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INSERTION LOSS AND ISOLATION OF P-I-N SWITCH BASED ON SiC FAMILY

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ABSTRACT

The switching characteristics, insertion loss, and isolation properties of Wide Band Gap (WBG) semiconductors cubic and hexagonal SiC based p-i-n diode at higher frequency (~50GHZ) have been presented in this paper. The p-i-n diode can be used in series and shunt both as single pole single through (SPST) switch and single pole double through (SPDT) switch or single pole malty through (SPNT) switch. The resistance of the switch is the function of frequency and it also depends on characteristics and the geometric structure of intrinsic region. Insertion loss and isolation depend on series resistance and junction capacitance respectively. At higher frequencies the switch shows low resistance, low insertion loss and better isolation. The results are compared with that obtained for switch using GaAs.

Keywords: SiC, p-i-n diode, diffusion length, stored charge, impedance, loss, isolation, RF switch and normalized resistance.

I. INTRODUCTION

p-i-n diode can be used as RF and microwave switch and detector. In microwave test systems for signal routing between instruments and devices under test p-i-n diode is very effective. This solid state switch is more reliable and exhibit a longer life time and also offer a faster switching than other microwave switches. The usages of microwave and millimeter wave systems have influenced the need of low cost, higher efficiency and high frequency solid state devices [5,7].The impedance is calculated at high frequency as well as at low frequency to determine the characteristics such as insertion loss, isolation etc [1-4].The series impedance of p-i-n diode is controlled by stored charge (Q) in the i-region under forward bias condition [1,3].Where as the series impedance and junction capacitance determine the insertion loss and isolation of the switch [2]. For optimum efficiency at low cost and to meet up the requirement, the simulation of the design is necessary prior to fabrication. The characteristics of the switch depend on material property and the material property is controlled by the carrier mobility (μ), diffusion coefficient etc.

p-i-n diodes based on low band gap semiconductors such as Si and GaAs are fabricated and studied from very beginning of the application of these devices. But at high frequency these materials are not effective compare to wide band gap semiconductors. Among the wide band gap semiconductors SiC has been emerged as one of the best promising material at low as well as high frequency region. SiC can be used as any one of its crystallographic structures - cubic or hexagonal. In any way SiC offers several advantages like high power capability (both dc and microwave) and high breakdown voltage. It can be used over a wide temperature range. SiC again shows high operating frequency with low noise. In this paper the effort has been emphasized to study on p-i-n diode using SiC family (3C-SiC, 4H-SiC, 6H- SiC) as base material.

II. THEORY

The p-i-n diode consists of an intrinsic region (i) sandwich between p^+ and n^+ (Fig.1). The p^+ and n^+ are highly doped regions where as i region is lightly doped or intrinsic. Diode can operate in two modes 'On state' and 'Off state'. In the 'On state' the diode is under forward bias and in 'Off state' it goes in the reverse bias. Under forward bias charge is injected in the i region and with increase of forward bias more charge is injected which offers the low series impedance of the diode.

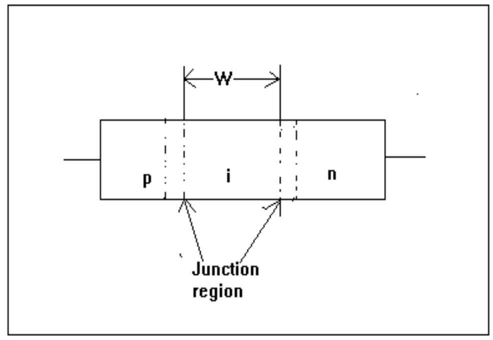

Fig.1: Basic structure of p-i-n diode

The equivalent circuit of p-i-n diode under forward bias is shown in Fig. 2a where R_s is the series impedance and L_s is the lead inductance. Under reverse bias, the developed electric field across the i region depletes mobile carriers and the diode presents high impedance. In the reverse bias this high impedance is represented by a parallel combination of resistance (R_p) and the junction capacitance (C_j) and its equivalent circuit is shown in Fig. 2b. When the p-i-n diode is subjected in the forward bias, it impedance becomes frequency dependent. This property is used for its switching action.

