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High Temperature Electronic Properties of a Microwave Frequency Sensor – GaN Schottky Diode

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Abstract

The potential energy barrier height, depletion layer thickness and junction capacitance properties of a microstructure GaN Schottky diode as a microwave frequency sensor have been estimated at extreme temperature (300 – 950K), under applied external bias (0 – 20V) by computational method based on the analytical expression obtained by the application of rule of thumb on the existing energy gap of n-GaN and existing solutions (depletion thickness and capacitance) of Poisson's equation. The results of the calculation shown that the barrier height decreases as the temperature increases, but abrupt increase in the barrier height was observed as the temperature continues to increase above 900K. This behaviour may be linked to thermal stability demonstrated by n-GaN Schottky diode at high temperature. Also, the depletion thickness decreases as the temperature increases and the capacitance decreases as the bias increases. The decrease of the capacitance is much at high temperature under the same applied bias condition. The GaN Schottky diode can be employed as microwaves frequency sensor at very high temperature.

Keywords: Barrier height, Depletion layer thickness, Junction capacitance, n-GaN Schottky diode, microwave sensor, high temperature.

1. Introduction

In recent time, n-GaN Schottky diode has attracted attention of scientists and engineers due to its reported comparable advantages such as high breakdown voltage and high operating temperature relative to their convectional counterparts: metal -Ge, -Si and -GaAs shottky diodes (Linden, 1976; Morkoc *et al.,*1999; Cao *et al.,*1999; Dang *et al.,*2000; Alade *et al.,* 2009a; Alade *et al.,* 2009b). Investigation of the electronic characteristics namely barrier height, depletion layer thickness and junction capacitance of the n-GaN Schottky diode has become necessary because of the importance of the device in microwave application as sensor device. Specifically, Schottky diodes possess excellence performance when used as the gate electrodes for high-power IMPATT oscillators, and photo detectors employed in microwave communication systems (Shurmer, 1971; Linden, 1976; Sze, 1981; Materka and Kacprzak, 1985; Bamigboye and Chike-Obi 1987).

Similar research studies have been done previously by several authors on the characterization of barrier heights, depletion layers and junction capacitance and other important parameters of metal -Ge, -Si and -GaAs schottky diodes as microwave radio frequency detectors (Shurmer, 1971; Linden, 1976; Sze, 1981; Materka and Kacprzak, 1985). Despite reported several advantages possessed by the n-GaN Schottky diode, to the best of my knowledge published work on the electronic characterisation of the device as a microwave sensor at high temperature is very scarce. Therefore, the electronic properties of the device need to be further investigated.

Therefore, in this paper, the numerical investigation of the electronic properties n-GaN Schottky microwave sensor in terms of the potential energy barrier height, depletion layer thickness and junction capacitance as function of high temperature and applied bias is carried out. The computations are based on the derived and existing analytical models. For now, it is not possible to employ the experimental measurement techniques namely, current-voltage, capacitance-voltage, activation energy and photoelectric methods to measure the characteristics because of limited access to the equipment and extremely high cost of setting up the experimental measurements.

2. Methodology

2.1 Theoretical Background

The electrostatic analysis of a metal-semiconductor junction provides knowledge about the charge and field potential in the depletion region. It is also required to obtain the capacitance voltage characteristics of the diode. Since there is no new electrostatic analysis for the n-GaN Schottky diode, the existing electrostatic analysis of the metal-semiconductor junction is reviewed (as shown in Figure 1) and adopted for n-GaN Schottky diode in this study.

Figure 1 shows the idealized energy band diagram of the metal-semiconductor Schottky barrier. In the absence of the contact field the energy levels in the metal and in the semiconductor are represented by horizontal lines. This expresses the fact that the energy of an electron occupying this level, for instance, the lower level of the conduction band, is the same everywhere in the semiconductor and does not depend on the position of the electrons. In the presence of a contact potential difference, inside the layer in which the contact field is concentrated, a force acts on the electron pushing through it out of the layer as shown in the figure 1. To overcome this force work should be performed and this work is equal to the potential energy of the electron in the contact field (Gavryushin and Ukauskas, 2002; Sapoval and Hermann, 2004). The potential energy barrier between the extrinsic n-type semiconductor and the metal can be expressed as (Sze, 1981; Gavryushin and Ukauskas, 2002; Sapoval and Hermann, 2004):

