Chapter – VIII
Experimental and Theoretical Studies on the Series Resistance of Ka-band IMPATT diodes

8.1. Introduction

IMPATT devices have emerged as most powerful solid-state devices for generation of high CW and pulsed power in millimeter wave frequencies [7] and also for silicon monolithic millimeter-wave integrated circuit’s (SIMMWIC’s), IMPATT diode provides high oscillator output power with high DC to RF conversion efficiency [8]. Several workers have examined the possibility of high power generation either from a single IMPATT diode or from several diodes by using the power combining technique. The parasitic positive series resistance $R_s$ which originates from the unswept epilayer, package contacts and the passive circuit is a dominant factor, which limits the output power from an IMPATT source. The negative resistance of millimeter wave IMPATT diode is in the range of only a few ohms. The positive series resistance $R_s$ therefore has to be kept to a minimum possible value by appropriate technology in order to obtain maximum output power from the device. A direct measurement of series resistance $R_s$ by a network analyzer is difficult due to
circuit modeling difficulties and network analyzer error [167], [168]. The author has developed a computer simulation method to determine the series resistance $R_s$ of millimeter wave Ka-band packaged SDR IMPATT diode. The method incorporates accurate values of ionization rates and drifts velocities and utilizes small signal admittance characteristics at threshold condition. The threshold condition is obtained when the small signal conductance of the packaged diode just becomes negative and the device susceptance becomes just positive. The values of series resistance $R_s$ obtained from small signal simulation are compared with measured values of series resistance $R_s$ using modified Alderstein expression [169], [130].

In the following sections of this Chapter i.e, 8.2 and 8.3 a computer based method is described for calculation of Series resistance $R_s$ of a millimeter wave Ka-band packaged IMPATT diode from Small signal conductance – susceptance characteristics. The Series resistance $R_s$ is calculated at the threshold condition when the small signal conductance of the packaged diode just becomes negative and the device susceptance becomes positive. Again, the value of Series resistance $R_s$ is experimentally determined from the measurement of threshold current and threshold frequency of silicon Ka-band IMPATT diode embedded in a resonant cap cavity; the calculated values of $R_s$ agree well with the experimental measured values.

In section 8.4 the effect of package parameters and series resistance on the admittance properties of silicon SDR Ka-band IMPATT diodes will be presented. The effect of increasing current density has been studied for both unpackaged and packaged IMPATT diodes by considering an equivalent model of IMPATT diode chip with and without package parameters taking into account the effect of series resistance of IMPATT diode. A package inductance of 0.080 nH and a package
capacitance 0.110 pF are taken in the simulation. The dc bias current density is varied from $9.0 \times 10^7 - 1.2 \times 10^8$ A/m$^2$ in steps of $0.5 \times 10^7$ A/m$^2$ to study the effect of current density on the admittance properties of unpackaged and packaged IMPATT diode at Ka-Band.

### 8.2. Equivalent Model of IMPATT Diode

An equivalent representation of the IMPATT diode in RF circuit is shown in Fig.8.1. G and B are the diode conductance and susceptance obtained from simulation programme by using realistic values of ionization rate and drift velocities. $R_s$ is the series resistance of the device, $g$ is the load conductance and $L$ is the circuit inductance, which is tuned to give the desired frequency.

![Equivalent model of IMPATT diode without package parameter](image)

Fig.8.1. Equivalent model of IMPATT diode without package parameter

In a practical oscillator circuit, the steady-state condition for oscillation is given by 
[130]

$$g = -G - B^2 R_s$$  \hspace{1cm} (8.2.1)

Considering higher order term, a more accurate expression of the steady-state condition for oscillation can be written as

$$g = -G - G^2 R_s - B^2 R_s$$  \hspace{1cm} (8.2.2)
In the practical case, it is a good approximation to take \( g = 0 \) at the oscillation threshold [130].

Then the equation (8.2.2) reduces to

\[
0 = -G_{th} - G_{th}^2 R_s - B_{th}^2 R_s
\]

or,

\[
R_s = \frac{|G_{th}|}{G_{th}^2 + B_{th}^2}
\]  

(8.2.3)

where, \( G_{th} \) = Small signal threshold conductance of the diode when the conductance of the packaged diode becomes just negative.