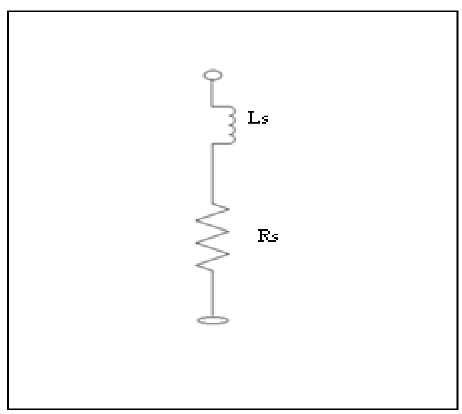

Fig.2a: Equivalent circuit at forward bias

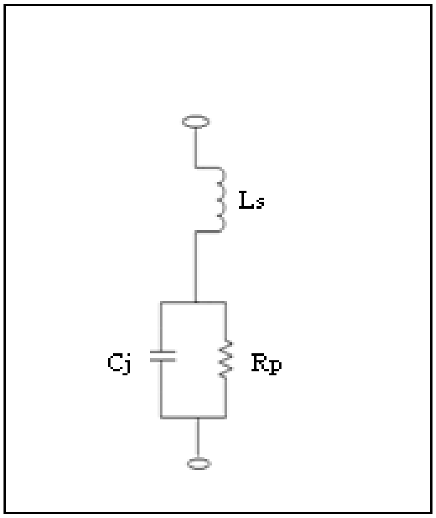

Fig.2b: Equivalent circuit at reverse bias

The existing electrical field in the p-i-n diode i.e within the intrinsic region is usually constant. The signal handling capacity of a device depends on its break down voltage and in p-i-n diode the breakdown voltage is related to the electric field as

$$V_b = E.W \quad (1)$$

In practical use the value of constant electric field can be considered as 12V/micron. The breakdown voltage of p-i-n diode depends on length (W) of intrinsic region. The different parameters of different semiconductor materials used in this paper are shown in Table I with their breakdown voltage.

At low frequency p-i-n diode shows high resistance but low resistance at high frequency and the resistance is determined by the junction resistance (R_j) and the intrinsic resistance (R_i).

TABLE I: The different parameters of different semiconductor materials

Material	Diffusion constant of Electrons, D_n $(cm^2/v-s)$	Diffusion constant of Holes(D_p) $(cm^2/v-s)$	Length of i region, W (μm)	Breakdown voltage, V_b (V)
GaAs	220	10.4	1.35	16.2
3C-SiC	20	8	1.54	18.48
4H-SiC	22	3	2.1	25.2
6H-SiC	90	2	1.81	21.72

Considering both junctions symmetric, the resistance of the switch is

$$R_T = R_i + 2R_j \quad (2)$$

The intrinsic resistance of p-i-n diode depends on length (W) of the i region and the carrier diffusion length (L) in this region and also on forward bias current (I_0) and R_i is expressed as [1, 6, 8]

$$R_i = \left(\frac{kT}{qI_0}\right)\left(\frac{W}{L}\right)\tanh\left(\frac{W}{2L}\right) \quad (3)$$

Diffusion length in the i-region is estimated by the carrier life time (τ) and the effective diffusion constant (D_{eff})

$$L = \sqrt{D_{eff}\tau} \quad (4)$$

The effective diffusion constant (D_{eff}) in the i region is determined by diffusion coefficients of hole (D_p) and electron (D_n) and written as [2].

$$D_{eff} = \sqrt{\frac{2D_pD_n}{D_p + D_n}} \quad . \qquad (5)$$

At forward bias condition the stored charge ($Q=I_0\tau$) depends on carrier life time (τ) and forward bias current (I_0). The junction resistance (R_j) varies with frequency and as a function of frequency it can be expressed [1, 6]

$$R_j\ f = \left(\frac{kT}{qI_0}\right)\beta \tanh \frac{W}{2L}\ \cos\ \phi-\theta/2 \ ....(6)$$

The normalized resistance can be written as

$$\frac{R_T}{R_i} = 1 + \frac{2R_j(f)}{R_i} \ \ldots\ldots\ldots\ldots\ldots\ldots\ \ldots\ (7)$$

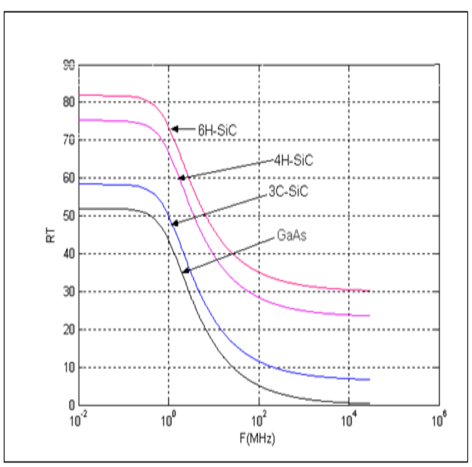

Fig.3: Total resistance p-i-n diode at 1mA forward current.

