free path length, cooling length, etc. The flow of a strong electric current through a semiconductor disturbs the energy balance between current carriers and phonons, causing a number of nonlinear effects [1]. In semiconductor structures, an external electric field acts along with built-in fields, which leads to a stronger heating of carriers than in a homogeneous sample. Starting from [2], the effect of carrier heating on the *I–V* characteristics of a rectifying contact has been studied. It is shown that taking into account heating (cooling) shifts the current-voltage characteristic (*I–V* characteristics) towards higher voltages. The effect of heating of current carriers on the operation of a metal-semiconductor contact has been studied by many authors [3–5]. In these works, it was assumed that the phonon gas is in equilibrium and its temperature is equal to the ambient temperature.

I–V characteristics rectifier contacts are often different from the theoretical. The reason for this may be the mechanisms of current transfer through the junction.

In particular, recombination currents in the barrier region [6], leakage currents [7], and carrier heating [8] will lead to a deviation of the *I–V* characteristics from nonideality. The experimental *I–V* characteristics is usually approximated by the following expression [9]:

$$J = J_s\left(\exp\frac{eU}{mkT}-1\right), \tag{1}$$

here m – is the coefficient of imperfection.

It was shown in [10, 11] that the heating of carriers during the passage of a direct current through the barrier contributes to the nonideality parameter of the diode. The purpose of this work is to calculate the *I–V* characteristics and the coefficient of nonideality of the rectifying contact, taking into account the heating of charge carriers and phonons.

2. RESULTS AND DISCUSSION

2.1. *I–V* CHARACTERISTICS AT A METAL-SEMICONDUCTOR CONTACT DURING HEATING OF ELECTRONS AND PHONONS

To calculate the current through a metal-semiconductor contact, it is necessary to know the temperature of carriers and phonons in the near-contact region of the diode. Let us consider the Schottky contact at the point $x = 0$ located at the metal-semiconductor interface, the barrier height φ_0, and the thickness of the space charge region δ. For simplicity, we assume that the conditions of the diode theory are valid. When current passes through the barrier, the carriers are heated by the barrier field and by the field applied from outside. In the approximation of the two-temperature model, the energy received by the electrons from the field is transferred to the phonons and through the phonon and electronic subsystem due to thermal conductivity is transferred to the contacts [1].

The electron and phonon temperatures are determined from the solution of the system of equations and with boundary conditions [12]:

$$T_{e,p}(x) = T - \Phi_{e,p}(x)J\varphi\ , \tag{2}$$

where $\Phi_{e,p}(x)$ is a parameter depending on the dimensions of the diode and the boundary conditions. In the bulk of the sample, when moving away from the boundary of the space charge region and the ohmic contact, the temperatures of electrons and phonons coincide with each other with exponential accuracy due to the cooling length k^{-1}. In this section, we can assume that electrons and phonons have the same temperatures and linearly depend on the coordinate x.

In the diode theory approximation, the *I–V* characteristics has the following form [13]:

$$j = j_s\left[\left(\frac{T_e}{T_p}\right)^{1/2}\exp\left(\frac{e\varphi_0}{kT_p}-\frac{e(\varphi_0-U)}{kT_e}\right)-1\right]. \qquad (3)$$

Here U is the voltage drop across the barrier, T_p – the phonon temperatures, T_e – the electron temperatures. Expressions (2) and (3) determine the *I–V* characteristics of the diode in the parametric form of both electron heating and phonon heating. It contains as a parameter the surface and bulk thermal conductivity of electrons and phonons ($\chi_{e,p}$ and $\eta_{e,p}$). The expression for $\Phi_e(\delta)$ includes the sample size (k_a). Therefore, changing the size of the sample can change the *I–V* characteristics of the Schottky diode and its other characteristics. Hence it follows that thermal size effects are observed in the Schottky diode. In fact, these thermal size effects (TSE) are due to the heating of barrier carriers due to the Pelte effect. If we assume that the electronic and phonon thermal conductivities are infinitely large ($\chi_{e,p}\to\infty$ and $\eta_{e,p}\to\infty$), then heating can be neglected and we obtain the usual *I–V* characteristics of the Schottky diode. In the case of a strong electron-phonon interaction, electrons and phonons have the same temperatures ($T_e = T_p$) and then the *I–V* characteristics will deviate from the ideal one. For convenience, the *I–V* characteristics of the Schottky diode is presented in a dimensionless form:

$$I = \exp\left(Y - \frac{Y-V}{\theta_e}\right) - 1 \qquad (4)$$

$$\theta_e = 1 - B_e I\left(Y - V\right) \qquad (5)$$

where $I = \dfrac{j}{j_s}$ is the dimensionless current, $Y = \dfrac{e\varphi_0}{kT}$ is the dimensionless height of the potential barrier, $V = \dfrac{eU}{kT}$ is the dimensionless voltage, $\theta_e = \dfrac{T_e}{T}$ is the dimensionless electron temperature.

$$B_e = \frac{j_s\frac{k}{e}}{\chi_e k_a}\Phi_e\left(\delta\right) \text{ or } B_e = \Phi_e\sqrt{\frac{1}{3\pi\left(r+5/2\right)}}\sqrt{\frac{\tau_\varepsilon}{\tau_p}e^{-Y}}\,, \qquad (6)$$

where τ_e is the energy relaxation time, τ_p is the momentum relaxation time, r are the numbers determining the mechanisms of the momentum scattering.

Figure 1 shows the *I–V* characteristics of a Schottky diode for different values B_e.

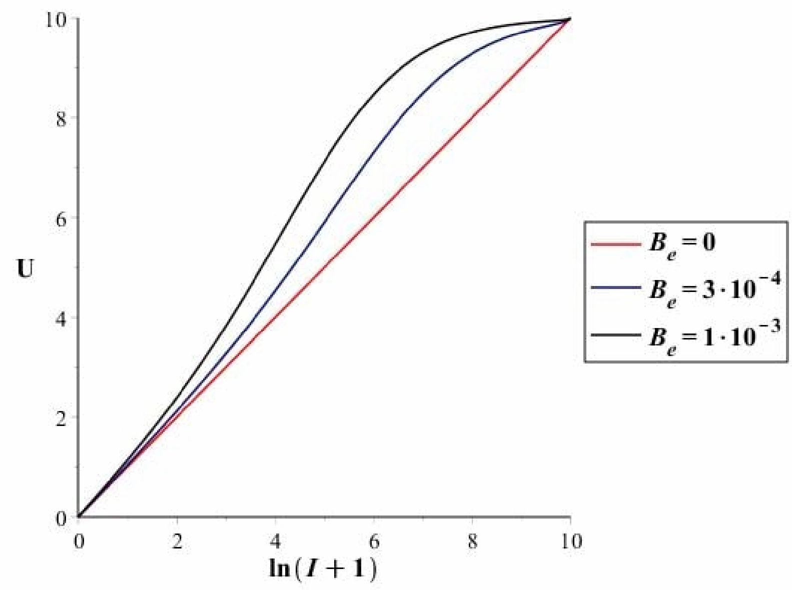

Fig. 1 – *I–V* characteristic of a Schottky diode for different values B_e.

2.2. NON-IDEAL CVC OF THE SCHOTTKY DIODE DUE TO THE HEATING OF ELECTRONS AND PHONONS

Usually, the *I–V* characteristic of a real diode approximates in expression (1). For convenience, we write expression (1) in a dimensionless form:

$$I = \exp \frac{V}{m} - 1 . \tag{7}$$

Assuming that the coefficient of imperfection m is due to heating and equating expression (4) to (7), we obtain:

$$\frac{V}{m} = Y - \frac{Y - V}{\theta_e} .$$

Taking into account expression (5), we obtain the following expression for the coefficient of imperfection m

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

This formula is valid for currents when the Joule heating of the base is less than the heating of the barrier region. The dependence of *m* on the dimensions of the diode and the parameters of the semiconductor is determined by formula (6). For each value B_e and potential barrier *Y* it is possible to determine the dependence of the nonideality factor on the current. At low currents ($I\to 0$) is determined by the diode parameter B_e and *Y*:

$$m=1+B_eY^2. \tag{9}$$

Hence it follows that when the heating of carriers and phonons is taken into account, the coefficient of nonideality is always different from unity. Figures 2 and 3 show the dependences on the height of the equilibrium potential barrier for small currents ($I\to 0$) and various values of B_e.