\( B_{th} \) = Small signal threshold susceptance of the diode, corresponding to the threshold conductance \( G_{th} \).

![Fig.8.2 Equivalent model of IMPATT diode with package parameters](image)

Considering the package inductance \( L_p \) and package capacitance \( C_p \), the equivalent circuit of the IMPATT diode with package parameters is shown in Fig.8.2 and the expression of \( R_s \) is modified to
where, \( B_p = \frac{1}{\omega C_p} \) = Effective susceptance caused by package parameters.

8.3. Simulation of Series Resistance

The author has designed a silicon SDR (p⁺nn⁺ type) IMPATT diode for operation in Ka-band, through double iterative dc and small signal simulation programme which is described in details in Chapter III.

The method involves simultaneous solution of following Poisson’s equation and Carrier continuity equation

\[
\frac{\partial E(x)}{\partial x} = \frac{q}{\epsilon} \left[ N_D - N_A + p(x) - n(x) \right] \quad (8.3.1)
\]

\[
\frac{\partial p}{\partial t} = \frac{1}{q} \frac{\partial}{\partial x} J_p + g \quad (8.3.2.a)
\]

\[
\frac{\partial n}{\partial t} = \frac{1}{q} \frac{\partial}{\partial x} J_n + g \quad (8.3.2.b)
\]

The boundary conditions are (i) The electric field at the two edges of the depletion layer becomes zero, i.e. (i) \( E(-x_1) = 0 \) and \( E(+x_2) = 0 \) and (ii) Normalized carrier current densities at the two edges are \( P(-x_1) = -1 \) and \( P(x_2) = +1 \) where, \( P(x) = (J_p - J_n) / (J_p + J_n) \).

On splitting the diode impedance \( Z(x, \omega) \) obtained from Gummel – Blue equation [85], into its real part \( R(x, \omega) \) and imaginary part \( X(x, \omega) \), two differential equations are framed [141].

\[
\frac{d^2 R}{dx^2} + (\alpha_n - \alpha_p) \frac{dR}{dx} - 2\alpha \frac{\omega}{v} \frac{dX}{dx} + \left( \frac{\omega^2}{v^2} - H \right) = 0 \quad (8.3.3.a)
\]
\[
\frac{d^2X}{dx^2} + (\alpha_n - \alpha_p) \frac{dX}{dx} - 2R \frac{\omega}{v} \frac{dR}{dx} + \left( \frac{\omega^2}{v^2} - H \right) X + 2\sigma \frac{\omega}{v} R + \frac{\omega}{v_i} = 0
\] (8.3.3.b)

The expressions for \( R, X, H, \alpha_n \) and \( \alpha_p \) are given in Chapter III.

Solving the above two equations simultaneously, the small signal integrated parameters like impedance (Z), conductance (G) and susceptance (B) are obtained. The integration of \( R(x) \) and \( X(x) \) profiles over the depletion layer gives, the total negative resistance \( Z_R \) and \( Z_X \) of the diode.

\[
Z_R = \int_{-x_1}^{x_2} R(x) \, dx
\] (8.3.4.a)

\[
Z_X = \int_{-x_1}^{x_2} X(x) \, dx
\] (8.3.4.b)

The diode impedance \( Z \) is given by

\[
Z(\omega) = \int_{-x_1}^{x_2} Z(x, \omega) \, dx = Z_R + jZ_X
\] (8.3.5)

Hence, the diode conductance (G) and susceptance (B) are given by

\[
G = \frac{Z_R}{(Z_R)^2 + (Z_X)^2}
\] (8.3.6.a)

\[
B = -\frac{Z_X}{(Z_R)^2 + (Z_X)^2}
\] (8.3.6.b)

The symbols used in above equations have their usual significance. Realistic field and temperature dependent carrier ionization rates and drift velocities [142], [143] corresponding to the junction temperature of 225° C are taken. The effect of mobile space charge has also been considered. The device parameters used for the present study are given in Table: 8.1. The dc current density is varied from \( 9.0 \times 10^7 \) - \( 1.2 \times 10^8 \) A/m\(^2\). The G-B plots corresponding to maximum and minimum current...
densities are shown in Fig. 8.3. The optimum frequency of operation for the designed diode is found to vary in the range of 37-40 GHz.

