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Aspects of WBG 4H-Sic Over Si IMPATT Diode at X Band

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Abstract: *The microwave properties of Wide Band Gap (WBG) 4H-SiC single drift region ($n^{++}np^{++}$) IMPATT diode have been studied over well studied and established Si diode counterpart at an experimental current of 25 mA at 300K and at X band [1]. The results on the electric field characteristics, negative resistivity profiles in the depletion region and the frequency dependence of conductance vssusceptance profiles indicate a sharp improvementof 4H-SiC as a core element in impatt diode fabrication. The SiC material significantly yields higher breakdown field, dc to ac conversion efficiency, negative conductance and good frequency selectivity property at X band.*
Keywords*: IMPATT diode, 4H-SiC, WBG, X band.*

I. Introduction

The challenges in the impatt technology are to develop high microwave power with minimum heat dissipation in the device. Where, WBG materials have immerged as significant sources of ac power both in GHz and THz bands [2-3 .The availability of 4H-SiC poly types in bulk wafer form [4] has helped SiC as mature WBG semiconductor. Scientists have been showing significant interest in developing solid state sources as a high-power source. However, this is unapproachable by conventional Silicon and GaAs based materials. WBG semiconductors offer alternative to traditional Si and GaAs with a higher output power resulting from increased critical field, higher band gap energy, higher saturation velocity and much better thermal conductivity [5].A higher value of breakdown field(E_c) resultsin high breakdown voltage, which enhances the output-power level of the devices. On the other way diode with higher doping and at low current density would result higher electric field at junction with a reduction in the drift region. Thus not only the high power but also the high frequency operation capability is expected from these WBG impatts.

First experimental studies on WBG SiC material have been done by Yuan et al [2]. The breakdown field distribution and the negative resistance properties in the depletion zone give a clear insight regarding the suitability of a material as mm wave power source [6]. Normally the p-n junction generates the maximum negative resistance in the depletion zone. The depletion layer indicates the undepleted region which may yield parasitic series resistance, and the punch through condition of the field may also shift the operating frequency of the diode [7].It is known that the doping profile and the bias current density determine the nature of electric field under avalanche breakdown condition, indicating its punched through, exact type andundepleted epitaxial layer.

To ensure that the parasitic resistances to be small, the doping and the current density is normally such chosen that the depletion layer sweeps into the entire whole p-n junction region. By increasing the doping level one may expect to use higher current level without causing space charge effect. But in this case the limitation would be the thermal heat dissipation due to the series resistance in the undepleted layer. Therefore, optimum CW performance would be obtained at low current level.The power loss due to unsweptepitaxy can be reduced in punched through structures. At large RF voltage the diode may fall below punch through for some part of the RF cycle. The degree of punch through depends on the doping density at lower bias current. The over punched through diode results lower value of negative conductance [7].At present, pulsed impatt diodes are being used as devices for mm wave radar for delivery of high pulsed power and in these cases punch through is observed due to lower active region thickness and higher dc current.

This paper reports a study on4H-SiCimpatts properties, compared with those of wel studied Si based impatt diodes, which are designed to operate under the same width, doping density and bias current density.But in most of the published works [8] comparison on WBG materials have been studied under different doping density, width and current densities to optimize the diode structures at the required frequency band.

II. Simulation Technique

Single-drift-region (SDR) $n^{++}np^{++}$diodes have designed through a generalized double-iterative simulation scheme used for analysis of IMPATT action [9]. In this dc method, the computation starts from the field maximum near the metallurgical $p^{++}n$ junction. The distribution of dc electric field in the depletion layer is obtained by a double iterative simulation method, which involves iteration over the magnitude of field maximum (E_m) and its location in the depletion layer.

The field dependent carrier ionization coefficients of 4H-SiC, as well as the mobility and saturated drift velocities of carriers in 4H-SiC [10] have been used in the computation for the profiles of electric field and carrier currents. The effect of mobile space charge in the depletion region of the diode has also been taken into account.The small signal simulation technique is also found to be quite satisfactory for WBG material devices [11-13].

The leakage current multiplication for electron (Mn) and hole (Mp) has been considered to be 10^3 due to optically generated carriers, which is greater than the ideal high value (10^6) [3]. Because the effect of shining light from the junction side in a top-mounted $p^{++}nn^{++}$ IMPATT dominates the photocurrents. The expression for the electron current multiplication factor then changes as

$$Mn = \frac{Jo}{[Jns(th) + Jns(opt)]}$$

Table 1: The material parameters for 4H-SiC and Si [10].

