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Series Resistance of Silicon Millimeter Wave (Ka-band) IMPATT Diodes

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ABSTRACT

The paper describe a computer-based method to calculate the series resistance R_s of a millimeter wave Ka-band packaged IMPATT diode from small signal conductance-susceptance characteristics. The series resistance R_s has been 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 has been determined from the measurement of threshold current and threshold frequency with the silicon Ka-band IMPATT diode embedded in a resonant cap cavity which agrees well with the values obtained by the computer method.

Keywords: Conductance, IMPATT diode, series resistance, small signal, susceptance

1. INTRODUCTION

The IMPATT devices have emerged as most powerful solid-state devices for generation of high CW and pulsed-power in millimeter wave frequencies[1]. For silicon monolithic millimeter wave integrated circuits (SIMMWICs), the IMPATT diode provides high oscillator output power combined with high efficiency[2]. Since last four decades, several workers have been exploring the possibility of high-power generation either from a single IMPATT diode or from several diodes 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 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 the minimum possible value by appropriate technology to obtain maximum output power from the device. A direct measurement of series resistance R_s by a network analyser is difficult due to circuit modelling difficulties and network analyser error[3,4]. A computer-based method has been developed using accurate values of ionisation rates and drift velocities for determination of the series resistance R_s of millimeter wave Ka-band packaged SDR IMPATT diode utilising small signal conductance-susceptance characteristics at threshold condition (i.e., when the small signal conductance of the packaged diode just becomes negative and the device susceptance becomes just positive). The values obtained for series resistance R_s utilising small signal computer analysis have been compared with measured values of series resistance R_s using modified Alderstein expression[5,6].

Specifications of Ka-band SDR IMPATT diode used in experimental study are

Frequency range	(f)	= 35 – 42 GHz
Breakdown voltage	$(V_B)_{Max}$	= 45 Volts
Maximum current	$(I)_{Max}$	= 150 mA
Power output	$(P)_{Max}$	= 100 mW
Package inductance	(L_P)	= 0.080 nH
Package capacitance	(C_P)	= 0.110 pF
Device capacitance	(C_d)	= 0.400 pF

2. SERIES RESISTANCE BASED ON COMPUTER ANALYSIS

An equivalent representation of the IMPATT diode in RF circuit is shown in Fig.1, where G and B are the diode conductance and susceptance obtained through computer analysis using realistic values of ionisation 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.

In a practical oscillator circuit, the steady-state condition for oscillation[6] is given by

$$g = -G - B^2 R_S \quad (1)$$

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

$$g = -G - G^2 R_S - B^2 R_S \quad (2)$$

In the practical case, it is good approximation to take

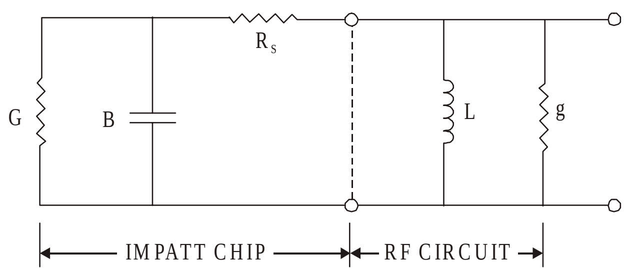

Figure 1. Equivalent model of IMPATT diode without package.

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$g = 0$ at the oscillation threshold[6].

Then the Eqn (2) reduces to

$$0 = -G_{th} - G_{th}^2 R_S - B_{th}^2 R_S$$

$$B = \frac{Z_X}{(Z_R)^2 + (Z_X)^2} \quad (3)$$

where, G_{th} is small signal threshold conductance of the diode when the conductance of the packaged diode becomes just negative. B_{th} is the small signal threshold susceptance of the diode, corresponding to the threshold conductance G_{th}.

Considering the package inductance L_P and package capacitance C_P, the equivalent circuit of the IMPATT diode with package parameter is shown in Fig. 2 and the expression of R_S is modified to

$$R_S = \frac{|G_{th}|}{\left[G_{th}^2 + (B_{th} - B_P)^2\right]} \quad (4)$$

where, $B_P = \dfrac{1}{\omega L_P - \dfrac{1}{\omega C_P}}$

= Effective susceptance caused by package parameters.

