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Heating of the Electrons and the Rectified Current at the Contacts That Are in an Alternating Electromagnetic Field

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Abstract

The paper deals with the heating of electrons and current rectification in contact, which is located in an alternating electromagnetic field. It was found that the electrical component of the microwave (UHF) waves inside the p-n-junction was curved. This leads to the perpendicular component of the electric field of the microwave wave. This component modulates the height of the potential barrier with the frequency of the microwave. In the p-n-junction, straightening microwave current occurs. It is shown that the rectifying contact in the microwave electromagnetic field is always an electromotive force. This is due to carrier heating and straightening microwave current. It is shown that electron heating and straightening of the microwave power will lead to higher ideality factor of the diode.

Keywords

Hot Electrons, The Microwave Field, The Open Circuit Voltage, Short Circuit Current, CVC, p-n-Junction

1. Introduction

Experimental studies of the heating of the charge carriers by the strong electric field in inhomogeneous semiconductors began with thermopower measurements of hot charge carriers occurring at the p-n-junction. In [1], it used an ultrahigh frequency (UHF)-electric field to warm up the charge carriers in the measurement of the thermopower of hot electrons at UT p-n-junction. In this case, the electric field vector is oriented along a concentration gradient, so that the ends of the sample are oriented along the longitudinal thermopower of hot charge carri-

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ers, a signal rectification of alternating current. In order to avoid straightening AC p-n-junction, in the measurement of the thermopower of hot carriers, the vector of the microwave electric field is directed perpendicular to the concentration gradient [2].

[3] studied the current and the emf arising in asymmetrical p-n-junctions under the influence of a strong microwave field. It revealed that, in asymmetric p-n-junction, a strong microwave field for the analysis of voltages and currents must be considered as the heating of electrons and holes.

In [4], the results of theoretical and experimental studies of the emergence of negative differential resistance in the diode structures are based on the p-n-junction in a strong microwave field.

Under the influence of the electromagnetic wave, it increases the average energy of the carriers in the contact area with the metal-semiconductor interface. As a result, the potential barrier of electrons is heated by flowing current [2]. On the other hand, due to changes in the barrier height at the contact, alternating current generated by the electric field of the wave is rectified. Due to the fact that the directions of the currents of hot carriers and rectified currents are identical, establishing the true mechanism of the generated EMF diode is an important issue.

The aim of this work is to study electron heating and current rectification to contact in an alternating electromagnetic field.

2. Influence of Electron Heating and Current Rectification on Track in a Strong Microwave Field

We estimate the current arising under the influence of electromagnetic waves on a thin Schottky diode. If the wave period longer than the transit time of electrons through the barrier, on the basis of the theory of electron diode current passing through the barrier is given by:

$$j = j_s\left[\exp\left(\frac{e\varphi_0}{kT} - \frac{e\varphi + eU_B\cos(\omega t)}{kT_e(t)}\right) - 1\right] \tag{1}$$

where j_s is the saturation current; φ_0 is the height of the potential barrier in the absence of an electromagnetic wave; $\varphi = \varphi_0 - U$; U is the resulting voltage across the diode; $U_B = -\int_0^d E_B \mathrm{d}x$ is the AC voltage of the incident wave, created by the barrier diode; T is the temperature of the lattice; *k* is the Boltzmann constant; $T_e(t)$ is the temperature of the electron gas in contact with the region; E_B is the electric field of the wave; *e* is the charge of the electron.

The average value of the diode current is determined by the following integral:

$$\frac{\bar{j}}{j_s} = \int_0^{2\pi}\left\{\left(\frac{T_e}{T}\right)^{\frac{1}{2}}\exp\frac{e}{k}\left[\frac{\varphi_0}{T} - \frac{\varphi_0 + U(t) + U_B\cos(\omega t)}{T_e(\omega t)}\right] - 1\right\}\frac{\mathrm{d}(\omega t)}{2\pi}. \tag{2}$$

The values of the electron temperature are determined by the wave field strength.

At low wave power can not take into account the heating of the electrons, while the constant current arises only because of rectification:

$$\frac{\bar{j}}{j_s} + 1 = \exp\left(-\frac{eU_0}{kT}\right)\int_0^{2\pi}\exp\left(-\frac{eU_B\cos(\omega t)}{kT}\right)\frac{\mathrm{d}(\omega t)}{2\pi}. \tag{3}$$

Here U_0 is the DC offset applied to the barrier.

