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MEASUREMENT OF ELECTRICAL SERIES RESISTANCE OF SILICON SINGLE DRIFT REGION IMPATT DIODE BASED ON THE STUDY OF THE DEVICE AND MOUNTING CIRCUIT AT THRESHOLD CONDITION

Dibyendu GHOSHAL
National Institute of Technology, Agartala Barjala, Jirania, Tripura (West), PIN- 799 055, India
dghoshal_diet@rediffmail.com

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Abstract
A study is made on the electrical series resistance of silicon flat profile SDR (n^+ - n – p^+) Impatt diode using the results obtained from computer aided study to find the device and circuit conductance and the experimental data regarding the oscillation threshold frequency and currents. The result obtained from the present analysis gives an excellent accuracy with that supplied in manufacturer's data.

Keywords: Impatt diode; electrical series resistance; silicon; mounting circuit

I. INTRODUCTION

Electrical series resistance of an Impatt diode is an important device parameter which can greatly limit microwave and millimetre wave power generation by the device. Series resistance is intrinsic by nature and it arises during doping process, due to the part of undepleted zone in the active region as a consequence of mismatch between the doping concentration and the depletion layer width [1]. It is also caused due to the defects in contact making during the lead bonding process after the chip fabrication is over. The load impedance of the microwave or millimetre wave circuit embedding the diode also contributes to the positive parasitic resistance, always adds with the negative resistance of the diode thereby degrading the r. f. power generating efficiency of the Impatt diodes. The major problem in direct measurement of series resistance arises due to the network analyser error [2] and related computational difficulties. A number of theoretical, experimental and computer modelled studies [3 – 6] have been carried out to find the series resistance of SDR and DDR Impatt diodes. Recently, a number of simulation studies have carried out [7-10] to study the series resistance of Impatt devices fabricated based on indium phosphide and some other wide band gap semiconductors like 4H-SiC and gallium nitride (GaN). However, no analytical study to find series resistance based on detailed theoretical calculation of admittances of active device and embedding passive circuit is available in published literature. Thus a detailed and separate study about the device and circuit characteristics would provide a better understanding of the initiation of oscillation process.

In the present paper, theoretical analyses are carried out to find the device and circuit admittances at the oscillation threshold condition obtained from experimental observation made by the present author and their respective values are utilised in the formula for series resistance developed by Adlerstein et al [2]. Here a silicon SDR (n^+ - n – p^+) Impatt diode and a resonant cap type embedding circuit is considered. The series resistance of the active device is evaluated for different cap diameter and height combination yielding different oscillation threshold conditions. The results for the series resistance have been found to have close similarity to the values supplied by manufacturer's data .

The resonant cap structure is schematically shown in Fig. 1 and the equivalent circuit for active device and passive load offered by the embedding cap circuit is shown in Fig. 2.

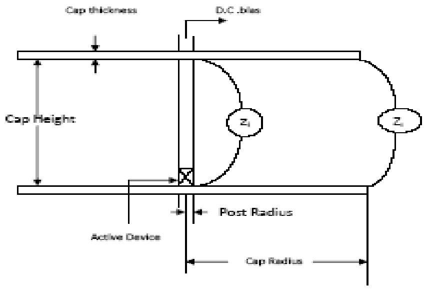

Figure 1. Oscillator Model for radial transmission line

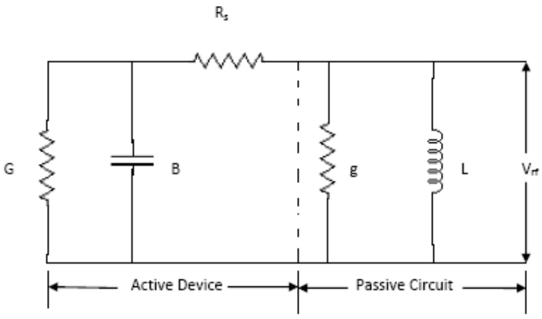

Figure 2. Equivalent circuit of Active device and Passive circuit elements in the oscillating condition of a negative resistance device oscillator

The following formula has been given by [2],

$$g = - G - B^2 R_s \qquad (1)$$

where g is the circuit conductance offered to the diode, G and B are the negative conductance and positive susceptance of the Impatt diode. Analytical models to obtain G and B yield their best possible accuracy when r.f. voltage is small and the absolute uncertainty in g is least when values of g is small. These conditions can be best satisfied experimentally at the oscillation threshold when low power and low current conditions prevails.