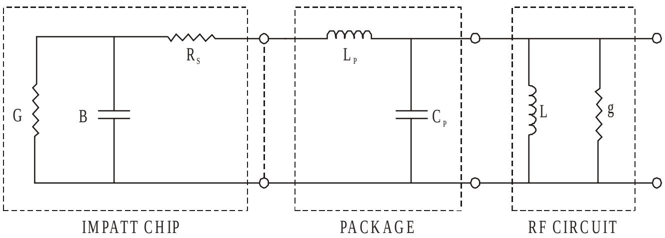

Figure 2. Equivalent model of IMPATT diode with package.

2.1 Computer Analysis

A silicon SDR (p^+nn^+ type) IMPATT diode has been designed for operation in Ka-band, through double iterative dc and small signal computer analysis. The following assumptions are made in dc and small signal computer analysis of IMPATT diodes[7,11]. (a) One dimensional model of the *p-n* junction has been considered, (b) The electron and hole velocities have been taken to be saturated and independent of the electric field throughout the space charge layer, and (c) Carrier diffusion has been neglected.

In this method the computation starts from the field maximum near the metallurgical junction. The distribution of the electric field and carrier currents in the depletion layer are obtained by the double-iterative computer method, which involves iteration over the magnitude of field maximum and its location in the depletion layer.

The method is used for a simultaneous solution of Poisson and Carrier continuity equations.

$$\frac{\partial E(x)}{\partial x} = \frac{q}{\in}\left[N_D - N_A + p(x) - n(x)\right] \quad (5)$$

$$\frac{\partial p}{\partial t} = \frac{1}{q}\frac{\partial J_P}{\partial x} + g \quad 6(a)$$

$$\frac{\partial n}{\partial t} = -\frac{1}{q}\frac{\partial J_n}{\partial x} + g \quad 6(b)$$

with the boundary condition: (i) The electric field at the two edges of the depletion layer becomes zero, i.e.,

$E(-x_1) = 0$ and $E(+x_2) = 0$ and (ii) Normalised carrier current densities at the two edges are $P(-x_1) \approx -1$ and $P(x_2) \approx +1$ where, $P(x) = (J_p - J_n) / (J_p + J_n)$.

On splitting the diode impedance $Z(x,\omega)$ obtained from Gummel-Blue method[7], into its real part $R(x,\omega)$ and imaginary part $X(x,\omega)$, two differential equations are framed[8]. Solving these 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.

$$Z_R = \int_{-x_1}^{x_2} R(x)dx \ \ \& \ \ Z_X = \int_{-x_1}^{x_2} X(x)dx$$

The diode impedance Z is given by

$$Z(\omega) = \int_{-x_1}^{x_2} Z(x,\omega)dx = Z_R + jZ_X \quad (7)$$

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

$$G = \frac{Z_R}{(Z_R)^2 + (Z_X)^2} \quad 8(a)$$

$$B = -\frac{Z_X}{(Z_R)^2 + (Z_X)^2} \quad 8(b)$$

The symbols used have their usual significance. Realistic field and temperature dependence of carrier ionisation rates and the drift velocities[9,10] at 225 °C have been taken, and the effect of mobile space charge has been considered. The device parameters taken for this present analysis are shown in Table 1. The dc current density has been varied from 9.0×10^7 A/m^2 to1.2 $\times$ 10^8 A/m^2. The *G-B* plot corresponding to maximum and minimum current densities have been shown in Fig. 3. The optimum frequency of operation for the designed diode has been observed to vary from 37 GHz–40 GHz.

