

The Nonideality Coefficient of Current-Voltage Characteristics for Asymmetric p-n-Junctions in a Microwave Field

Gafur Gulyamov^{1,2}, Muhammadjon Gulomkodirovich Dadamirzaev^{1,2},
Hasan Yusupovich Mavlyanov^{1,2}

¹Namangan Engineering Pedagogical Institute, Namangan, Uzbekistan

²Namangan State University, Namangan, Uzbekistan

Email: dadamirzaev70@uamail.uz

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Abstract

It is shown that the nonideality coefficient m actually depends on the electron temperature T_e , and the hole temperature T_h . We get more general expression for the nonideality coefficient, taking into account the concentration of electrons and holes, as well as their temperature, coefficient and diffusion length, the temperature of the phonons, the applied voltage, and the height of the potential barrier.

Keywords

Hot Electrons, The Microwave Field, The Open Circuit Voltage, Short Circuit Current, Current-Voltage Characteristics of p-n-Junction, The Nonideality Coefficient

1. Introduction

The development occupies an important place in microelectronics, semiconductor devices; therefore it requires a deep study of the physical fundamentals of semiconductor devices based on p-n-junction and the impact of external and internal factors on the characteristics of these devices. The main characteristic of a semiconductor diode based on p-n junction is a voltage-current characteristic. The theory of an ideal p-n junction was developed by Shockley [1]. CVC real p-n-junction is different from the ideal. For CVC real p-n-junction from Shockley was introduced the nonideality coefficient [2]. External influences—pressure, light, temperature and other fac-

tors affect the nonideality coefficient of Current-Voltage Characteristics for p-n-junction.

In the works of S. P. Ashmontas [3] [4], the effect of the heating of electrons was examined in the p-n-junction under the influence of the microwave field by the nonideality coefficient.

The nonideality coefficient of CVC silicon p-n-junction in a microwave field was studied in the works of A. I. Veynger and others [5] [6], where the abnormally high currents and electromotive force (EMF) had been observed.

However, the above-mentioned work is not considered dependence of the nonideality coefficient of the simultaneous heating of electrons and holes.

The aim of this work is to study the effect of heating of electrons and holes by a nonideality coefficient of CVC p-n-junction.

2. Theoretical Studies of Nonideality Coefficient of CVC Asymmetric p-n-Junction in a Microwave Field

The resulting expression of your total current passing through the diode consists of electron and hole currents and is defined as follows [7] [8]:

$$\bar{I} = \frac{eD_e n_p}{L_e} \left\{ \left(\frac{T_e}{T} \right)^{\frac{1}{2}} \exp \left(\frac{e\varphi_0}{kT} - \frac{e(\varphi_0 - U)}{kT_e} \right) \int_0^{2\pi} \exp \left(- \frac{eU_B \cos(\omega t)}{kT_e} \right) \frac{d(\omega t)}{2\pi} - 1 \right\} + \frac{eD_h p_n}{L_h} \left\{ \left(\frac{T_h}{T} \right)^{\frac{1}{2}} \exp \left(\frac{e\varphi_0}{kT} - \frac{e(\varphi_0 - U)}{kT_h} \right) \int_0^{2\pi} \exp \left(- \frac{eU_B \cos(\omega t)}{kT_h} \right) \frac{d(\omega t)}{2\pi} - 1 \right\} \quad (1)$$

where, $I_{se} = \frac{eD_e n_p}{L_e}$; $I_{sh} = \frac{eD_h p_n}{L_h}$ are the saturation currents for electrons and holes; φ_0 : height of the potential

barrier in the absence of an electromagnetic wave; $\varphi = \varphi_0 - U$; U : a voltage across the diode; $U_B = -\int_0^d E_B dx$:

AC voltage of the incident wave created by the barrier diode; T is the temperature of the lattice; k : Boltzmann constant; T_e and T_h : the temperatures of electrons and holes; E_b —electric field of the wave; e is the charge of an electron; D_e and D_h —diffusion coefficients of electrons and holes, L_e and L_h —their diffusion length; n_p and p_n —the concentration of minority carriers.

Using the mean value theorem [9]:

$$\int_a^b f(x) dx = f(\xi) \int_a^b dx = f(\xi)(a-b),$$

we received for the considered case

$$f(U_B) = \left| \frac{1}{2\pi} \int_0^{2\pi} \exp \left(- \frac{eU_B \cos(\omega t)}{kT_e} \right) d(\omega t) \right| \approx \left| \exp \left(- \frac{eU_B |\cos(\omega t)|}{kT_e} \right) \right| \gg 1$$

of formula (1) we have to CVC p-n-junction following expression:

$$\bar{I} = \frac{eD_e n_p}{L_e} \left\{ \left(\frac{T_e}{T} \right)^{\frac{1}{2}} \exp \left(\frac{e\varphi_0}{kT} - \frac{e(\varphi_0 - U) + eU_B |\cos(\omega t)|}{kT_e} \right) - 1 \right\} + \frac{eD_h p_n}{L_h} \left\{ \left(\frac{T_h}{T} \right)^{\frac{1}{2}} \exp \left(\frac{e\varphi_0}{kT} - \frac{e(\varphi_0 - U) + eU_B |\cos(\omega t)|}{kT_h} \right) - 1 \right\}. \quad (2)$$