Table: 8.1

Device Parameter for Ka-Band Analysis

<table>
<thead>
<tr>
<th>$W_n$ [μm]</th>
<th>$N_d$ [$m^{-3}$]</th>
<th>Temp. [$^\circ$C]</th>
<th>Diode area [$m^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4</td>
<td>2.7x10^{22}</td>
<td>225</td>
<td>0.155x10^{-6}</td>
</tr>
</tbody>
</table>

Fig. 8.3. $G - B$ Plot from Small signal Analysis
8.3.1. Results from the simulation

A value of package inductance of $L_p = 0.080$ nH and capacitance of $C_p = 0.110$ pF for SDR Ka Band IMPATT diode is considered in the Small signal simulation for calculation of series resistance. The series resistance $R_s$ of the diode is determined from the threshold condition of oscillation of the diode, i.e. when both the circuit conductance $g$ and the power output from the device are minimum. Thus the series resistance $R_s$ of the diode can be accurately determined from the small signal simulation at the threshold condition by using the expression given in (8.2.4). The values of series resistance $R_s$ obtained from simulation programme are given in Table: 8.2 for various current densities.

Table: 8.2

<table>
<thead>
<tr>
<th>$J$ (A/m$^2$)</th>
<th>$I_{th}$ (mA)</th>
<th>$f_{th}$ (GHz)</th>
<th>$f_{opt}$ (GHz)</th>
<th>$G_{th}$ (mho)</th>
<th>$B_{th}$ (mho)</th>
<th>$B_p$ (mho)</th>
<th>$R_s$ (ohm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.00x10$^7$</td>
<td>25.81</td>
<td>25.60</td>
<td>37.00</td>
<td>-5.2089x10$^{-4}$</td>
<td>1.4664x10$^{-3}$</td>
<td>-2.1323x10$^{-2}$</td>
<td>1.002</td>
</tr>
<tr>
<td>9.50x10$^7$</td>
<td>27.00</td>
<td>26.30</td>
<td>37.50</td>
<td>-5.1443x10$^{-4}$</td>
<td>1.6238x10$^{-3}$</td>
<td>-2.2229x10$^{-2}$</td>
<td>0.904</td>
</tr>
<tr>
<td>1.00x10$^8$</td>
<td>27.98</td>
<td>27.10</td>
<td>38.00</td>
<td>-6.5286x10$^{-4}$</td>
<td>2.0663x10$^{-3}$</td>
<td>-2.3309x10$^{-2}$</td>
<td>1.013</td>
</tr>
<tr>
<td>1.05x10$^8$</td>
<td>29.27</td>
<td>27.70</td>
<td>38.50</td>
<td>-6.7414x10$^{-4}$</td>
<td>2.1384x10$^{-3}$</td>
<td>-2.4153x10$^{-2}$</td>
<td>0.975</td>
</tr>
<tr>
<td>1.10x10$^8$</td>
<td>30.35</td>
<td>28.30</td>
<td>39.00</td>
<td>-7.0771x10$^{-4}$</td>
<td>2.2492x10$^{-3}$</td>
<td>-2.5028x10$^{-2}$</td>
<td>0.951</td>
</tr>
<tr>
<td>1.15x10$^8$</td>
<td>30.79</td>
<td>28.90</td>
<td>39.50</td>
<td>-7.2861x10$^{-4}$</td>
<td>2.4197x10$^{-3}$</td>
<td>-2.5937x10$^{-2}$</td>
<td>0.906</td>
</tr>
</tbody>
</table>
8.3.2. Experimental determination of Series Resistance

The value of series resistance \( R_s \) is determined from the measurement of threshold current \( I_{th} \) and threshold frequency \( f_{th} \) from the modified Alderstein expression [169].

\[
R_s = \left( \frac{d_i d (d + 1) I_{th}}{0.7414 \left( d + 1 \right) f_{th} C_d^2 f_{opt}^4} \right) \frac{f_{opt}}{f_{th}}
\]

(8.3.7)

Where, \( d_i \) = derivative of the electron ionisation rate with respect to electric field.