Table 1. Device paramter for Ka-Band analysis

W_n (μm)	N_d (m^{-3})	Temp. (^{0}C)	Diode area (m^2)
1.4	2.7×10^{22}	225	0.155×10^{-8}

2.2 Results

For calculation of the value of series resistance R_s, a typical value of package inductance L_P = 0.080 nH, capacitance

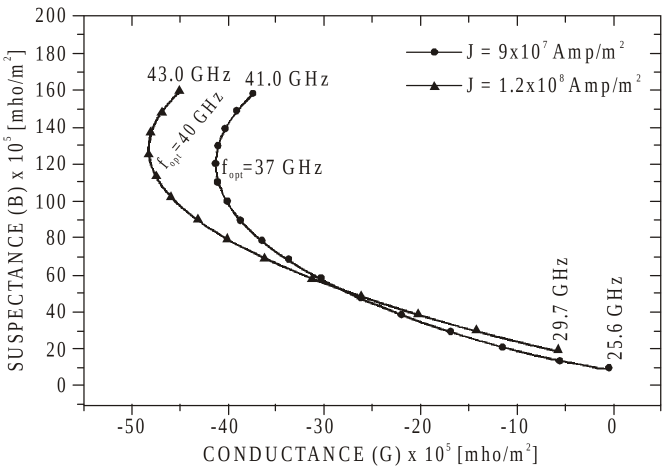

Figure 3. *G-B* plot from computer analysis.

C_P = 0.110 pF of SDR Ka Band IMPATT diode has been included in the small signal analysis. The series resistance R_s of the diode is determined from the threshold condition of oscillation of the diode, i.e., when the circuit conductance *g* and the power output from the device are assumed to be minimum. Thus the series resistance R_s of the diode can be determined from the small signal analysis at the threshold condition with good accuracy using the Eqn (4). The values of series resistance R_s obtained from computer analysis have been shown in Table 2 for various current densities.

3. SERIES RESISTANCE BASED ON EXPERIMENTAL STUDY

The value of series resistance R_S has been determined from the measurement of threshold current I_{th} and threshold frequency f_{th} from the modified Alderstein expression[5] as

$$R_s = \left(\frac{[d_n d\,(c+1) I_{th}]}{[0.74\Pi^4 (d+1)\, f_{th}^2 C_d^2]} \right) \left(\frac{f_{opt}}{f_{th}} \right) \qquad (9)$$

where, d_n is the derivative of the electron ionisation rate wrt electric field; I_{th} is the threshold current at which the oscillation just starts; f_{th} and f_{opt} are experimentally measured threshold and optimum frequency respectively; and C_d is the device capacitance.

$$c = \frac{\alpha_p}{\alpha_n} \quad \text{and} \quad d = \frac{v_p}{v_n}$$

where $\alpha_n, \alpha_p, v_n, v_p$ are the electron and hole ionisation rates and drift velocities at the maximum field point in the depletion layer, respectively.

3.1 Experiments

Experiments were carried out using silicon Ka-band SDR IMPATT diodes, embedded in a resonant-cap cavity shown in Fig. 4 and the block diagram of the measurement test set up is in Fig. 5. Measured value of various parameters, i.e., threshold current, threshold frequency, and optimum frequency at optimised condition has been plotted in Fig. 6 and a typical output power and frequency of the resonant-cap oscillator with cap dia = 4.0 mm, height = 1.40 mm, and thickness = 0.60 mm is plotted against the dc bias current flowing through the diode is shown in Fig. 7.

3.2 Results

The values of different quantities α_n, *d*, *c* for calculating series resistance R_S from Eqn (9) have been obtained from the small signal analysis. The typical values used for silicon SDR (p^+nn^+ type) at Ka-band are α_n = 0.23372, *d* = 0.97978, *c* = 0.63058, C_d =0.400 pF. The values of series resistance R_s

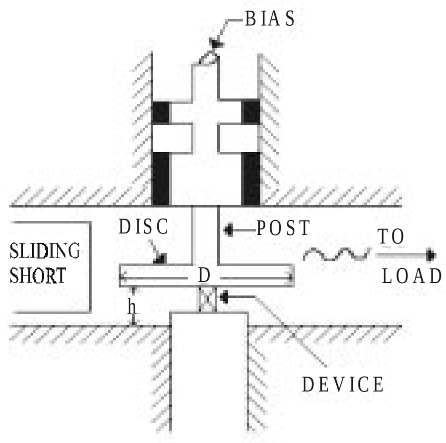

Figure 4. Schematic diagram of Ka-Band resonant cap cavity.