II. DETAILED PROCEDURE TO FIND THE SERIES RESISTANCE

II.1 Experimental procedure

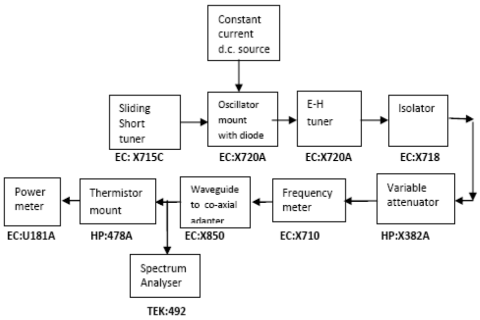

Figure 3. Experimental setup to study the properties of negative resistance device oscillator at X-band

An assortment of circular resonant cap structures having various combinations are taken and experiments are carried out (set up shown in Fig. 3) to find the oscillation frequency, and current at the threshold of oscillation and the results are shown in Table 1. The choice of cap diameter, height, diameter of the contact post and cap thickness is not arbitrary [11-12].

II.2 Theoretical analysis for circuit impedance

The performance characteristics of resonant cap oscillator may be realised from the analysis of radial transmission line [11]. The total impedance offered by the cap structure to the active diode placed at the cap centre (at $r = r_i$) is given by [11],

$Z_{iT} = -(h/2\pi r_i)\,[Z_i]$ where h is the height of the resonant cap from the bottom surface of the waveguide and ri is the radius of the contact post below the cap. Z_i is the wave impedance realised at the device plane i.e., at $r = r_i$.

The circuit impedance R_c and reactance X_c may be separated as

$R_c = -(h/2\pi r_i)\,\mathrm{Re}[Z_i]$

$X_c = -(h/2\pi r_i)\mathrm{Im}[Z_i]$.

When device circuit interaction is considered, for the initiation of the oscillation process,

$$R_c - R_d = 0 \qquad (2)$$

$$X_c + X_d = 0 \qquad (3)$$

where R_d and X_d are the negative resistance and packaged reactance of the Impatt diode, respectively, both being the function of r.f. current and frequency $X_d = -1/w\,C_d$ where C_d is parallel composition of the diode chip capacitance C_j (=0.2 pF for the present case) and the package capacitance C_p (= 0.3 pF for the present case) .

The load conductance g (vide Fig. 2) is given by,

$$g = R_c / (R_c^2 + X_c^2)\ . \qquad (4)$$

The equations (2) and (3) may not be satisfied at the same frequency. In fact equation (3) describes the initiation of oscillation where equation (2) indicates its quite stable state. Circuit parameters and circuit impedance is more dependent on frequency than the amplitude of the r.f. current passing through it whereas the device impedance depends on both frequency and r.f. current amplitude.

Thus, it is seen that equation (3) involves various parameters of the circuit structure like radius, height and thickness of the cap and radius of the contact post and frequency. The equation (3) may be solved for Z_L and its value will vary on the operating frequency. The variation of Z_L against frequency near threshold situation is shown in Fig. 4 and has been listed in Table 1.

Figure 4. Variation of Load Impedance at cap edge Vs Threshold frequency.

Table 1: Calculation of circuit conductance at oscillation threshold condition based on experimental data (Diode cross section area = 6.64 X 10^{-9} m^2).