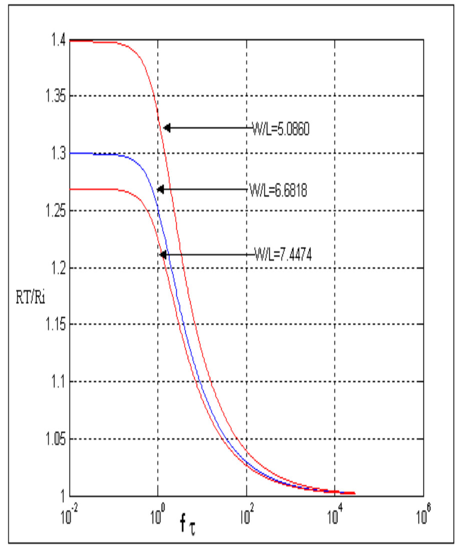

Fig.4: The normalized resistance of 6H-SiC p-i-n diode with frequency-lifetime product (fτ).

The insertion loss and isolation of an RF or microwave switch are interdependent and these are important determining characteristics of a switch. The switch may be used in series or shunt or series-shunt connection. For series and shunt connection the insertion loss (IL) and isolation (ISO) are determined by series resistance and junction capacitance of the switch [2] and they are expressed as

$$IL(Series) = 20\log_{10}[1 + \frac{R_T}{2Z_0}] \qquad (8)$$

$$IL(Shunt) = 10\log_{10}[1 + (\frac{Z_0}{2X_C})^2] \qquad (9)$$

$$ISO(Series) = 10\log_{10}[1 + (\frac{X_C}{2Z_0})^2] \qquad (10)$$

$$ISO(Shunt) = 10\log_{10}[1 + (\frac{Z_0}{2R_T})]. \qquad (11)$$

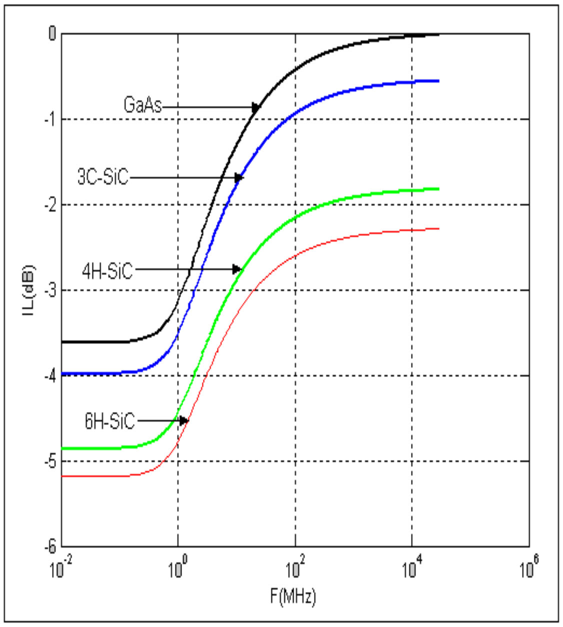

Fig.5: Insertion loss of p-i-n diode at 1mA forward current for series connection.