At low wave power ($T_e = T_h = T$; $U_B \neq 0$), when there is only outrage the potential barrier height, using the formula (2) obtain the CVC p-n-junction:

$$\bar{I} = (I_{se} + I_{sh}) \left[\exp \left(\frac{e(U - U_B |\overline{\cos(\omega t)})}{mkT} \right) - 1 \right], \quad (3)$$

to take a logarithm of the expression (3), while taking into account the perturbation of the potential barrier height for the nonideality coefficient of current-voltage characteristics for p-n-junctions find the following formula:

$$m = \frac{e \left[U - U_B |\overline{\cos(\omega t)} \right]}{kT \ln \left(\frac{I}{I_{se} + I_{sh}} + 1 \right)}. \quad (4)$$

High power microwave energy heated electrons and holes have different temperatures. In the works of A. I. Vengera and other experiments were conducted in a highly asymmetrical p-n-junction, where $p_p \gg n_n$ and $T_e > T_h > T$. However, under these conditions, the main share of the total current flowing through the p-n-junction, make hot holes [7]. Then the CVC p-n-junction consists of a second portion of the formula (2) and the first member can be neglected:

$$\bar{I} = \frac{eD_h p_n}{L_h} \left\{ \left(\frac{T_h}{T} \right)^{\frac{1}{2}} \exp \left(\frac{e\varphi_0}{mkT} - \frac{e(\varphi_0 - U) + eU_B |\overline{\cos(\omega t)}}{mkT_h} \right) - 1 \right\}. \quad (5)$$

Hence, for the nonideality coefficient we obtain the following expression:

$$m(T_h, T, U_B) = \frac{e \left\{ \varphi_0 T_h - T \left[\varphi_0 - U + U_B |\overline{\cos(\omega t)} \right] \right\}}{\ln \left(\left(\frac{I_h}{I_{sh}} + 1 \right) \left(\frac{T}{T_h} \right)^{\frac{1}{2}} \right) kTT_h}. \quad (6)$$

It is seen that the nonideality coefficient is mainly dependent on the temperature of the holes.

If $p_p \ll n_n$, then a major share to the total current flowing through the p-n junction, to introduce hot electrons. Then, similarly to the formula (6) we get:

$$m(T_e, T, U_B) = \frac{e \left\{ \varphi_0 T_e - T \left[\varphi_0 - U + U_B |\overline{\cos(\omega t)} \right] \right\}}{\ln \left(\left(\frac{I}{I_{se}} + 1 \right) \left(\frac{T}{T_e} \right)^{\frac{1}{2}} \right) kTT_e}. \quad (7)$$

This expression depends mainly on electron temperature.

According to the analysis of the results shows that in the special case when $T_e = T_h = T$; $U_B = 0$ from (1) to obtain an expression for the nonideality coefficient of current-voltage characteristics of p-n-junction where the charge carriers are not warmed up.

We get more general expression for the nonideality coefficient, which takes into account the asymmetry of concentration, temperature, diffusion coefficients, diffusion length for electrons and holes, the temperature of the phonons, and the applied voltage, the height of the potential barrier. Analyses show that the nonideality coefficient strongly influenced by the concentration of charge carriers and the temperature perturbation potential barrier height, which are consistent with experimental results. In addition to the analytical expressions ((4), (6), (7)) on the basis of formula (1) can be transcendental equation coefficient imperfection independent simultaneous heating of electrons and holes. In addition to the analytical expressions ((4), (6), (7)) on the basis of formula (1) we received a transcendental equation for the nonideality coefficient, which depends on the simultaneous heating of electrons and holes.

$$\bar{j} = \frac{eD_e n_p}{L_e} \left\{ \left(\frac{T_e}{T} \right)^{\frac{1}{2}} \exp \left(\frac{e\varphi_0}{mkT} - \frac{e(\varphi_0 - U)}{mkT_e} \right) \int_0^{2\pi} \exp \left(- \frac{eU_B \cos(\omega t)}{mkT_e} \right) \frac{d(\omega t)}{2\pi} - 1 \right\} + \frac{eD_h p_n}{L_h} \left\{ \left(\frac{T_h}{T} \right)^{\frac{1}{2}} \exp \left(\frac{e\varphi_0}{mkT} - \frac{e(\varphi_0 - U)}{mkT_h} \right) \int_0^{2\pi} \exp \left(- \frac{eU_B \cos(\omega t)}{mkT_h} \right) \frac{d(\omega t)}{2\pi} - 1 \right\}. \tag{8}$$

Using this formula, for different values of m we can construct CVC p-n-junction (Figures 1-3).