$$q\phi_{bn} = q(\phi_m - \phi_s) \qquad (1)$$

Where, q is the electronic charge, ϕ_m and ϕ_s are work functions of metal and semiconductor respectively. The potential energy barrier height, ϕ_{bn} is the potential difference between the Fermi energy, E_F of the metal and the band edge where the majority carriers reside. Applying the rule of thumb by Gavryushin and Ukauskas (2002) on the energy gap of n-GaN Schottky, the potential energy barrier height of the device is determined as:

$$\phi_{b(n-GaN\,\text{Shottky})} = \frac{1}{3}\left(3.503 + \frac{5.08\times10^{-4}T^2}{T-996}\right), \qquad \text{eV} \qquad (2)$$

Where, T is the temperature.

As the electron moves inside the space charge layer, its potential energy $\phi(x)$ increases reaching its maximum at the surface of the semiconductor and it can be estimated as:

$$\phi(0) = qV_{bi} \qquad (3)$$

Where, V_{bi} is called the built-in potential which is the difference between the Fermi energy of the metal and that of the semiconductor. It can be estimated approximately as:

$$V_{bi} = \phi_m - \phi_s \qquad (4)$$

Quantum mechanical calculations lead to the conclusion that the application of an external bias (V) to the device results in an inclination of its energy bands relative to the horizontal Fermi level. The contact field acts in the same way causing deflection of the energy bands. Several authors have calculated the potential energy $\phi(x)$ of the electrons going from n-type semiconductor to metal by solving the ρ(x) set up Poisson equation which relates the field port V(x) to the space charge density $\rho(x)$ under the appropriate boundary conditions (Sze, 1981; Gavryushin and Ukauskas, 2002; Sapoval and Hermann, 2004): . The solutions obtained under the full depletion approximation analysis are as follows:

(1) The depletion layer thickness d, given by:

$$d = \sqrt{\frac{2\varepsilon_s \phi(0)}{q^2 N_d}} \qquad (5)$$

In relation to the analysis of figure 1, Equation 5 can also be re-written as:

$$d = \sqrt{\frac{2\varepsilon_s (V_{bi} - V)}{q^2 N_d}} \quad , \text{ meter} \qquad (6)$$

(2) The junction capacitance C_j, given by:

$$C_j = \frac{A\varepsilon_s}{d}, \qquad \text{Farad} \qquad (7)$$

Where, ε_s is the semiconductor (n-GaN) permittivity in Fm^{-1}, A is the contact area in m^2 and N_d is the background doping concentration in m^{-3}.

2.2 Computation

The computation of the potential energy barrier height, depletion layer thickness and junction capacitance characteristics of metal-n-GaN Schottky diode as function of temperature and applied bias, based on the derived and existing analytical models as discussed in section 2.1 above, were carried out by visual basic programming with the aid of visual basic version 6.0 program compiler.

It is assumed that the contact area of n-GaN Schottky diode employed in the computation is circular and the area is 7.85×10^{-9} m^2 based on experience (Morkoc *et al.*,1999; Cao *et al.*,1999; Dang *et al.*,2000; Alade *et al.*, 2009a;