\( I_{th} \) = threshold current at which the oscillation just starts.

\( f_{th} \) = experimentally measured threshold frequency.

\( f_{opt} \) = experimentally measured optimum frequency.

\( C_d \) = device capacitance.

\[
c = \frac{\alpha_p}{\alpha_n} \text{ and } d = \frac{v_p}{v_n}
\]

Where \( \alpha_n, \alpha_p, v_n, v_p \) are respectively the ionization rates of electron and holes and their drift velocities at the maximum field point in the depletion layer.

8.3.2.1 Measurement technique to obtain series resistance

Experiments are carried out by using silicon Ka-band SDR IMPATT diodes, having specification given in Table: 8.3. IMPATT diode is embedded in a resonant-cap cavity [152], shown in Fig. 8.4. The block diagram of the measurement test set up is shown in Fig. 8.5 and photograph in Fig. 8.6. Measured values of various parameters i.e. threshold current, threshold frequency and optimum frequency at optimized condition are plotted in Fig. 8.7. The output power and frequency of the
resonant-cap oscillator with cap diameter = 4.0 mm, height = 1.40 mm and thickness = 0.60 mm are plotted against the dc bias current flowing through the diode, is shown in Fig.8.8.

Table: 8.3
Specification of Ka-band SDR IMPATT diode used in experimental study

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency range (f)</td>
<td>35 – 42 GHz</td>
</tr>
<tr>
<td>Breakdown voltage (V_B)_{Max}</td>
<td>45 Volts</td>
</tr>
<tr>
<td>Maximum current (I)_{Max}</td>
<td>150 mA</td>
</tr>
<tr>
<td>Power output (P)_{Max}</td>
<td>100 mW</td>
</tr>
<tr>
<td>Package inductance (L_P)</td>
<td>0.080 nH</td>
</tr>
<tr>
<td>Package capacitance (C_P)</td>
<td>0.110 pF</td>
</tr>
<tr>
<td>Device capacitance (C_d)</td>
<td>0.400 pF</td>
</tr>
</tbody>
</table>

Fig.8.4. Schematic diagram of Ka-band resonant cap cavity
Fig. 8.5. Test set up for determination of Threshold Current, Threshold Frequency and Optimum Frequency at optimized condition to obtain the of Series resistance

Fig. 8.6. Photograph of series resistance measurement test bench
Fig. 8.7. Measured Value of Various Parameters i.e. Threshold Current, Threshold Frequency and Optimum Frequency at Optimized Condition.

Fig. 8.8. Dc Bias Current Vs Frequency and Output Power
8.3.2.2 Results of Experimental study

The values of different quantities $d, d, c$ for calculating series resistance $R_s$ from equation (8.3.7) are obtained from the small signal simulation. The values used for silicon SDR ($p^+nn^+$ type) at Ka-band are $d = 0.23372$, $d = 0.97978$, $c = 0.63058$, $C_d = 0.400 \text{ pF}$. The values of series resistance $R_s$ obtained from experimental study are given in Table 8.4 for various cap heights. The values of series resistance $R_s$ obtained from simulation and experimental measurement are plotted against the threshold frequency $f_{th}$, shown in Fig. 8.9 and it is observed that the values of series resistance obtained from simulation and experimental study in close agreement.

