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Current-Temperature Formulation for n-GaN Schottky Diodes

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Abstract: The relationship between current and temperature is formulated analytically for n-GaN Schottky diodes based on the thermionic emission theory and the consideration of the experimental facts on the high thermal stability of the device. The energy-temperature transformation of the electrons in the conduction band of the device by application of the statistical mechanics principles (density of state and Fermi-Dirac distribution) resulted into an integral equation of current as a function of temperature for the device. The integral equation is solved analytically using power series expansion. The solution obtained is current-temperature formulation for GaN-Schottky diodes. This formulation will be a very useful tool in analysis and optimization of the GaN-Schottky diodes for applications at high temperatures. The second series of this study, which will come out very soon will establish the agreement between this formulation and the experimental results available on n-GaN Schottky diodes, using computer simulation technique.

Key words: Current-temperature formulation, fermi-dirac function, maxwell-boltzmann principle, n-GaN schottky diode

INTRODUCTION

In recent time, n-GaN Schottky diodes (i.e., metal-GaN junction diodes) have been discovered to possess high thermal stability, which offer many advantages required for solar cell devices and advanced microwave communication systems (Shurmer, 1971; Schmitz *et al*., 1996; Morkoc *et al*., 1999). In order to develop high performance, GaN-Schottky diode suitable for application at high temperatures, accurate modeling is required for adequate analysis and optimization of the device in terms of its design parameters. It is evident that VLSI-component industry requires more financial investment than ever in order to measure the characteristics and performance of the manufactured electronic devices and for the equipment necessary to their development. So modeling of electronic components constitutes a research field that is currently very important throughout the world. To continue, this evolution, the existing models must be improved and new models have to be developed (Djeffal *et al*., 2005).

Current and temperature have been recognized as important parameters for development of Schottky diodes. For instance, current affects the junction resistance where, the frequency conversion takes place when Schottky diode is applied as a microwave mixer diode (Shurmer, 1971; Linden, 1976; Sze, 1981; Schmitz *et al*., 1996). However, the studies that describe analytically the relationship between current and temperature of GaN-Schottky diode are very scarce. Also, the experimental investigation of the effect of high temperature on current of GaN-Schottky diode is very expensive, so very scarce. This study tries to address the formulation of current-temperature model of GaN-schottky diodes based on the available theory and experimental facts about the device.

In this study, current-temperature model for GaN-Schottky diode is formulated using energy-temperature transformation of the electrons in the conduction band of GaN-Schottky diode, by the application of the statistical mechanics principles that is the density of state and Fermi-Dirac statistics. The formulation will be a very useful tool in analysis and optimization of the GaN-Schottky diodes for applications at high temperatures.

SCHOTTKY DIODE MODEL DESCRIPTION

Brief review of electrons density due to thermionic emission: Electrons in the conduction band of a crystal can be viewed as sitting in a potential box formed by the crystal boundaries (Fig. 1). This potential box for electrons is usually deeper in a metal than in a semiconductor. Some electrons from the metal will move into the semiconductor and some electrons from the semiconductor (n-type) will move into the metal. However,

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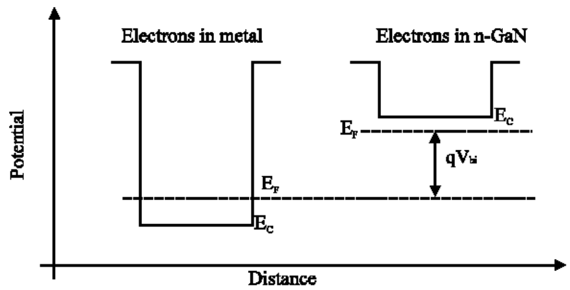

Fig. 1: Schematic energy diagram for electrons in the conduction bands of a metal and a semiconductor

since the barrier for the electrons escape from the metal is higher, more electrons will transfer from the semiconductor into the metal than in opposite direction. At thermal equilibrium (i.e., with no external voltage applied), the metal will be charged negatively and semiconductor will be charged positively forming a dipole layer and hence, no more current flow, until bias is applied (Shurmer, 1971; Sze, 1981).

In this study, temperature is considered as the dominant process for current flowing in n-GaN Schottky diode. So, the current due to thermionic emission is presented. The thermionic emission theory postulates that only energetic carriers, those, which have energy equal to or larger than the conduction band energy at the metal-semiconductor interface, contribute to the current flow.