Alade *et al.,* 2009b). Metals such as Ni, Au and Pt are assumed as the diode metal contacts, and metals such as Al, and Cr assumed as the metal ohmic contacts. The following fixed constant parameters were used for the simulation: ε_s of Wurtzite n-GaN ~ 9.0 Fm^{-1}, N_d of n-GaN ~ 1 x 10^{23} m^{-3} and electronic charge q = 1.6 x $10^{-19}C$ (Morkoc *et al.,*1999; Cao *et al.,*1999; Dang *et al.,*2000; Alade *et al.,* 2009a; Alade *et al.,* 2009b). The temperature was varied from 300 to 950K under the applied biases of 0V, 0.1V, 0.4V, 1.0V, 2.0V, 10.0V, 15.0V and 20.0V. The algorithms are as follows:

```
Private Sub Command1_Click()
Dim b, T As Single
Dim strB, strE, strM As String
'strB = "T = "
strE = " " '& "b = "
For T = 300 To 950 Step 1
b = Abs(1 / 3 * (3.503 + ((0.000508 * T * T) / (T – 996))))
'strM = strM & Cstr(T)
strM = strM & strE
strM = strM & b & vbCrLf
txtdisplay.Text = strM
Refresh
Next T
End Sub
```

```
Private Sub Command1_Click()
Dim d, d1, e, b, v, q, n As Double
Dim T As Integer
Dim strBegin As String
Dim strEnd As String
Dim strMsg As String
'strBegin = "T = "
strEnd = " " '& "d = "
q = 1.6E-19
v = 0
n = 1E+23
e = 9
For T = 300 To 950 Step 1
b = Abs(1/3 * (3.503 + ((0.000508 * T * T)/(T – 996)))) * 1.6 * 1E-19
d1 = Abs(((2 * e * (b – v))/(q * n)))
d = d1 ^ 0.5
'strMsg = strMsg & strBegin
'strMsg = strMsg & Cstr(T)
strMsg = strMsg & strEnd
strMsg = strMsg & d & vbCrLf
txtdisplay.Text = strMsg
Refresh
Next T
End Sub
```

```
Private Sub Command1_Click()
Dim d, d1, e, b, v, q, n, a, c, r As Double
Dim T As Integer
Dim strBegin As String
Dim strEnd As String
Dim strMsg As String
'strBegin = "T = "
strEnd = " " '& "f = "
q = 1.6E-19
v = 1.0
```

```
n = 1E+23
a = 0.00000000785
e = 9
r = 0.000000000000001
For T = 300 To 950 Step 1
b = Abs(1/3 * (3.503 + ((0.000508 * T * T)/(T – 996)))) * 1.6 * 1E-19
d1 = Abs(((2 * e * (b – v))/(q * n)))
d = d1 ^ 0.5
c = (a * e) / d
f = 1 / (2 * 3.142 * c * r)
'strMsg = strMsg & strBegin
'strMsg = strMsg & Cstr(T)
strMsg = strMsg & strEnd
strMsg = strMsg & f & vbCrLf
txtdisplay.Text = strMsg
Refresh
Next T
End Sub
```

In the algorithms: b = barrier height, d = depletion layer thickness, c = Junction capacitance, n = background doping concentration, e = n-GaN permittivity, r = junction reactance, v = applied bias, a = contact area, and f = frequency.

3. Results and Discussion

The characteristics of a microstructure metal-n-GaN Schottky diode as microwave radio frequency sensor in terms of the electronic parameters namely; the potential energy barrier height, depletion layer thickness and junction capacitance have been numerically computed using the existing analytical models of the electronic parameters with the aids of visual basic programming. The effects of extreme temperature under external applied bias on the potential energy barrier height, depletion layer thickness and junction capacitance have been considered.

Figure 2 shows the plot of the barrier height of n-GaN Schottky diode microwave sensor against the temperature. The barrier height decreases expectedly as the temperature increases, but there is abrupt increase in the barrier height as the temperature continues to increase above 900K. The reason for this can not be immediately ascertained. However, this abrupt increase behaviour of the barrier height at high temperature may be due to the reported stability demonstrated by n-GaN Schottky diode at high temperature (Morkoc *et al.,*1999; Cao *et al.,*1999; Dang *et al.,*2000; Alade *et al.,* 2009a; Alade *et al.,* 2009b).

Figure 3 is the plot of depletion layer thickness of n-GaN Schottky diode microwave sensor against the temperature. Also expectedly, the depletion layer thickness decreases as the temperature increases. While, Figure 4 shows the plot junction capacitance of n-GaN Schottky diode microwave sensor against bias at various high temperature. The result shows that the capacitance decreases as the bias increases. This is also expected. However, the decrease is much at high temperature under the same applied bias condition.

