A New Modeling of the Junction Metal Semiconductor for Rectenna System

Abdelhak Hamid allah1, Ahmed Errkik2, Jamal Zbitou3, Larbi El Abdellaoui4, Abdelali Tajamouati5, Mohamed Latrach6
{abdelhakhamidallah@gmail.com1, ahmed.errkik@uhp.ac.ma2, zbitouj@gmail.com3}
LMEET Laboratory FST of Settat Hassan 1st University Morocco1,2,3,4,5, Microwave group ESEO Angers France6

Abstract. This article presents a new design and optimization of the junction Metal-Semiconductor (Au/n-GaAs) optimized in performances. This study has as objective the design of a new Schottky diode which is dedicated to the design of new RF-DC rectifiers in order to increase and to improve the performances of rectenna, and the microwave applications in general. The modeling is based initially on the determination of the breakdown voltage and then the calculation and optimization of all the principal parameters of the Schottky diode. For validation, the proposed study is compared with the commercial diodes.

Keywords: Junction Metal-Semiconductor, GaAs Schottky Diode, Schottky Barrier, Rectenna, Diode Modeling.

1 Introduction

The semiconductor devices are in the foreground of modern technology. Each day, the powerful semiconductor devices are developed and contribute to the spectacular results got in various spheres of the scientific and technology activity. The structures metal semiconductors (Schottky diode) are components widely used in microelectronics and microwaves applications for the manufacturing of integrated circuits on one hand and as a basic competent in commutation, on the other hand. In this context the Schottky diode is the most used element for the manufacturing and the design of the rectifier rectenna. Among the semiconductor with direct band gap and higher electronic mobility, the gallium arsenide (GaAs) [1, 2]. It’s a semiconductor which starts to become a serious competitor for silicon (Si). Moreover, it can easily be doped n or p, and its operating temperature reaches at least 600°C-700°C [3, 4]. Indeed, the characteristic of the metal-semiconductor junction is nonlinear when it functions at high powers and its performances on the conversion operation are very limited. The objective is the design of a diode Au/n-GaAs Zero biased, which works with low, high power levels and having a good detection sensitivity and good performance in terms of rectifying operation. The study begins with the fixation of a breakdown voltage which is suitable for high levels of power, then the optimization of the parameters and properties of the diode using the methodology detailed in Figure 1 and in the following section.
2 Modeling and optimized parameters

According to [5] a study conducted to evaluate the conversion efficiency of a rectenna. The breakdown voltage $V_{br}$, the zero-biased junction capacitance $C_{j0}$ and the series resistance $R_s$ are the principal elements which determine the efficiency of RF-DC conversion for a rectenna and the global performances of commercial diodes, those parameters are related to the properties of selected materials [1]. In addition, the maximum power of a rectenna or the critical input power where the output voltage DC becomes limited, is given by the following equation $P_{RF} = \frac{V_{br}^2}{4R_s}$. Therefore, this power is limited by the value of the breakdown voltage thus also limiting the efficiency and the performance of the rectenna. For this reason, we decided to begin this modeling with the determination of the breakdown voltage $V_{br}$ and then to extract and modeled all principal parameters of the diode.

2.1 Determination of drift region parameters

The breakdown voltage we had chosen for this study is $V_{br} = 100 \, V$. According to [6] the relationships between the breakdown voltage, the drift region width, and drift region concentration or (drift region doping) are expressed by the equations (1) and (2).
\[ N_d^+ = 2 \times 10^{18} \times (V_{br}^{-4/3}) \text{ cm}^{-3} \]  
\[ W_D = 2.67 \times 10^{10} \times (N_d^+)^{-7/6} \text{ cm} \]  

With \( N_d^+ \) is the drift region concentration and \( W_D \) is the drift region width, to see Figure 2.

![Fig. 2. Structure metal semiconductor.](image)

The value of the breakdown voltage decreases notably when the concentration increases, and conversely for the width the voltage increases. The variation between dimensions of the drift region and the breakdown voltage is traced in Figure 3.a and Figure 3.b.

![Fig. 3.a. Variation of the breakdown voltage \( V_{br} \) vs. Drift region concentration \( N_d^+ \).](image)

![Fig. 3.b. Variation of the breakdown voltage \( V_{br} \) vs. Drift region concentration \( N_d^+ \).](image)

### 2.2 Schottky barrier height \( \Phi_b \)

The barrier height can be expressed as (3)

\[ \Phi_b = \Phi_m - X_s \]  

With \( \Phi_m \) work function of the metal (gold for our study), and \( X_s \) is the electronic affinity of semiconductor (GaAs).

For our study, the work function of Au is \( \Phi_m = 5.06 \text{ eV} \) [7],[8], and the electronic affinity of GaAs is \( X_s = 4.07 \text{ eV} \) [1], therefore the barrier height is \( \Phi_b = 0.98 \text{ eV} \). Figure 4 is traced using the equation \( \Phi_b = 0.12\Phi_m + 0.37 \) [7], representing the variation between a barrier height and a work function.
Fig. 4. Barrier height values for different metals plotted against the metal work function.