The assumptions of the thermionic emission theory for Schottky diodes are Sze (1981): the barrier height $q\phi_{bn}$ is much larger than kT, thermal equilibrium is established at the plane that determines emission and the existence of a net current flow does not affect this equilibrium, so that one can superimpose two current fluxes-one from metal to semiconductor, the other from semiconductor to metal.

Because of these assumptions, the shape of the barrier profile is immaterial and the current flow depends solely on the barrier height ϕ_{bn}:

$$q\phi_{bn} = q(\varphi_m - \chi) \quad (1)$$

Where:

q = The electronic charge
k = The Boltzmann constant
T = The temperature
φ_m = The metal work function
χ = The electron affinity of the semiconductor

The current I flowing in an n-type semiconductor can be expressed as Shurmer (1971):

$$I = q\mu_n n\xi \quad (2)$$

Where:

μ_n = The electron mobility ($cm^2 Vs^{-1}$)
ξ = The electric field intensity ($V cm^{-1}$)

The electrons Velocity (V) can be expressed by Shurmer (1971):

$$v = \mu_n\xi \quad (3)$$

Then,

$$I = qvn \quad (4)$$

The current from the semiconductor to the metal ($I_{s\text{-}m}$) is then given by the concentration of electrons (dn) with energies sufficient to overcome the potential barrier and traversing in the x direction:

$$I_{s\rightarrow m} = \int_{E_F+q\phi_b}^{\infty} qvdn \quad (5)$$

Where:

$E_F+q\phi_{bn}$ = The minimum energy required for thermionic emission into the metal
v = The electron velocity in the direction of transport

The number of occupied conduction-band is given by Sze (1981):

$$n = \int_{E_c}^{E_{top}} N(E)F(E)dE \quad (6)$$

Where:

E_c = The energy at the bottom of the conduction band
E = The energy at the top
N (E) = The density of state, i.e., the number of electrons occupying the energy levels of the semiconductor at low enough energy and temperature

The approximate expression for N (E) near bottom of the conduction band is Valerie (1998):

$$N(E) = \frac{4\pi(2m^*)^{1/2}}{h^3}\sqrt{E - E_c} \quad (7)$$

Where:

m* = Effective mass of electron in semiconductor
h = Plank constant

F (E) is the Fermi-Dirac distribution function from Fermi-Dirac statistics. Fermi-Dirac statistics is a system of quantum statistics that is used to describe the behaviour of solids in terms of free electron model. In this model, the most weakly bound electrons of the constituent atoms are considered to behave as a gas subject to certain conditions: the electrons are free to move in any direction through the solid, they do not interact with each other are subject to the Pauli's exclusion principle (that no two electrons in an atom can exist in the same quantum energy state). The probability of an energy level of energy E being occupied by an electron is given by the Fermi-Dirac distribution function F (E) and approximately expressed as Valerie (1998):

$$F(E) = \exp\left[-\frac{(E - E_C + qV_n)}{kT}\right] \quad (8)$$

$$qv_n = E_c - E_F \quad (9)$$

Where, E_F is the Fermi energy (level) defined as the maximum electronic energy level that is occupied by an electron in a solid at lowest possible temperature.

From Eq. 6, the electron density dN (i.e., electrons that is responsible for the current flows) in an incremental energy (dE) is:

$$dN = N(E)F(E)dE \quad (10)$$

Substituting Eq. 7 and 8 into Eq. 10 yields:

$$dn = \frac{4\pi(2m^*)^{1/2}}{h^3}\sqrt{E - E_c}\exp\left[-\frac{(E - E_c + qV_n)}{kT}\right]dE \quad (11)$$

CURRENT-TEMPERATURE FORMULATION FOR N-GAN SCHOTTKY DIODES

Analysis by statistical mechanics provided the Maxwell-Boltzmann principle (Illingworth, 1998). When dealing with a large number of particles in thermal equilibrium to which Newtonian mechanics can be applied, the energy associated with each degree of freedom has the same average value this average value depends only on the temperature. So in general, at temperature T (Whelan and Hodgson, 1974):

$$\begin{aligned}\text{Energy of a molecule} &= \left(\frac{m^* v^2}{2} = \frac{3}{2}kT\right) \\ &= (N\,\text{degree of freedom}) \times \frac{1}{2}kT\end{aligned} \quad (12)$$

Where, m* is the effective mass of the electrons in n-GaN. The Eq. 12 implies that energy of a molecule (½NkT) is associated with translational motion, which has N degrees of freedom.