<table>
<thead>
<tr>
<th>Cap Height $(h \pm h \text{ mm})$</th>
<th>Sliding Short Position $(l \pm \Delta l \text{ Mm})$</th>
<th>Threshold Current $(I_{th} \pm \Delta I) \text{ mA}$</th>
<th>Threshold Frequency $(f_{th} \pm \Delta f) \text{ GHz}$</th>
<th>Optimum Frequency $(f_{opt} \pm \Delta f) \text{ GHz}$</th>
<th>Series Resistance $R_s \text{ Ohm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00 ± 0.01</td>
<td>2.850 ± 0.001</td>
<td>41.20 ± 0.01</td>
<td>30.20 ± 0.01</td>
<td>35.30 ± 0.01</td>
<td>1.038</td>
</tr>
<tr>
<td>1.20 ± 0.01</td>
<td>5.500 ± 0.001</td>
<td>42.00 ± 0.01</td>
<td>30.80 ± 0.01</td>
<td>35.70 ± 0.01</td>
<td>1.009</td>
</tr>
<tr>
<td>1.40 ± 0.01</td>
<td>3.100 ± 0.001</td>
<td>44.50 ± 0.01</td>
<td>31.50 ± 0.01</td>
<td>36.00 ± 0.01</td>
<td>1.008</td>
</tr>
<tr>
<td>1.60 ± 0.01</td>
<td>4.720 ± 0.001</td>
<td>48.60 ± 0.01</td>
<td>32.10 ± 0.01</td>
<td>36.80 ± 0.01</td>
<td>1.067</td>
</tr>
</tbody>
</table>
FIG. 8.9. Threshold Frequency Vs Series Resistance $R_s$ from Simulation and Experimental study
8.4. The Effect of Package Parameters and Series Resistance on the Admittance Properties of Silicon SDR Ka-band IMPATT diodes

In this section a study of the effects of current density on the admittance properties of unpackaged and packaged IMPATT diode at Ka-Band will be presented. The author has designed a silicon SDR (p⁺nn⁺) IMPATT diode for Ka-band operation, by using double iterative DC and small signal simulation programme which involve simultaneous solution of Poisson’s equation and Carrier continuity equation with appropriate boundary conditions at the depletion layer edges, described earlier in section 8.3. The effects of current densities of both unpackaged and packaged IMPATT diode are analysed by using, an equivalent model of IMPATT diode, chip with and without package parameters where the series resistance of IMPATT diode is included described in section 8.2. A package inductance of 0.080 nH and a package capacitance 0.110 pF are taken for simulation. The dc current density is varied from 9.0 x 10⁷ – 1.2 x 10⁸ A/m² in steps of 0.5 x10⁷ A/m² for studying the effects of current density on the admittance properties of unpackaged and packaged IMPATT diode at Ka-Band operation.

8.4.1 Results and Discussions

The author has taken into account the realistic field and temperature dependent carrier ionization rates and drift velocities of charge carriers at 225°C [142],[143]. The effect of mobile space charge is also incorporated in the simulation. The value of series resistance of Ka-band IMPATT diode is taken from [170]. The device parameters used for this present study are given in Table .8.5.
The dc current density is varied from $9.0 \times 10^7 - 1.2 \times 10^8$ A/m$^2$ in steps of 0.5 $\times 10^7$ A/m$^2$ to study its effect on the admittance properties of IMPATT diodes for both unpackaged and packaged condition. The Conductance ($G$) vs Susceptance ($B$) plots provide information regarding the range of frequency of IMPATT operation and also the optimum frequency corresponding to maximum negative conductance. The Conductance ($G$) - Susceptance ($B$) plot at each current density is shown in Figs. 8.10 to 8.16 for both unpackaged and packaged condition. Current density vs Conductance plots of both unpackaged and packaged IMPATT diode are shown in Fig. 8.17. It is observed that the peak value of negative conductance of unpackaged diode increases from $-4.1561 \times 10^6$ mho/m$^2$ to $-4.8163 \times 10^6$ mho/m$^2$, when the current density increases from $9.0 \times 10^7$ A/m$^2$ to $1.2 \times 10^8$ A/m$^2$ where as the same for packaged diode increases from $-2.4699 \times 10^6$ mho/m$^2$ to $-2.5717 \times 10^6$ mho/m$^2$. Current density vs. susceptance plots for both packaged and unpackaged IMPATT diode are shown in Fig. 8.18. It is observed that the susceptance of unpackaged diode corresponding to peak negative conductance increases from $12.009 \times 10^6$ mho/m$^2$ to $12.560 \times 10^6$ mho/m$^2$ when the current density increases from $9.0 \times 10^7$. 