Table 2. Series resistance R_S from computer analysis

J (A/m2)	I_{th} (mA)	f_{th} (GHz)	f_{opt} (GHz)	G_{th} (mho)	B_{th} (mho)	B_P (mho)	R_S (ohm)
9.00×107	25.81	25.60	37.00	-5.2089×10^{-4}	1.4664×10^{-3}	-2.1323×10^{-2}	1.002
9.50×107	27.00	26.30	37.50	-5.1443×10^{-4}	1.6238×10^{-3}	-2.2229×10^{-2}	0.904
1.00×108	27.98	27.10	38.00	-6.5286×10^{-4}	2.0663×10^{-3}	-2.3309×10^{-2}	1.013
1.05×108	29.27	27.70	38.50	-6.7414×10^{-4}	2.1384×10^{-3}	-2.4153×10^{-2}	0.975
1.10×108	30.35	28.30	39.00	-7.0771×10^{-4}	2.2492×10^{-3}	-2.5028×10^{-2}	0.951
1.15×108	30.79	28.90	39.50	-7.2861×10^{-4}	2.4197×10^{-3}	-2.5937×10^{-2}	0.906
1.20×108	32.83	29.70	40.00	-8.7958×10^{-4}	2.9780×10^{-3}	-2.7204×10^{-2}	0.965

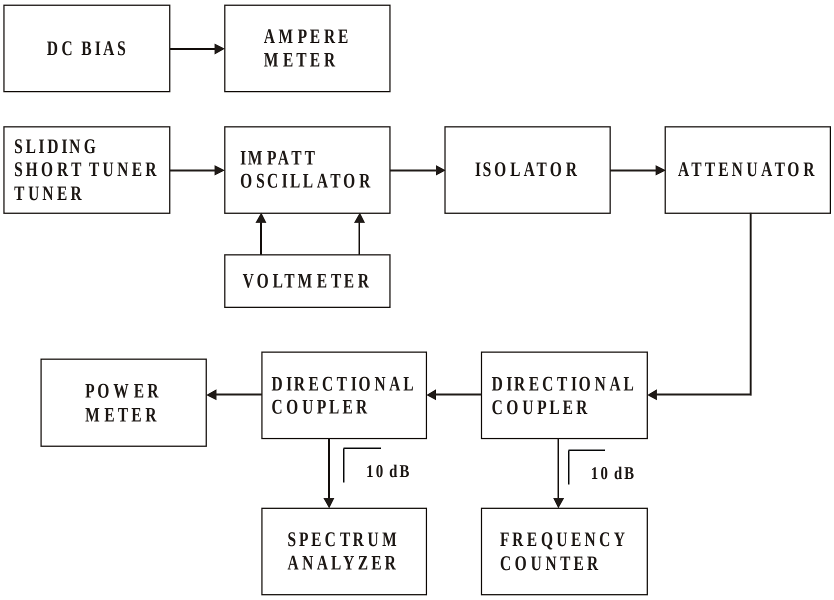

Figure 5. Block diagram of Ka-band measurement test setup.

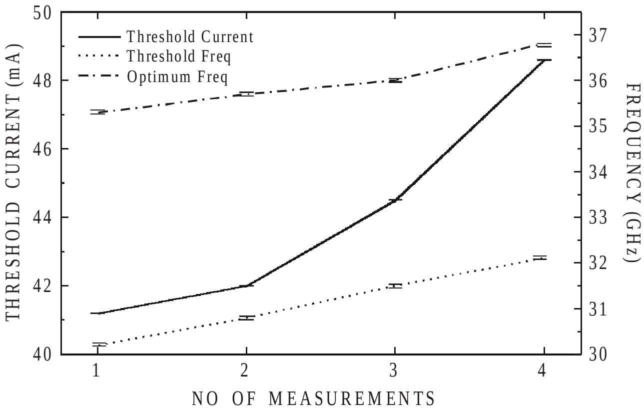

Figure 6. Measured value of various parameters, i.e., threshold current, threshold frequency, and optimum frequency at optimised condition.