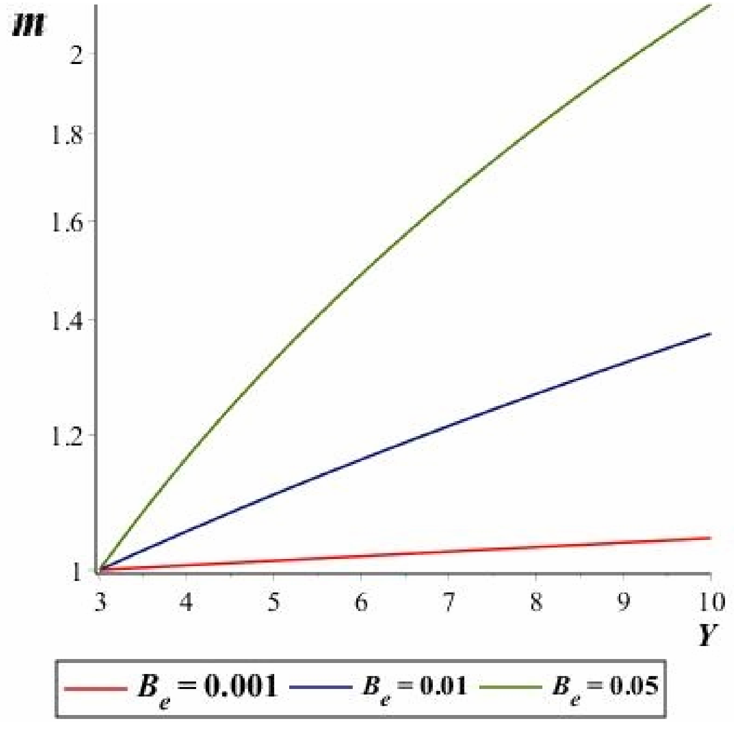

Fig. 2 – Dependence of the coefficient of imperfection on the potential barrier for different temperatures.

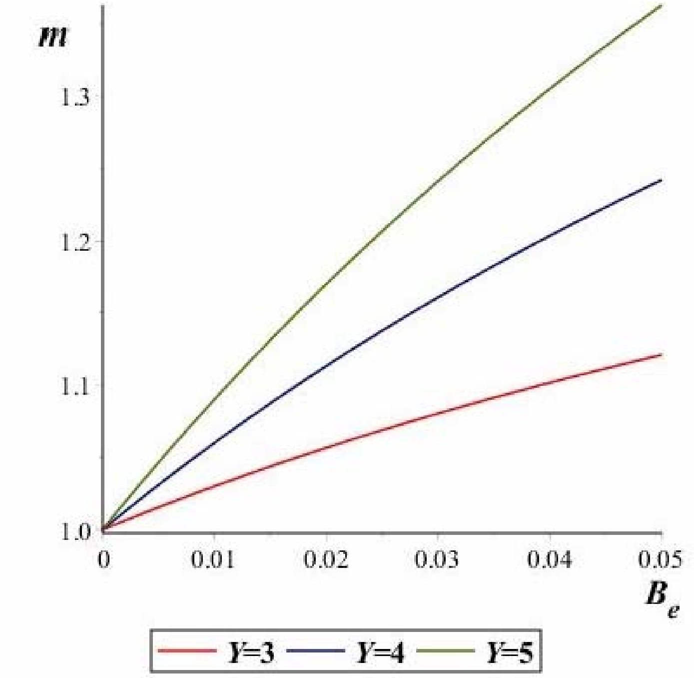

Fig. 3 – Temperature dependence of the coefficient of imperfection for various potential barriers.