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**Table: 8.5**

Device Parameters used for the study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_n$</td>
<td>1.4 $\mu$m</td>
</tr>
<tr>
<td>$N_d$</td>
<td>$2.7 \times 10^{22}$ m$^3$</td>
</tr>
<tr>
<td>Diode area</td>
<td>$0.155 \times 10^8$ m$^2$</td>
</tr>
<tr>
<td>Package Inductance ($L_p$)</td>
<td>0.080 nH</td>
</tr>
<tr>
<td>Package capacitance ($C_p$)</td>
<td>0.110 pF</td>
</tr>
<tr>
<td>Device capacitance</td>
<td>0.400 pF</td>
</tr>
</tbody>
</table>
A/m$^2$ – $1.2 \times 10^8$ A/m$^2$ while the same for packaged diode increases $28.775 \times 10^6$ mho/m$^2$ to $37.210 \times 10^6$ mho/m$^2$. Variation of Current density with peak frequency is shown in Fig.8.19 for both packaged and unpackaged condition. It is observed that the peak frequency varies in the range of 37.00 GHz to 40.00 GHz for unpackaged diode where as the frequency increases from 33.00 GHz to 37.50 GHz at packaged condition. Fig.8.20 shows the variation of quality factor of both unpackaged and packaged device. The values of Peak frequency ($f_d$, $f_p$), Conductance ($G_d$, $G_p$), Susceptance ($B_d$, $B_p$) and Quality factor ($Q_d$, $Q_p$) are tabulated in Table 8.6 for unpackaged and packaged IMPATT diodes.

Fig.8.10. Conductance ($G$) Vs Susceptance ($B$) plot of unpackaged and packaged IMPATT diode at Current density ($J$) = $9 \times 10^7$ Amp/m$^2$
Fig. 8.11. Conductance (G) Vs Susceptance (B) plot of unpackaged and packaged IMPATT diode at Current density (J) = 9.5x10^7 Amp/m²

Fig. 8.12. Conductance (G) Vs Susceptance (B) plot of unpackaged and packaged IMPATT diode at Current density (J) = 1.0x10^8 Amp/m²
Fig. 8.13. Conductance (G) Vs Susceptance (B) plot of unpackaged and packaged IMPATT diode at Current density (J) = 1.05x10^8 Amp/m²

Fig. 8.14. Conductance (G) Vs Susceptance (B) plot of unpackaged and packaged IMPATT diode at Current density (J) = 1.10x10^8 Amp/m²
Fig. 8.15. Conductance (G) Vs Susceptance (B) plot of unpackaged and packaged IMPATT diode at Current density (J) = 1.15x10^6 Amp/m^2

Fig. 8.16. Conductance (G) Vs Susceptance (B) plot of unpackaged and packaged IMPATT diode at Current density (J) = 1.20x10^6 Amp/m^2
Fig. 8.17. Current density Vs Conductance plot for both unpackaged and packaged diode.

Fig. 8.18. Current density Vs Susceptance plot for both unpackaged and packaged diode.
Fig. 8.19. Current density Vs Optimum frequency plot for both unpackaged and packaged diode

Fig. 8.20. Current density Vs Quality factor ($Q_d$, $Q_p$) for both unpackaged and packaged diode
Table: 8.6

Values of Peak frequency \((f_d, f_p)\), Conductance \((G_d, G_p)\), Susceptance \((B_d, B_p)\)
Quality factor \((Q_d, Q_p)\) and for unpackaged and packaged diode