2.3 Donor concentration $N_d$ and the built-in voltage $V_{bi}$

To calculate the built-in voltage, we substitute the equations (3) and (5) into (4), the curve that models the evolution of $V_{bi}$ is given in the Figure 5.a. Regarding the breakdown voltage $V_{br}$, we replace the relations (4), (5) and (6) in the equation (7). The curve in Figure 5.b shows the variation between the donor concentration $N_d$ and voltage $V_{br}$, we note we have a high donor concentration the breakdown voltage decreases [1], [9], [10].

\[
V_{bi} = \Phi_b - \frac{KT}{q} \times \ln \left( \frac{N_c}{N_d} \right)
\]

\[
N_c = 4.7 \times 10^{17} \times \left( \frac{T}{300} \right)^{3/2} 2.49 \times 10^6
\]

\[
E_{cr} = \frac{1 - 0.25 \times \log(N_d \times 10^{-10})}{\epsilon_s \times (E_{cr})^2}
\]

\[
V_{br} = \frac{\epsilon_s \times (E_{cr})^2}{2qN_d - V_{bi}}
\]

Where $V_{bi}$ is the built-in voltage and, $N_c$ the density of states at the conduction band edge, $E_{cr}$ is the critical electric field, $\epsilon_s$ is the permittivity of the semiconductor.

The donor concentration and the built-in voltage we got for $V_{br} = 100$ V, $AeN_d = 5 \times 10^{22} \text{m}^{-3}$, and $V_{bi} = 0.99$ V.
2.4 Depletion layer width $W$, and $C_{j0}$ zero bias junction capacitance

The equation to calculate $W$ is given in the following form (8).

$$ W = \frac{2\varepsilon_S}{qN_d} (V_{bi} - V - kT/q) $$

(8)

Where $V$ is the applied bias, $q$ the electronic charge, $T$ is the temperature (K), with $kT/q \approx 26$ mV for $T=25°C$.

The results of the variation of depletion layer width $W$ versus donor concentration and the applied bias are given within the Figure 6. The condition to respect between depletion region width $W$ and diode thickness $d$ is defined by $W < d$. The presence of the depletion region generates a static capacity $C_{j0}$ or (zero bias junction capacitance) is defined by the relation (9)

$$ C_{j0} = \sqrt{\frac{q\varepsilon_S N_d S^2}{2V_{bi}}} $$

(9)

2.5 The saturation current current $I_s$, (I-V) characteristics of the modeled diode

The saturation current is expressed by the equation (10). On the other hand, in the bibliographical support [7] the ideality factor or the emission constant is $n = 1.01$ for a metal function work $\Phi_m = 5.06$ . Concerning how to trace the characteristic (I-V-T), we use the Shockley equation (11). The Figure 7 represents the characteristic in forward bias and under linear scale.

$$ I_s = S \times A \times T^2 \times \left[ \exp \left( \frac{-q\Phi_m}{kT} \right) \right] $$

(10)

With $S$ the diode area, $A = 8.2 \times 10^4 A/m^2 K^2$ the effective Richardson constant $K = 38 \times 0.6285 \times 10^{-4}$ is Boltzmann’s constant.
I = I_s \times \left[ \exp \left( \frac{qV}{nKT} \right) - 1 \right] \tag{11}

Fig. 6. Depletion layer width $W$ vs. Donor concentration $N_d$, and $V$.

Fig. 7. Linear scale characteristic (I-V-T).

2.6 Series resistance $R_s$

The series resistance consists of three resistances $R_s = R_g + R_{ch} + R_c$ where $R_g, R_{ch}, R_c$ are respectively the junction resistance, the canal resistance, and contact resistance; the three resistances are given by equations (12), (13), (14). After the calculation and the simplification between all equations, the value obtained for the series resistance is $R_s = 4.6 \, \Omega$, the variation of the latter is shown in Figure 8.

\[
R_g = \frac{\rho_m D}{3 W} \tag{12}
\]

\[
R_{ch} = \frac{R_1 (R_2 + R_3)}{R_1 + R_2 + R_3} \tag{13}
\]

\[
\begin{align*}
R_1 &= \frac{1100 L}{a N_d^{0.82} A} \tag{13a} \\
R_2 &= \frac{1100 L}{a^+ (N_d^+)^{0.82} A} \tag{13b} \\
R_3 &= \frac{1100 L a}{N_d^{0.82} W_D} \tag{13c} \\
R_c &= \frac{P \times \sqrt{(a^+)(N_d^+)^{0.66}}}{2100} \tag{14}
\end{align*}
\]

\[
P = 2D + 2L + W \tag{14a}
\]

Where $\rho_m = 2.5 \times 10^{-8} \, \Omega \, m$ [4] is the metal resistivity, $W_D$ is the drift region width $N_d^+$ is the drift region concentration; all the other parameters are detailed in Figure 9.a and Figure 9.b.
2.7 Electron mobility $\mu$ and cutoff frequency $f_c$