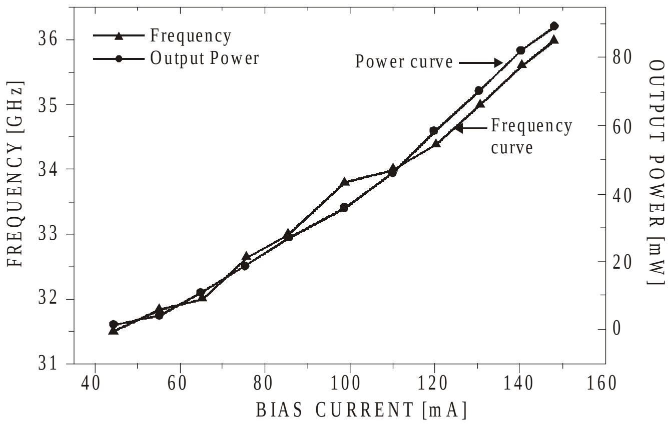

Figure 7. Dc bias current vs frequency and output power.

obtained from experimental study have been shown in Table 3 for various cap heights. The value of series resistance R_s obtained from computer analysis and experimental measurement has been plotted against the threshold frequency f_{th} , shown in Fig. 8 and it is found that the values of series resistance obtained from both the methods are in close agreement with a maximum 10.2 per cent variation.

5. CONCLUSIONS

A computer-based method for determination of the series resistance R_s of a millimeter wave Ka-band SDR IMPATT diode has been presented. 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

Table 3. Series resistance R_s from experimental study

Cap height ($h \pm \Delta h$) (mm)	Sliding short position ($l \pm \Delta l$) (mm)	Threshold current ($I_{th} \pm \Delta I$) (mA)	Threshold frequency ($f_{th} \pm \Delta f$) (GHz)	Optimum frequency ($f_{opt} \pm \Delta f$) (GHz)	Series resistance R_s (ohm)
1.00 ± 0.01	2.850 ± 0.001	41.20 ± 0.01	30.20 ± 0.01	35.30 ± 0.01	1.038
1.20 ± 0.01	5.500 ± 0.001	42.00 ± 0.01	30.80 ± 0.01	35.70 ± 0.01	1.009
1.40 ± 0.01	3.100 ± 0.001	44.50 ± 0.01	31.50 ± 0.01	36.00 ± 0.01	1.008
1.60 ± 0.01	4.720 ± 0.001	48.60 ± 0.01	32.10 ± 0.01	36.80 ± 0.01	1.067

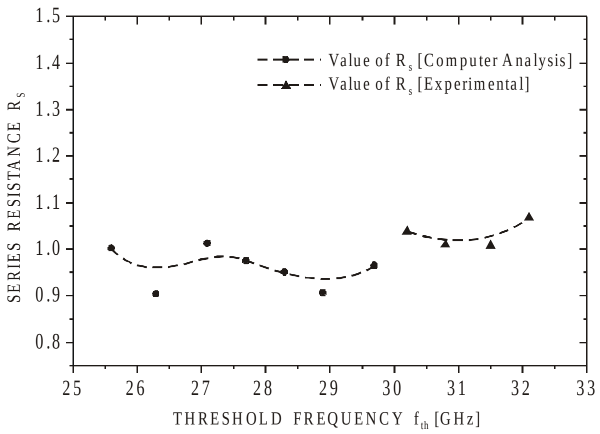

Figure 8. Threshold frequency vs series resistance R_s from computer analysis and experimental measurement.

measurement or manufacturer's data. Finally, the values of series resistance R_s obtained from computer analysis have been compared with experimentally measured value of series resistance R_s using modified Alderstein expression[5,6]. The agreement with the values calculated from the present computer-based method is found to be good. The method should also be applicable to the higher millimeter wave frequency bands, since the basic conditions chosen are the low-power, low-current oscillation threshold where small signal analysis holds good.

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