<table>
<thead>
<tr>
<th>(J) (A/m(^2))</th>
<th>(f_d) (GHz)</th>
<th>(f_p) (GHz)</th>
<th>(G_d) (mho/m(^2))</th>
<th>(G_p) (mho/m(^2))</th>
<th>(B_d) (mho/m(^2))</th>
<th>(B_p) (mho/m(^2))</th>
<th>(Q_d)</th>
<th>(Q_p)</th>
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<tbody>
<tr>
<td>9.00x10(^7)</td>
<td>37.00</td>
<td>33.00</td>
<td>-4.1561x10(^8)</td>
<td>-2.4699x10(^8)</td>
<td>12.009x10(^6)</td>
<td>28.775x10(^6)</td>
<td>2.8894</td>
<td>11.6502</td>
</tr>
<tr>
<td>9.50x10(^7)</td>
<td>37.50</td>
<td>34.60</td>
<td>-4.2925x10(^8)</td>
<td>-2.5286x10(^8)</td>
<td>12.047x10(^6)</td>
<td>32.218x10(^6)</td>
<td>2.8065</td>
<td>12.7414</td>
</tr>
<tr>
<td>1.00x10(^8)</td>
<td>38.00</td>
<td>35.00</td>
<td>-4.3767x10(^8)</td>
<td>-2.5210x10(^8)</td>
<td>12.121x10(^6)</td>
<td>32.556x10(^6)</td>
<td>2.7694</td>
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<tr>
<td>1.05x10(^8)</td>
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<td>35.2</td>
<td>-4.5322x10(^8)</td>
<td>-2.5717x10(^8)</td>
<td>12.210x10(^6)</td>
<td>32.450x10(^6)</td>
<td>2.6940</td>
<td>12.6181</td>
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<td>1.10x10(^8)</td>
<td>39.00</td>
<td>36.50</td>
<td>-4.6792x10(^8)</td>
<td>-2.5385x10(^8)</td>
<td>12.315x10(^6)</td>
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<td>2.6318</td>
<td>13.9428</td>
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<tr>
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<td>39.50</td>
<td>37.00</td>
<td>-4.7787x10(^8)</td>
<td>-2.5687x10(^8)</td>
<td>12.419x10(^6)</td>
<td>36.484x10(^6)</td>
<td>2.5988</td>
<td>14.2033</td>
</tr>
<tr>
<td>1.20x10(^8)</td>
<td>40.00</td>
<td>37.50</td>
<td>-4.8163x10(^8)</td>
<td>-2.5099x10(^8)</td>
<td>12.560x10(^6)</td>
<td>37.210x10(^6)</td>
<td>2.6078</td>
<td>14.8253</td>
</tr>
</tbody>
</table>

8.5 Conclusion

A simulation method is developed for the determination of the series resistance \(R_s\) of a millimeter wave Ka-band SDR IMPATT diode. The method requires the values of threshold conductance \(G_{th}\), susceptance \(B_{th}\) of the packaged diode which can be obtained from the well established small signal study and the values of package parameters \(L_P\) and \(C_P\) from direct measurement or manufacturer's data. Finally, the values of series resistance \(R_s\) obtained from simulation are compared with experimentally measured value of series resistance \(R_s\) by using modified Alderstein expression [130, 169]. The values obtained from the present simulation method is found to be in close agreement. The method is also applicable at higher millimeter wave frequency bands.
The author has designed a silicon SDR (p+nn+) IMPATT diode by using double iterative dc and small signal simulation programmes. An equivalent circuit model of IMPATT diode chip with and without package inductance (LP) and package capacitance (CP) is considered in the simulation by taking into account the effect of series resistance (RS). The dc current density is varied in the range of $9.0 \times 10^7$ A/m$^2$ to $1.2 \times 10^8$ A/m$^2$ in steps of $0.5 \times 10^7$ A/m$^2$. It is observed that the peak negative conductance increases from $-4.1561 \times 10^6$ mho/m$^2$ to $-4.8163 \times 10^6$ mho/m$^2$ and from $-2.4699 \times 10^6$ mho/m$^2$ to $-2.5717 \times 10^6$ mho/m$^2$ with increasing the current density for both unpackaged and packaged diodes. The susceptance value corresponding to peak negative conductance increases from $12.009 \times 10^6$ mho/m$^2$ to $12.560 \times 10^6$ mho/m$^2$ and from $28.775 \times 10^6$ mho/m$^2$ to $37.210 \times 10^6$ mho/m$^2$ for unpackaged and packaged IMPATT diode respectively. It is also observed that the peak frequency shifts upward from 37.00 GHz to 40.00 GHz for unpackaged diode and from 33.00 GHz to 37.50 GHz for packaged diode.