Detected voltage in the diode is given by:

$$U = \frac{kT}{e}\left\{\ln\left(1 + \frac{\bar{j}}{j_s}\right) - \ln\left[\int_0^{2\pi}\exp\left(-\frac{eU_B}{kT}\cos(\omega t)\right)\frac{\mathrm{d}(\omega t)}{2\pi}\right]\right\}. \tag{4}$$

It follows that the open circuit voltage at $j = 0$:

$$U_{oc} = \frac{kT}{e} \ln\left[\int_0^{2\pi} \exp\left(\frac{eU_B}{kT}\cos(\omega t)\right)\frac{d(\omega t)}{2\pi}\right]. \quad (5)$$

Short-circuit current is the following:

$$\frac{j}{j_s} + 1 = \frac{1}{2\pi}\int_0^{2\pi} \exp\left(-\frac{eU_B}{kT}\cos(\omega t)\right) d(\omega t). \quad (6)$$

Equation (5) defines the CVC diode situated in the field of the electromagnetic wave when the current occurs only through rectification of alternating current.

At high power microwave energy when $T_e \neq T$, CVC diode has the following form:

$$\frac{\bar{j}}{j_s} + 1 = \left(\frac{T_e}{T}\right)^{\frac{1}{2}} \exp\left[\frac{e}{k}\left(\frac{\varphi_0}{T} - \frac{\varphi_0}{T_e} - \frac{U}{T_e}\right)\right]\int_0^{2\pi} \exp\left(-\frac{eU_B\cos(\omega t)}{kT_e}\right)\frac{d(\omega t)}{2\pi}. \quad (7)$$

Using Formula (7) we will investigate the effect of electron heating in the CVC p-n-junction in a strong microwave field. CVC p-n-junction temperature change of the electrons is shown in **Figure 1**.

This shows that the inclusion of straightening and heating of electrons increases in the strong currents of the diode microwave field. The degree of increase of the current is determined by the following factor:

$$\int_0^{2\pi} \exp\left(-\frac{eU_B\cos(\omega t)}{kT_e}\right)\frac{d(\omega t)}{2\pi} \quad (8)$$

when $\left|\frac{eU_B}{kT_e}\right| \gg 1$ this value increases rapidly and strongly affects the CVC diode.

Now consider the short-circuit current of the Formula (7) (for $U = 0$) we have the following expression for the short-circuit current:

$$\frac{\bar{j}_{sc}}{j_s} + 1 = \left(\frac{T_e}{T}\right)^{\frac{1}{2}} \exp\left[\frac{e}{k}\left(\frac{\varphi_0}{T} - \frac{\varphi_0}{T_e}\right)\right]\int_0^{2\pi} \exp\left(-\frac{eU_B\cos(\omega t)}{kT_e}\right)\frac{d(\omega t)}{2\pi}. \quad (9)$$

This shows that the inclusion of rectification increases the short circuit current by a factor of (8).

C using the Formula (9) is plotted as the short circuit current of the electron temperature (**Figure 2**).

Figure 2 that the short circuit current is strongly dependent on the temperature of the electrons. With the increase of the electron temperature increases rapidly short-circuit current.

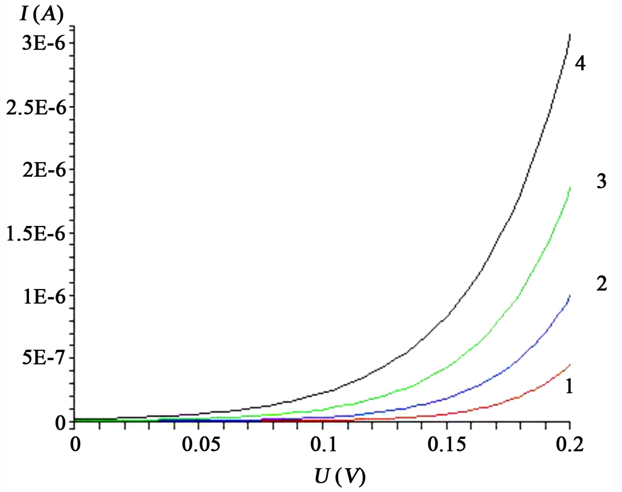

Figure 1. CVC p-n-junction at different electron temperature. 1—T_e = 300 K, 2—T_e = 350 K, 3—T_e = 400 K, 4—T_e = 450 K.