4. Conclusion

GaN Schottky diode is a device that has attracted attention of the researchers in recent time own to its unique advantages: high breakdown voltage and high operating temperature which can be useful when applied as a microwave sensor at high temperature. Therefore, this paper presents the numerical investigation of the electronic properties n-GaN Schottky microwave sensor in terms of the potential energy barrier height, depletion layer thickness and junction capacitance as function of high temperature and applied bias, based on the existing analytical models of the electronic parameters of metal-semiconductor contacts. The results obtained are in good agreement with the previous hypothesis about the device.

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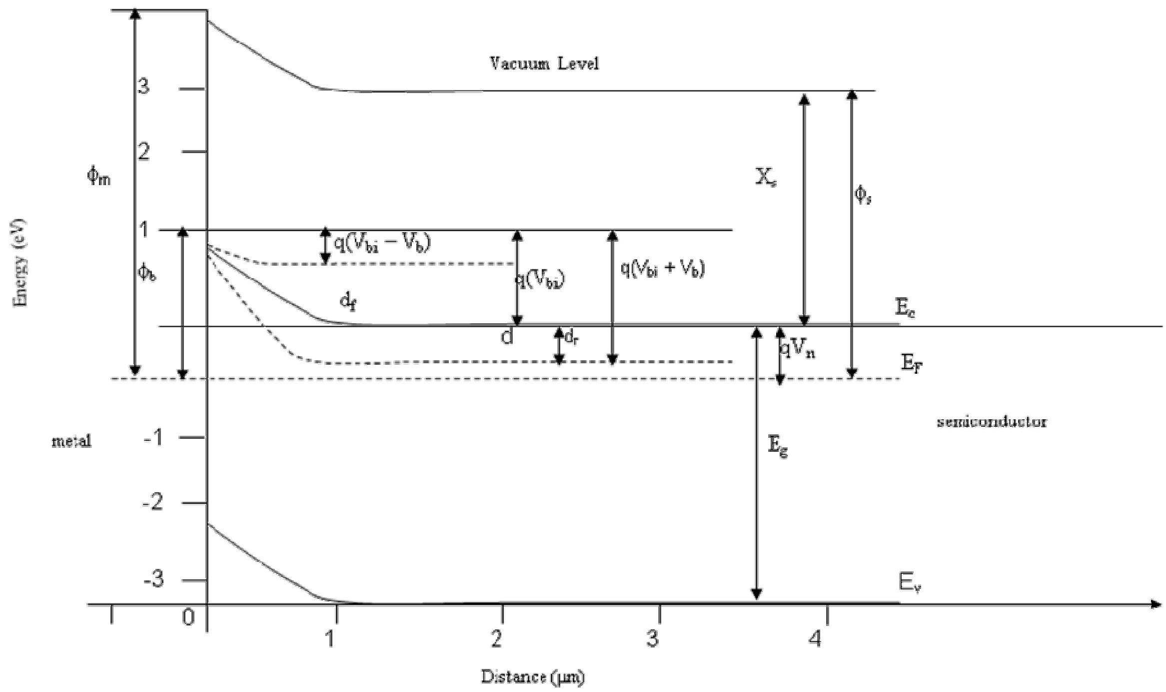

Figure 1. Idealized energy band diagram of Pt / n-GaN Schottky barrier. It also shows (i) the deflection of semiconductor energy bands by contact field and (ii) the effect of the forward bias V_b and reverse bias on the contact field and depletion width d (d_f = depletion width under forward bias, d_r = depletion width under reverse bias).