The graphs show that the nonideality coefficient is more sensitive to the microwave field and the current-voltage characteristics of p-n-junction is shifted to higher direct voltage with an increase in the nonideality coefficient.

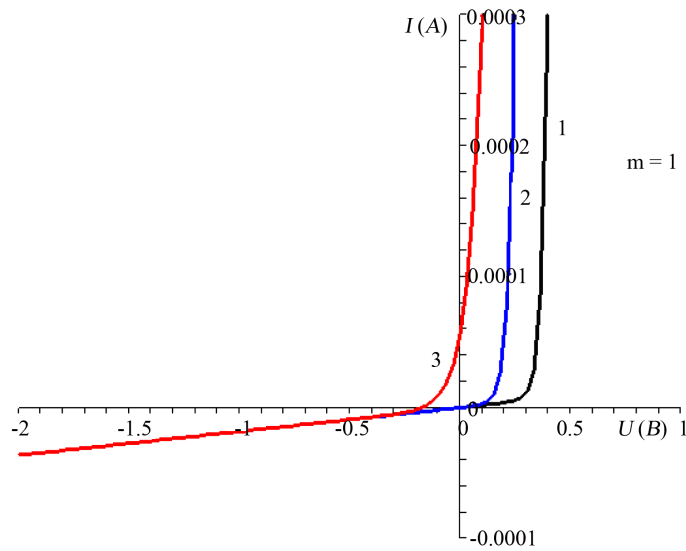


Figure 1. CVC p-n-junction, provided: 1—without the microwave field, 2—at low microwave powers wave and 3—at high power microwave energy and $m = 1$.

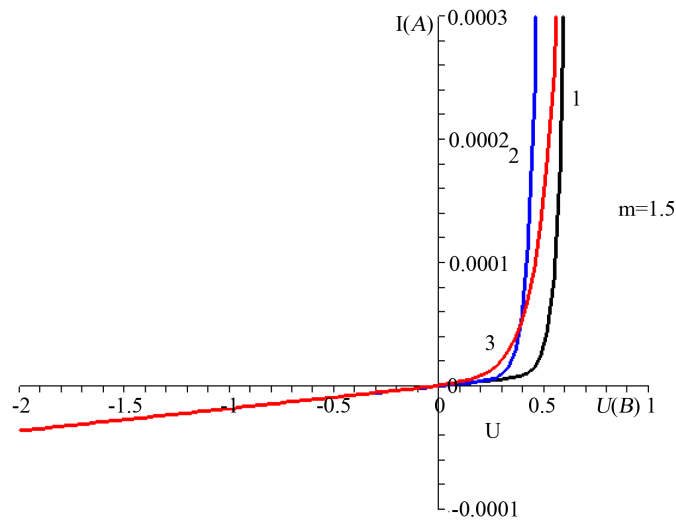


Figure 2. CVC p-n-junction, provided: 1—without the microwave field, 2—at low microwave power wave, and 3—at high power micro-wave energy and $m = 1.5$.

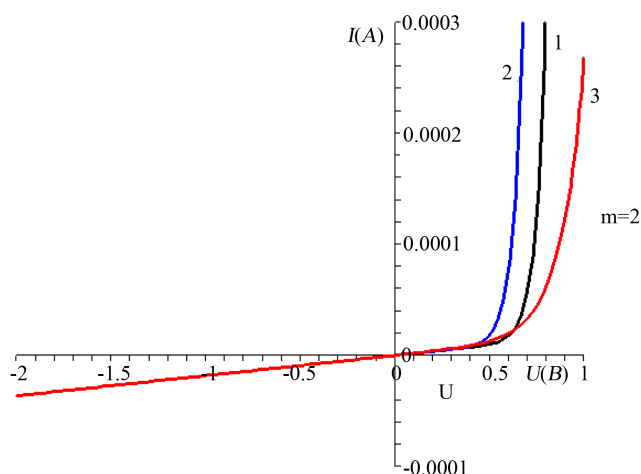


Figure 3. CVC p-n-junction, provided: 1—without the microwave field, 2—at low microwave powers wave, and 3—at high power microwave energy and $m = 2$.

3. Conclusions

The results show that the nonideality coefficient m really depends on the electron temperature and the temperature of the holes.

With $p_p \gg n_n$ the nonideality coefficient is determined by the temperature of the hole, and when $p_p \ll n_n$ electron temperature. We obtain a formula the nonideality coefficient for different conditions. It is shown that the nonideality coefficient m is more sensitive to the power of the microwave field. We get more general expression for the nonideality coefficient, taking into account the concentration of electrons and holes, as well as their temperature coefficient and diffusion length, the temperature of the phonons, the applied voltage, and the height of the potential barrier.

We get more general expression for the nonideality coefficient, taking into account the concentration of electrons and holes, as well as their temperature, diffusion coefficient and diffusion length, temperature phonons, applied voltage and indignation potential barrier height.

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