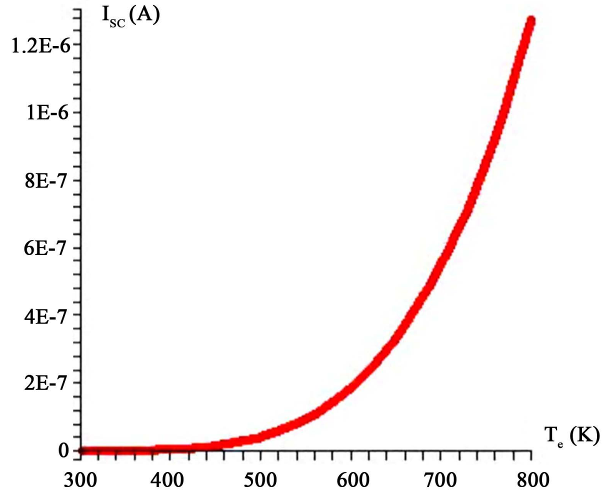

Figure 2. Dependence of short circuit current on the electron temperature according to the Formula (9).

For the open-circuit voltage of hot electrons from the Formula (7) (for $j = 0$) we have the following expression:

$$U_{oc} = -\varphi_0\left(\frac{T_e}{T} - 1\right) - \frac{kT_e}{\mathrm{e}}\ln\left[\left(\frac{T_e}{T}\right)^{\frac{1}{2}}\right]\int_0^{2\pi}\exp\left(-\frac{\mathrm{e}U_B\cos(\omega t)}{kT_e}\right)\frac{\mathrm{d}(\omega t)}{2\pi}. \quad (10)$$

The first term of this formula gives emf, heated by the electron in the potential barrier [2], and the second part—the voltage generated due to rectification. However, it should be noted that the second portion (10) differs from the rectifying electromotive force (5), when the electrons are not warmed up. If you do not take into account current rectification caused by electromagnetic wave, the first term of the Formula (10) corresponds to the EMF of the heated electrons produced in the potential barrier φ_0 [2].

Formula (10) allows to analyze graphically the dependence of $f(U_{oc}, T_e)$. **Figure 3** shows the dependence of the open circuit voltage of the electron temperature $f(U_{oc}, T_e)$. This shows that in the p-n-junction due to the heating of electrons increases the open circuit voltage.

Analyze the second part of the Formula (10) is associated with straightening:

$$U_{\mathrm{rect}} = \frac{kT_e}{\mathrm{e}}\ln\left[\theta^{\frac{1}{2}}\int_0^{2\pi}\exp\left(-\frac{Y_B}{\theta}\cos(2\pi z)\right)\mathrm{d}z\right] \quad (11)$$

where $\theta = \frac{T_e}{T}$ is the dimensionless electron temperature; $Y_B = \frac{\mathrm{e}U_B}{kT_e}$ is the dimensionless potential wave; $z = \omega t$.

This formula shows that the dependence of $Y_B U_{\mathrm{rect}}$ differs from linearity. The linear dependence of the detected voltage of the electric field of the wave, is often regarded as the result of rectification of the AC signal. From the analysis of (11) we can conclude that this conclusion is not always justified. This is due to the fact that the deviation from the linear dependence of the rectified voltage on the intensity of the microwave field is due to the heating of the electrons.

In [5] in order to eliminate the current rectification in the microwave electromagnetic field of the p-n-junction plane is set parallel to the electric field component of the wave. There is assumed that the detection signal occurs only due to heating of charge carriers. The temperature value of the electron gas, calculated from the experimental data on the basis of this assumption turned several times greater than the expected [5]. To explain these anomalously high values of the thermoelectric power of hot carriers in [5] was introduced ideality factor, and it was believed that he was connected with the process of recombination in the p-n-junction.