This shows that, depending on the specific parameters, *m* can take on different values. If $B_eY^2 << 1$, $m = 1$ then the *I–V* characteristic is ideal. If $B_eY^2 \approx 1$, then $m = 2$. It follows from here that if heating is taken into account, the barrier's own field can give a contribution of the same order as recombination, and the fact that *m* obtained from the experiment lies within $1 \le m \le 2$ the limits does not mean that the recombination current is significant. The change in the coefficient *m* due to changes in temperature due to the contact field is not small, and in some cases can be decisive. At low currents, *m* does not tend to unity, but differs from unity to expression (9). The reason for this is that the heat released at the barrier depends linearly on the current and at low currents the carrier energy also changes, while the Joule heat depends quadratically on the current and tends to zero faster at low currents. In this case, the barrier field plays the main role in heating.

3. CONCLUSIONS

The heating of carriers by the internal field of the rectifying contact linearly depends on the current and leads to a deviation of the *I–V* characteristic from imperfection, as a result of which the imperfection coefficient will be different from unity even when $I \to 0$. Hence it follows that the effect of heating of electrons and phonons on the *I–V* characteristic of a rectifying contact is always significant and neglecting it is not always justified.

Thus, in barrier structures, TSE are more pronounced than in homogeneous samples. The nonideality *I–V* characteristic of the Schottky diode depends on the parameters of the semiconductor and the potential barrier. The heating of carriers and phonons leads to a coefficient of nonideality different from unity.

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REFERENCES

1. F.G. Bass, V.S. Bochkov, Y.G. Gurevich, *Electrons and phonons in limited semiconductors*, Nauka, Moscow, 1984.
2. K. Bouzidi, M. Chegaar and M. Aillerie, Energy Procedia **18**, 1601–1610 (2012). https://doi.org/10.1016/j.egypro.2012.06.001
3. A. Chvála, J. Marek, J. Drobný, Ľ. Stuchlíková, A. Alberto Messina, V. Vinciguerra, D. Donoval, Mater. Today: Proc. **53**, 285–288 (2021). https://doi.org/10.1016/j.matpr.2021.06.150
4. G. Gulyamov, K.B. Umarov, Semicond. **28**, 409–411 (1994).
5. G. Gulyamov, K.B. Umarov, Semicond. **29**, 17–19 (1995).
6. C. T. Sah, R. N. Noyce, and W. Shokley, Proc. IRE **45**, 1228 (1957). http://dx.doi.org/10.1109/JRPROC.1957.278528
7. Ya.A. Fedetov, *Osnovy fiziki poluprovodnikovyh priborov*, Sovetskoe radio, Moscow, 1969.
8. N.A. Ablyazimova, A.I. Veynger, V.S. Pitanov, Physics and Technics of Semiconductors **26**, 1041–1047 (1992).
9. V. Jha, H. Surdi, M. Faizan Ahmad, F. Koeck, R. J. Nemanich, S. Goodnick, T. J. Thornton, Solid State Electron. Lett. **186**, 108154 (2021). https://doi.org/10.1016/j.sse.2021.108154
10. J. Park, B-G. Park, H. Baek, G-M. Sun, Nucl. Eng. Technol. 1738–5733 (2022). https://doi.org/10.1016/j.net.2022.08.022
11. K. Zeghdar, H. Bencherif, L. Dehimi, F. Pezzimenti, F. G. DellaCorte, Solid State Electron. Lett. **2**, 49–54 (2020). https://doi.org/10.1016/j.ssel.2020.08.001
12. G. Gulyamov, K.B. Umarov, IJOT **2**, 34–37 (2020). https://doi.org/10.31149/ijot.v2i12.1060
13. U. I. Erkaboev, G. Gulyamov, R. G. Rakhimov, Indian J. Phys. **96**, 2359–2368 (2021). https://doi.org/10.1007/s12648-021-02180-4