Since, bulk n-GaN materials (including thin films) are 3D systems (Morkoc *et al.*, 1999), it is expedient to express the kinetic energy of the conduction electrons in the n-GaN Schottky Diode as:

$$E - E_C = \frac{1}{2}m^* v^2 = \frac{3}{2}kT \quad (13)$$

It is the only electrons that posses temperature change (dT) that will be responsible for current flow in the device. Therefore, transforming from dE to dT yields:

$$dE = \frac{3}{2}kdT \quad (14)$$

Also, expressing electrons velocity in terms of temperature yields:

$$\bar{v} = \sqrt{\frac{3kT}{m^*}} \quad (15)$$

Substituting Eq. 13 and 14 into Eq. 11 yields:

$$dn = \frac{4\pi(3m^*k)^{3/2}}{h^3}T^{1/2}\exp\left(-\frac{3}{2}\right)\exp\left(-\frac{qV_n}{kT}\right)dT \quad (16)$$

Substituting Eq. 15 and 16 into Eq. 5 (and change energy interval to temperature interval) yields the current from the n-GaN to the metal:

$$I_{s-m} = \int_{T_o}^{\infty} q \times \frac{36\pi m^* k^2}{h^3}\exp\left(-\frac{3}{2}\right) \times T\ \exp\left(-\frac{qV_n}{kT}\right)dT \quad (17)$$

Where:

T_o = the minimum temperature required for thermionic emission into the metal

$$I_{s-m} = q \times \frac{36\pi m^* k^2}{h^3}\exp\left(-\frac{3}{2}\right)\int_{T_o}^{\infty} T\exp\left(-\frac{qV_n}{kT}\right)dT \quad (18)$$

$$\text{Let, } W = q \times \frac{36\pi m^* k^2}{h^3}\exp\left(-\frac{3}{2}\right) \text{ and } a = \frac{qV_n}{k} \quad (19)$$

$$\therefore I_{s-m} = W\int_{T_o}^{\infty} T\exp\left(-\frac{a}{T}\right)dT \quad (20)$$

The next step is to solve the set up integral Eq. 20. Consider the mathematical manipulation:

$$\int_{T_o}^{\infty}[\,] = \int_{T_o}^{T_f}[\,] + \int_{T_f}^{\infty}[\,], \text{ at the limit as } T_f \to \infty,\ \int_{T_f}^{\infty}[\,] \to 0 \quad (21)$$

$$\therefore I_{s-m} = W\int_{T_o}^{T_f} T\exp\left(-\frac{a}{T}\right)dT \quad (22)$$

Where:
T_f = Finite temperature

The integral Eq. 22 is solved using power series expansion:

$$\text{Let, } y = \int_{T_o}^{T_f} T\exp\left(-\frac{a}{T}\right)dT \tag{23}$$

$$\exp\left(-\frac{a}{T}\right) = 1 - \frac{a}{T} + \frac{a^2}{2T^2} - \frac{a^3}{6T^3} + \frac{a^4}{24T^4} \tag{24}$$

Equation 24 is approximated to fifth term because as T→8, the contribution of higher terms becomes insignificant:

$$\Rightarrow y = \int_{T_o}^{T_f} T\left(1 - \frac{a}{T} + \frac{a^2}{2T^2} - \frac{a^3}{6T^3} + \frac{a^4}{24T^4}\right)dT$$

$$= \int_{T_o}^{T_f}\left(T - a + \frac{a^2}{2T} - \frac{a^3}{6T^2} + \frac{a^4}{24T^3}\right)dT$$

$$y = \left|\frac{T^2}{2} - aT + \frac{a^2}{2}\ln T + \frac{a^3}{6T} - \frac{a^4}{48T^2}\right|_{T_o}^{T_f} \tag{25}$$

$$\therefore y = \frac{1}{2}\left(T_f^2 - T_o^2\right) - a\left(T_f - T_o\right) + \frac{a^2}{2}\left(\ln T_f - \ln T_o\right) + \frac{a^3}{6}\left(\frac{1}{T_f} - \frac{1}{T_o}\right) - \frac{a^4}{48}\left(\frac{1}{T_f^2} - \frac{1}{T_o^2}\right)$$

$$\Rightarrow I_{s-m} = W\begin{bmatrix} \frac{1}{2}\left(T_f^2 - T_o^2\right) - a\left(T_f - T_o\right) + \frac{a^2}{2} \\ \left(\ln T_f - \ln T_o\right) \\ + \frac{a^3}{6}\left(\frac{1}{T_f} - \frac{1}{T_o}\right) - \frac{a^4}{48}\left(\frac{1}{T_f^2} - \frac{1}{T_o^2}\right) \end{bmatrix} \tag{26}$$