Material	Band Gap energy Eg(eV)	Critical Electric field $E_c x10^7$ V.m^{-1}	Electron saturation velocity $v_{sn} x10^5$ m.s^{-1}	Thermal Conductivity K (W.m^{-1}.k^{-1})	Dielectric Constant ε_r
Si	1.12	3.0	1.0	150	11.9
4H-SiC	3.26	35.0	2.0	500	10.1

III. Results and discussions

It is evident from Fig. 1, that the maximum value of electric field (E_m) is significantly higher for the 4H-SiC impatt $n^{++}np^{++}$ diode both in the drift region and $p^{++}n$ junction.On the other hand Si diode yields lower value of field and some undepleted region. The field profile also indicates the punched through of SiC diode. As a result, drift region voltage (V_D), avalanche region voltage (V_A) and the total breakdown voltage (V_B) is higher for SiC. The normalized voltage drop (V_D/V_B) in the drift region is higher for SiC (70%) compared to Si (57.8%). The increased value of V_D/V_B provides higher efficiency 22.4% in SiC. The Si diode counterpart results some amount of undepleted region that may cause sufficient series resistance and heat loss in the active part of the device. The diode structure for Si is optimized for 12 GHz operation but the same for SiC diode has not been optimized in this analysis to compare under same diode structure of Si one. The electric field distribution for SiC is highly punched through at $n^{++}n$ interface on the otherhand Si diode results some undepleted region at the $n^{++}n$ side operating under the same condition. The DC and small signal results have been indicated in table 2. In spite of punched through condition, the efficiency of SiCincreased.

Table 2: The DC and small signal properties of 4H-SiC and Si IMPATT diodes at X band.

Material	DC properties				Small signal properties		
	V_A V	V_D V	V_B V%	η	G_p 10^5 S.m^{-2}	B_p 10^5 S.m^{-2}	f_p GHz
Si	45.0	62.5	108.0	18.5	-1.16	26.74	13.0
4H-SiC	44.3	106.0	150.0	22.4	-2.46	14.59	8.0

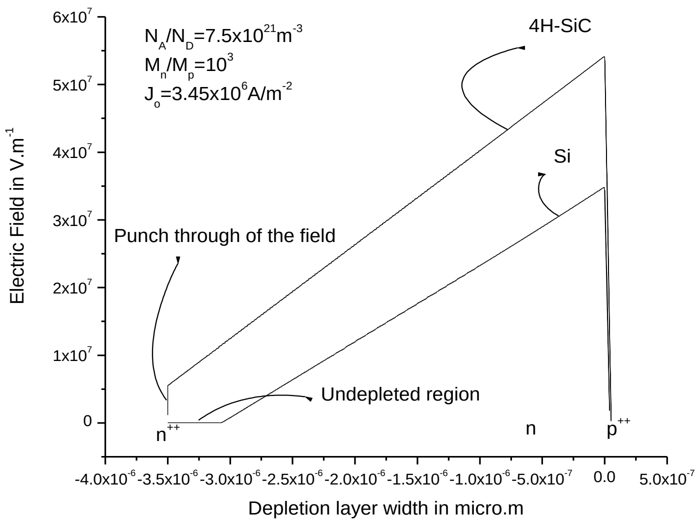

Fig.1 Electric field profiles in the depletion layer of 4H-SIC and Si IMPATT diodes at X band.

The negative conductance and susceptance (G-B) plots shown in Fig. 2 indicates the significant difference between SiC and Si. Both the material is suitable for operation in the X band where, the SiC yield higher value of G and the corresponding optimum frequency (fp) is 8 GHz and the same is 13 GHz for Si. The variation of G with frequency is less in Si compared to SiC.In punched through case, as these structures present an active layer thickness larger than the optimum one, they will naturally operate in the lower frequency zone than the design frequency. This suggests that the selective operation (i.e. operation of the diode at optimum frequency such as at 8GHz) of 4H-SiC would be more suitable than Si one.