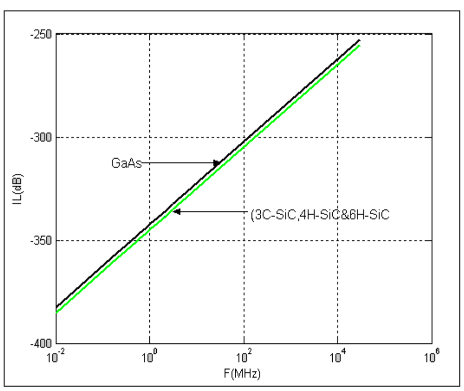

Fig.6: Insertion loss of p-i-n diode at 1mA forward current for shunt connection

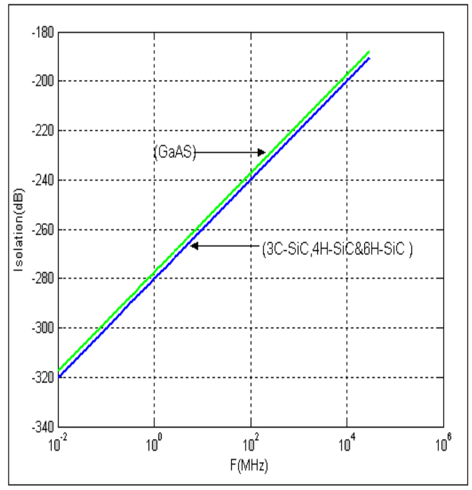

Fig.7: Isolation of p-i-n diode at 1mA forward current for series connection

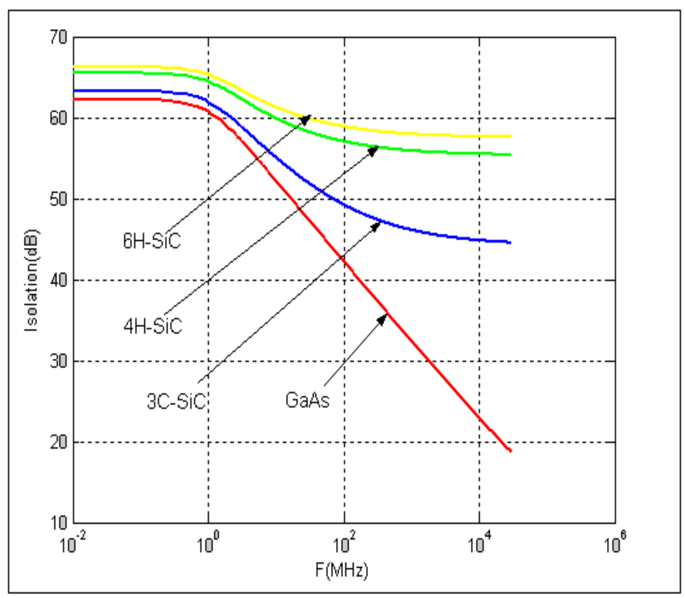

Fig.8: Isolation of p-i-n diode at 1mA forward current for shunt connection.

III. RESULT AND ANALYSIS

Using equations (2)-(7) the resistance of p-i-n switch has been estimated at 1 mA forward bias current. The nature of resistance of p-i-n diode at higher frequencies has been analyzed with W=0.12mils and Q=8.4C (Figs.3, 4).

Among the different materials used in the analysis, it has been reveled that 6H-SiC is wider band gap material and offers better applications at higher frequencies [9-11]. Thus the normalized resistance of p-i-n diode has been calculated using 6H-SiC as based material for different aspect ratio $\left(W/L\right)$ and is plotted as a function of $f\tau$ (Fig.4).

It is revealed that irrespective of base material p-i-n switch can offer better switching action. In 6H-SiC the off resistance is higher than 3C-SiC, 4H-SiC and GaAs. The insertion loss of 6H-SiC is also less compare to other material (Figs.5&6) which enables it more suitable for application at higher frequencies (~50 GHz or more). The normalized resistance of switch shows that W/L ratio has an important roll to control the characteristics. This is also implicated from eqn. (6). With the increase of diffusion length the intrinsic resistance becomes low but the transition of switch is not sharp compare to higher value of (W/L). Isolation increases with frequency irrespective of material property. But it is better for 6H-SiC (Figs.7&8). In shunt connection insertion loss increases sharply with frequency but in series initially insertion loss remains constant then increase with frequency but at higher frequency it again reaches a constant value and also for 6H-SiC the insertion loss is lower.

IV. CONCLUSION

The intrinsic region length and diffusion length play the crucial role in controlling the electrical characteristics of p-i-n switch. In series connected switch the insertion loss depends on material properties where as shunt connection the isolation of switch depends on material properties. In the analysis 6H-SiC has higher 'On resistance' and it offers low insertion loss and better isolation in shunt which goes to saturation at higher frequency.

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