Where,

$$a = \frac{qV_n}{k} = \frac{q}{k}\left(\phi_{bn} - V\right) \tag{27}$$

Since, the barrier height for electrons moving from the metal into the semiconductor remains the same, the current flowing into the semiconductor is thus, unaffected by the applied Voltage (V). It must therefore, be equal to the current flowing from the semiconductor into the metal when thermal equilibrium prevails (i.e., when V = 0) (Sze, 1981; Schmitz *et al*., 1996).
Then, setting V = 0:

$$\Rightarrow a = \frac{q\phi_{bn}}{k}, \text{ called } a_o = \frac{q\phi_{bn}}{k} \tag{28}$$

Substituting a = a_o into Eq. 26 yields:

$$\Rightarrow I_{m-s} = W\begin{bmatrix} \frac{1}{2}\left(T_f^2 - T_o^2\right) - a_o\left(T_f - T_o\right) + \frac{a_o^2}{2} \\ \left(\ln T_f - \ln T_o\right) \\ + \frac{a_o^3}{6}\left(\frac{1}{T_f} - \frac{1}{T_o}\right) - \frac{a_o^4}{48}\left(\frac{1}{T_f^2} - \frac{1}{T_o^2}\right) \end{bmatrix} \tag{29}$$

The total current flowing in the device is:

$$I_t = I_{s-m} - I_{m-s} \tag{30}$$

$$I_t = W\begin{bmatrix} a_v\left(T_f - T_o\right) + \frac{1}{2}\left(a^2 - a_o^2\right)\left(\ln\frac{T_f}{T_o}\right) \\ + \frac{1}{6}\left(a^3 - a_o^3\right) \\ \left(\frac{1}{T_f} - \frac{1}{T_o}\right) - \frac{1}{48}\left(a^4 - a_o^4\right)\left(\frac{1}{T_f^2} - \frac{1}{T_o^2}\right) \end{bmatrix} \tag{31}$$

Where,

$$a_v = \frac{qV}{k} \tag{32}$$

Assumption: $T_o < T_f$

RESULTS AND DISCUSSION

GaN Schottky diodes have been discovered to possess better performance namely high thermal stability. This makes it suitable candidate for solar cells and modern complex electronic integrated circuitry particular microwaves systems where temperature plays significant roles in the system performance. However, investigation of the effect of temperature on the important design parameter of the devices namely current has been very difficult experimentally due to the high financial investment involved. Therefore, analytical model of current-temperature characteristics of GaN schottky diodes is necessary. This will make the analysis and optimization of the device very easy and less expensive to be produced by the industry.

Based on the experience from the available experimental facts on GaN Schottky diode's thermal stability application of thermionic emission theory, current-temperature relationship is formulated for the device. The energy possessed by the electrons in GaN Schottky diode is transformed to the temperature parameter by the application of statistical mechanics principles the density of state and Fermi-Dirac distribution. This transformation yielded an integral equation of current as a function of temperature by some mathematical manipulation (Eq. 17). The integral equation obtained is solved analytically using power series expansion (Eq. 18-31). The solution obtained is the current-temperature formulation representing the current-temperature behaviors of the GaN schottky diodes. In the next edition of this study, the validity of the formulation for GaN schottky diodes will be established using computer simulation technique.

CONCLUSION

Accurate models of important design parameters are required for adequate development of GaN schottky diodes. The analytical expressions that describe the behavior of current as a function of temperature for GaN Schottky diode are scare in the literature. Also, the experimental investigations of the effect of temperature on current of n-GaN schottky diode are scare in the research. Therefore, this study formulated analytically the current-temperature model for GaN schottky diode. The model will be a useful tool for the analysis and optimization of the device.

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