The electron mobility is a concept used in physics to characterize the conducting mediums of the electric current; the gallium arsenide is a semiconductor with higher electronic mobility the maximum electronic mobility for GaAs is approximately $\mu_{max} = 9200 \text{ cm}^2/\text{V.s}$ at $T = 300K$. According to the supports [11], [12], there exist two equations to calculate the electronic mobility (15), (16). The variation of the mobility versus of temperature and donor concentration is presented in Figure 10.

$$\mu(N_d) = \mu_{min} + \frac{\mu_{max} - \mu_{min}}{1 + (N_d/N_{ref})^\alpha}$$  \hspace{1cm} (15)$$

$$\mu(T) = \mu(300K) \times \left(\frac{300K}{T}\right)^\alpha$$  \hspace{1cm} (16)$$

Where $\mu_{min}, \mu_{max}$ maximum and minimum mobility $N_{ref} = 1.26 \times 10^{17} \text{ cm}^{-3}$[1]. Reference doping concentration of GaAs, $\sigma = 2.15, \alpha = 0.61$ are two constants.

For traditional high-frequency model (Figure 11) of a Schottky diode, the cutoff frequency is given by the equation (17). For this study we find $f_c = 55 \text{ GHz}$. 
\[
\tilde{f}_c = \frac{1}{2\pi R_s C_{j0}}
\]  

\text{(17)}

![Fig. 10. Variation of electronic mobility vs. Temperature T and donor concentration \(N_d\).](image)

\text{Fig. 11. Traditional model of a Schottky diode with } R_s \text{ (series resistance), } C_j \text{ (junction capacitance), } R_j \text{ (junction resistance).}

Table 1. Comparison between our work and the commercial diode used in other works.

<table>
<thead>
<tr>
<th>Diode</th>
<th>Reference</th>
<th>(V_{br}) (V)</th>
<th>(R_s) (Ω)</th>
<th>(C_{j0}) (pF)</th>
<th>(I_s) (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAT-03</td>
<td>[13]</td>
<td>4.6</td>
<td>5.0</td>
<td>0.1385</td>
<td>13 (\times) (10^{-8})</td>
</tr>
<tr>
<td>KA-BAND</td>
<td>[5]</td>
<td>9.0</td>
<td>4.85</td>
<td>0.13</td>
<td>5.24 (\times) (10^{-15})</td>
</tr>
<tr>
<td>HSMS-2860</td>
<td>[14]</td>
<td>7.0</td>
<td>5.0</td>
<td>0.18</td>
<td>5 (\times) (10^{-8})</td>
</tr>
<tr>
<td>HSMS-2820</td>
<td>[15]</td>
<td>15.0</td>
<td>6.0</td>
<td>0.70</td>
<td>2.2 (\times) (10^{-3})</td>
</tr>
<tr>
<td>HSMS-2850</td>
<td>[16]</td>
<td>7.0</td>
<td>25.0</td>
<td>0.18</td>
<td>5.0 (\times) (10^{-8})</td>
</tr>
<tr>
<td>MA4E1317</td>
<td>[17]</td>
<td>7.0</td>
<td>4.0</td>
<td>0.02</td>
<td>-</td>
</tr>
<tr>
<td>Optimized Diode</td>
<td>This work</td>
<td>100</td>
<td>4.6</td>
<td>0.6291</td>
<td>6 (\times) (10^{-15})</td>
</tr>
</tbody>
</table>

Table 2. Parameters of optimized diode.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breakdown voltage</td>
<td>(V_{br})</td>
<td>100</td>
<td>V</td>
</tr>
<tr>
<td>Series resistance</td>
<td>(R_s)</td>
<td>4.6</td>
<td>Ω</td>
</tr>
<tr>
<td>Zero bias capacitance</td>
<td>(C_{j0})</td>
<td>0.6291</td>
<td>pF</td>
</tr>
<tr>
<td>Saturation current</td>
<td>(I_s)</td>
<td>6</td>
<td>fA</td>
</tr>
<tr>
<td>Built-in voltage</td>
<td>(V_N)</td>
<td>0.9</td>
<td>V</td>
</tr>
<tr>
<td>Barrier Height</td>
<td>(\Phi_b)</td>
<td>0.98</td>
<td>eV</td>
</tr>
<tr>
<td>Ideality factor</td>
<td>(n)</td>
<td>1.01</td>
<td>-</td>
</tr>
<tr>
<td>Cutoff frequency</td>
<td>(f_c)</td>
<td>55</td>
<td>GHz</td>
</tr>
</tbody>
</table>

3 Conclusion

We showed through this study a new modeling of metal semiconductor in Au/n-GaAs technology, in which we calculated all the principal parameters of the junction. Compared to the parameters of commercialized Schottky diode reported in previous work (Table 1), we can conclude that the modeled diode (Table 2) is more performing in several parameters and more...
precisely in the parameters which determine the efficiency of diode, and this was the global goal of our study. Moreover, the proposed study has a several advantages, firstly this study can be used as the guideline for diode conception of a rectifier design, for microwaves applications. Secondly, the study has enabled us to conceive adaptable diodes to our application. Finally, the study allows a high efficiency of microwave applications on which the diodes are the principal element like a rectenna.

References