Cap Diameter (mm)	Cap Height (mm)	I_{th}(mA)	f_{th} (GHz)	Circuit Conductance g(mho) X10^{-3}
13.220	3.819	9.10	8.011	3.16
12.710	3.438	10.40	8.546	3.26
12.192	3.048	14.41	9.096	3.47
11.605	2.604	15.12	9.721	3.62
11.128	2.250	17.35	10.221	3.70
10.668	1.905	21.11	10.706	3.84
9.815	1.234	22.12	11.651	3.86
9.200	0.778	25.72	12.295	4.06

It is seen from experimental results in Table 1 that different combinations of cap radius and height yield different threshold frequencies when the cap thickness and post diameter are kept fixed with the values 0.254 mm and 1.27 mm, respectively. It is observed from Fig. 4 that Z_L increases with the threshold frequency and the entire range of variation of the same over the X-band is found to be 30 ohms at threshold condition. Various values of Z_L and threshold frequencies are taken from the Fig. 4 and put in equations (2) and (3) and values of R_c and X_c are obtained. When R_c and X_c values thus calculated are put in equation (4) to get the value of circuit conductance g. Thus for each set of cap diameter and height combinations i.e., for different values of g are obtained and the result has been incorporated in Table 1. The values of g are found to have low magnitude which increases with increase of threshold frequency.

II.3 Theoretical analysis for device impedance:

A computer simulation study to obtain small signal conductance and susceptance for silicon single drift region ($n^+ - n - p^+$) flat profile Impatt diode is made following [13-14]. At the threshold of oscillation, the d.c. bias current density is usually low and corresponding power output is very low. For this reason, the diode junction temperature is kept at 100 C in theoretical analysis. Material parameters for silicon regarding ionisation coefficient [15] and drift velocities and mobilities of charge carriers [16] are taken from published literatures. The depletion layer width is considered to be 3.5 microns with n-type doping concentration of $6x\ 10^{21}\ m^{-3}$ and substrate doping density is $10^{26}\ m^{-3}$. The electron and hole multiplication factors are taken to be the same with a value of 10^6. The doping profile near the p^+ - n junction and n^+-n interface are assumed to have exponential and complementary error function, respectively [17]. The d.c. current density through the diode is assumed to be $7x10^6\ A/m^2$. The expression for small signal conductance G and susceptance B of the Impatt diode is given by [14],

$$G = Z_R / [(Z_R)^2+(Z_X)^2] \quad \text{and} \quad B = - Z_X/[(Z_R)^2+(Z_X)^2] \qquad (5)$$

where Z_R and Z_X are the total device resistance and reactance over the depletion layer width of the reversed biased Impatt diode . G and B are functions of r.f. voltage under steady state condition.

Various values of G and B are obtained for different threshold frequencies, keeping the current density corresponding to threshold condition of oscillation. Values of G and B for different sets of threshold current and oscillation frequency and corresponding values of series resistance are listed in Table 2.

Table 2

I_{th} (mA)	f_{th} (GHz)	Circuit Conductance g(mho)X10^{-3}	-G X 10^4 (mho/ m^2)	BX10^4 (mho/ m^2)	R_s (ohm)
9.1	8.011	3.16	47.69	26.34	1.74
10.4	8.546	3.26	49.23	26.8	1.78
14.41	9.096	3.47	52.42	27.34	1.8
15.12	9.721	3.62	54.61	27.9	1.68
17.35	10.221	3.7	55.81	28.02	1.62
21.11	10.706	3.84	57.96	28.14	1.51
22.12	11.651	3.86	58.22	28.82	1.47
25.72	12.295	4.06	61.24	29.72	1.45

III. RESULTS AND DISCUSSION

It is observed from Table 2 that values of series resistance vary from 1.74 to 1.45 Ω as the threshold frequency moves upwards from 8.01 to 12.295 GHz. It may be noted that the supplied value in the operational manual [18] of the manufacturer (Hewlett Packard: Application Note 935) for the series resistance of SDR X-band silicon Impatt diode (Model HP: 5082-0432) is 1.6 Ω. It may also be observed that the series resistance varies little over the entire X-band spanning more than 4 GHz.

IV. CONCLUSION

A theoretical analysis based experimental data as the input for determination of the electrical series resistance of a silicon SDR Impatt diode is presented. Although the present study is based on the diode embedded in a circular radial cavity, any other suitable mounting structure could be used for the same study provided the analysis of the mounting passive circuit is properly worked out. The current results indicate that the method used here may be considered suitable as the value of electrical series resistance broadly agrees to the manufacturer's data [18].

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Dedication

The author dedicates the present work to the loveliest memory of his late younger sister KUMARI SUMITA GHOSHAL who herself was a definition of beauty and wisdom.

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