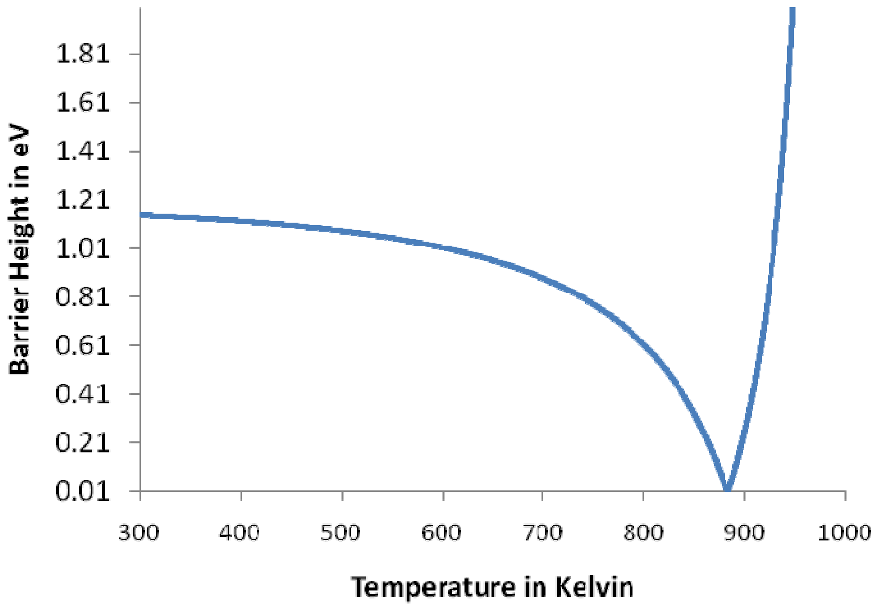

Figure 2. Showing the Barrier Height of n-GaN Schottky diode microwave sensor against Temperature.

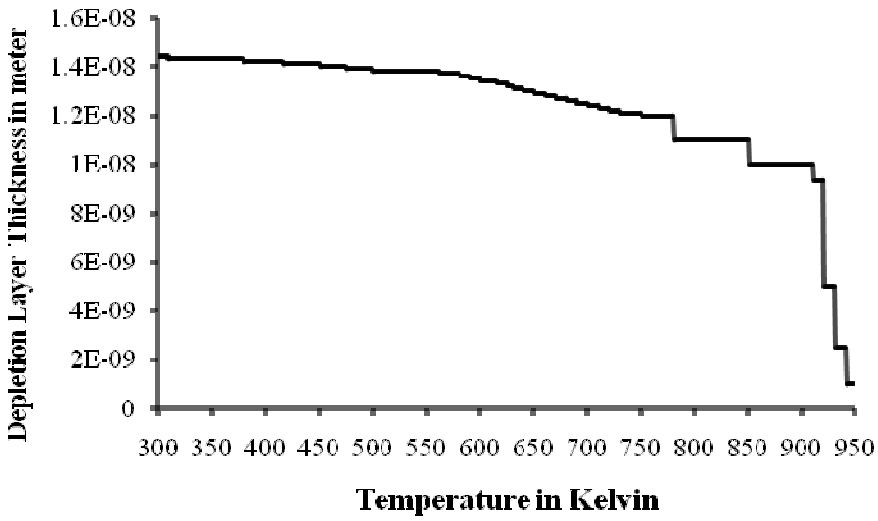

Figure 3. Showing the plot of Depletion layer thickness of n-GaN Schottky diode microwave sensor against Temperature.

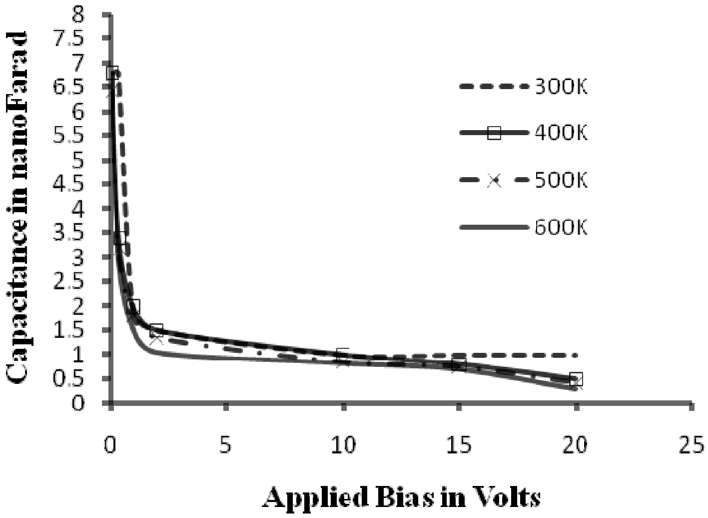

Figure 4: Showing the plot of Capacitance of n-GaN Schottky diode microwave sensor against Bias.