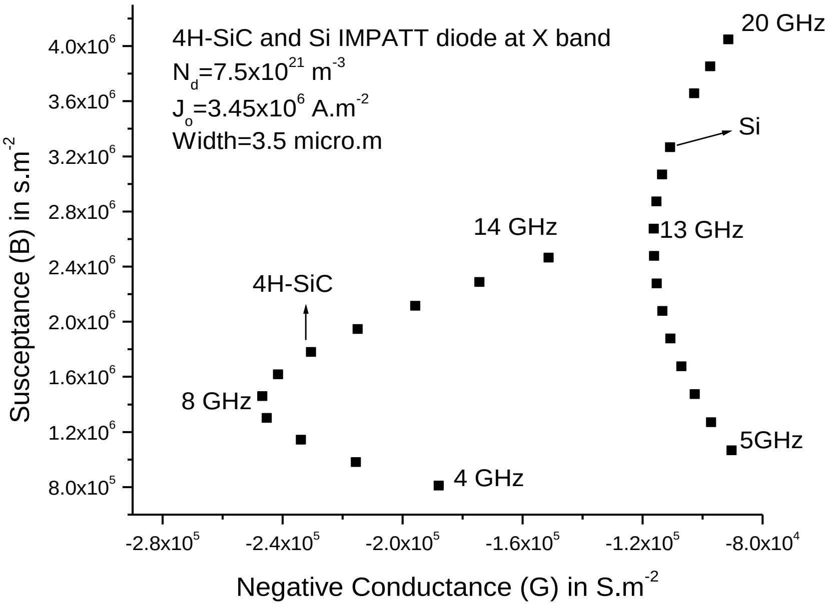

Fig. 2 Admittance Characteristics of 4H-SiC and Si IMPATT diode at X band.

The negative resistance profile in the depletion region is a good indicator on the contribution of microwave power generation from the IMPATT diodes. The negative resistivity profile shown in Fig.3 also clearly indicate that at optimum frequency SiC diode yield negative resistance contribution over the whole depletion layer. On the other way, Si diode yield positive resistance in some portion of the drift zone. Both the diode yields maximum negative resistance at the $p^{++}n$ junction.

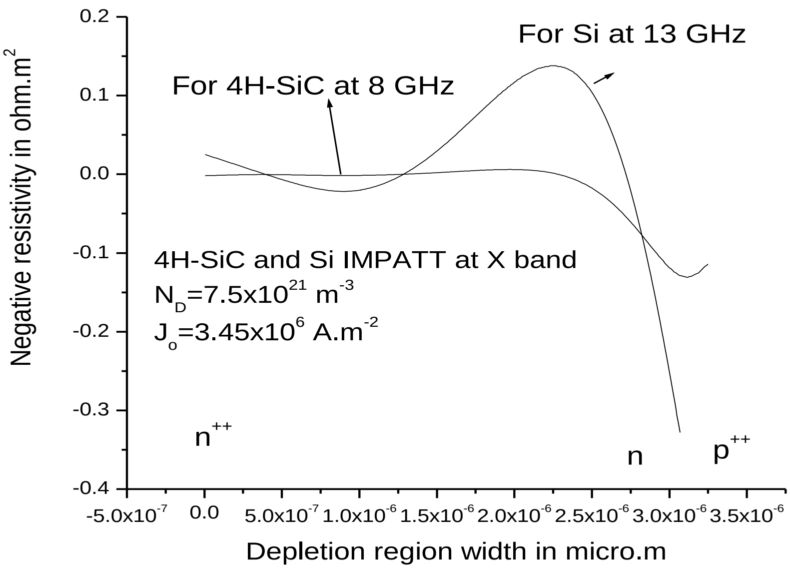

Fig. 3 Negative resistivity profiles in the depletion layer of 4H-SiC and Si IMPATT diodes at X band.

IV. Conclusions

The relevance of WBG 4H-SiC high power IMPATT oscillator over Si has been studied under the same design parameters. The study indicates that SiC is a good material for impatt fabrication in respect of CW and pulsed power yielding high breakdown field profile without showing any undepleted layer that may result heat dissipation. The study also provides a quantitative idea regarding the extent of optimum frequency shift in 4H-SiC arising from the punch through effect. Thus, the present study on SiC significantly challenges good improvement over the studies on Si impatts. The SiC will also be suitable for pulsed mode operation in the mm wave communication system, due to frequency chirp in the punch through condition of the diode.

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