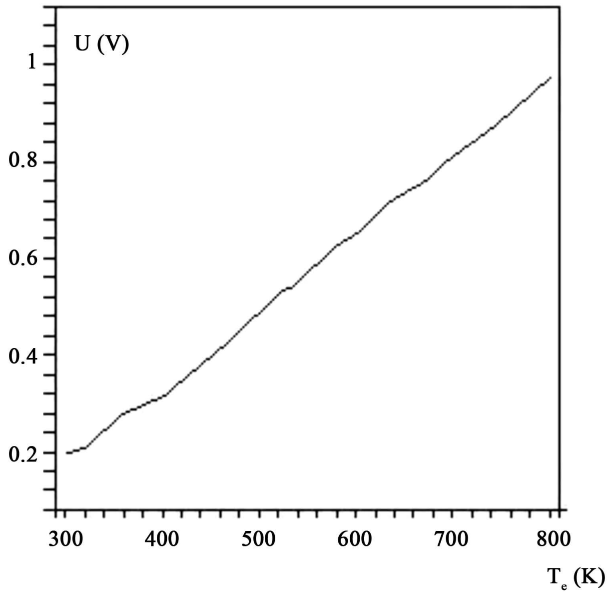

Figure 3. The dependence of the open circuit voltage of the electron temperature.

The emergence of large values of EMF [5], in our opinion may be due to the following reasons yet.

When the location of the p-n-junction in a microwave electromagnetic field is a redistribution of the field E_B waves in the space inside the sample. The result is distorted parallel to the plane of the E_B p-n-junction. This leads to the inevitable emergence of the electric field component perpendicular to the plane of the p-n-transition, which is not uniformly distributed in the p-n-junction. By turning the p-n-junction relative to E_B can be reduced to a minimum average value of the perpendicular component $E_\perp$, but it is impossible to completely eliminate. The parallel component of the electric field to the p-n-junction is not rectify the high frequency electric current, and is involved only in the heating media. A perpendicular component is at the p-n-junction rectification microwave current [6] [7]. Thus, in the rectifying contact in the electromagnetic field occurs as a heating carriers and straightening of the microwave power. Consequently, there is excessive DC component and generate additional EMF.

Therefore, a strong microwave field in the calculation of EMF occurring at the p-n-junction in addition to the heating of electrons must be considered and straightening of the microwave power.

The expression for the effective electron temperature, calculated from Formulas (7)-(10) has the form:

$$T_e^* = T_e\left[1+\frac{kT}{e\varphi_0}\ln\int_0^{2\pi}\exp\left(-\frac{eU_\perp\cos(\omega t)}{kT_e}\right)\frac{d(\omega t)}{2\pi}\right]. \quad (12)$$

Here $U_\perp = -\int_0^d E_\perp dx$, $E_\perp$—perpendicular component of the wave field to the surface of the p-n-junction.

You can enter the ideality factor m in the following form:

$$T_e^* = mT_e \quad (13)$$

$$m = \left[1+\frac{kT}{e\varphi_0}\ln\int_0^{2\pi}\exp\left(-\frac{eU_{B\perp}\cos(\omega t)}{kT_e}\right)\frac{d(\omega t)}{2\pi}\right]. \quad (14)$$

The second term in the square brackets is due to the more effective temperature of the electrons due to rectification. When $U_\perp = 0$ we have $T_e^* = T_e$, effective temperature coincides with the actual temperature of the electrons. In this case there is no extension. When $U_\perp \neq 0$ always have $T_e^* > T_e$, straightening as it effectively increases the temperature T_e^*. With the increasing power of the electromagnetic wave incident on the diode and the difference between T_e^* and T_e increases (see Equation (12)) T_e^* strong increase was also observed in the experiment [5]. The authors of these studies neglect the distortion of the microwave field, the increase associated with the increase T_e^* nonideality factor *m* with increasing electric field strength. However, there is no quantitative analysis. If we consider the rectification, we can quantitatively explain the relationship between m and the field strength. Effect of carrier heating charges on nonideality factor CVC p-n-junction is discussed in [8] [9].

3. Conclusion

The rectifying junction in the microwave electromagnetic field is always an electromotive force, which is due to electron heating and straightening microwave current. This is due to the distortion of the electric component of the microwave inside the p-n-junction. Distortion direction of the electric component of the microwave will cause the perpendicular component of the electric field that causes rectification of the microwave current through the p-n-junction. Heating of the electrons and the microwave current rectification increases the ideality factor of the diode.

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