IOSR Journal of Electronics and Communication Engineering (IOSR-JECE)
e-ISSN: 2278-2834,p- ISSN: 2278-8735.Volume 9, Issue 4, Ver. I (Jul - Aug. 2014), PP 46-49
www.iosrjournals.org

Optically induced series resistance and microwave properties of $n^{++}np^{++}$ X band Si IMPATT diode

P. De
Department of Physics, Gobardanga Hindu College, Affiliated to West Bengal State University,
P.O. Khantura, 24 PGS(N), W.B, Pin-743273, India

Abstract: *The effect of optically generated reverse saturation current on the series resistance and negative resistance properties of single drift region ($n^{++}np^{++}$) X band Si IMPATT diodes under (i) punch through, (ii) exact and (iii) undepleted field distributions have been studied. Simulation following Gummel-Blue approach [1] indicates an overall degradation of microwave properties with an increase of series resistance due to enhancement of illuminated leakage current.*
Keywords: *IMPATT diode, Series Resistance, Punch Through*

I. Introduction

After the experimental works of Yen et al [2] in 1977, Forrest et al [3] in 1978, Neece et al [4] in 1985 and Herczfeld et al [5] in 1986, the possibilities of controlling microwave properties using optical radiation have attracted research Scientists. Mazumder et al [6] in 1989, Banerjee et al [7] in 1994 and Dash et al in 2002 [8] theoretically studied the changes in microwave negative resistance properties by the incorporation of optical illumination for theoretically designed lhl & DDR high frequency diodes neglecting the significance of breakdown field characteristics of IMPATT diodes. The electric field distribution in the depletion layer is very important for optimization of the diode [9,10]. Because, the field profile controls mainly, (i) ionization rates (ii) breakdown voltage (iii) leakage current and (iv) series resistance of the diode. But investigations on the effect of optically induced reverse saturation currents on the different doping densities of IMPATTs creating specially the significant punch through, exact type and undepleted epitaxial layer are scarcely available. This prompted the author to investigate the changes in the value of crucial series resistance in cases of IMPATTs, operating under different electric field distribution conditions (as shown in Fig. 1) in the depletion layer, specially for punch through and the undepleted conditions.
The current multiplication factors for electron (M_n) and hole (M_p) under thermal and optical illumination are given by

$$M_n = \frac{J_o}{(J_{ns})_{th} + (J_{ns})_{opt}} \quad \text{and} \quad M_p = \frac{J_o}{(J_{ps})_{th} + (J_{ps})_{opt}}$$

where, $(J_{ns})_{opt}$ and $(J_{ps})_{opt}$ are the leakage current densities due to photo-generated electrons and holes respectively, which depend on the incident optical power [7,11] and J_o is the dc bias current density.

In case of un-illuminated diode, thermally generated leakage current $(J_{ns})_{th}$ is very small, which negligibly perturb the microwave properties of IMPATTs [11]. In this letter, increase of optically generated electron leakage current $(J_{ns})_{opt}$ is manifested as the lowering of electron multiplication factor (M_n) from 10^6 to 25. Also, the n^{++} side of $n^{++}np^{++}$ structure has been illuminated, because in Si, electron ionization rate is greater than hole ionization rate. The present study is completely based on the depletion layer characteristics of the semiconductor junction and relies on available data [12], taking any drastic assumption as followed by Mitra et al [12].

The static properties of the diode have been obtained following the method of Datta et al [13]. With the static parameters as input, the spatial variation of the diode negative resistivity and the reactivity in the depletion layer have been obtained solving the device equations, described elsewhere [1,11,14,15,16]. The series resistance has been calculated following the relation of Adlerstein et al [17].

II. Results And Discussions

The diode with appropriate field distribution in the depletion region (doping = 7.01×10^{21} m^{-3}, shown in Fig. 1) operates exactly in the X band with center frequency (f_c) at 13 GHz as shown in Fig. 2. It also yields maximum negative conductance under un-illuminated condition (for which $M_n=10^6$). But the values of conductance decrease drastically with high illumination condition (for which $M_n=25$), with an upward shift in the operating frequency to 15 GHz.

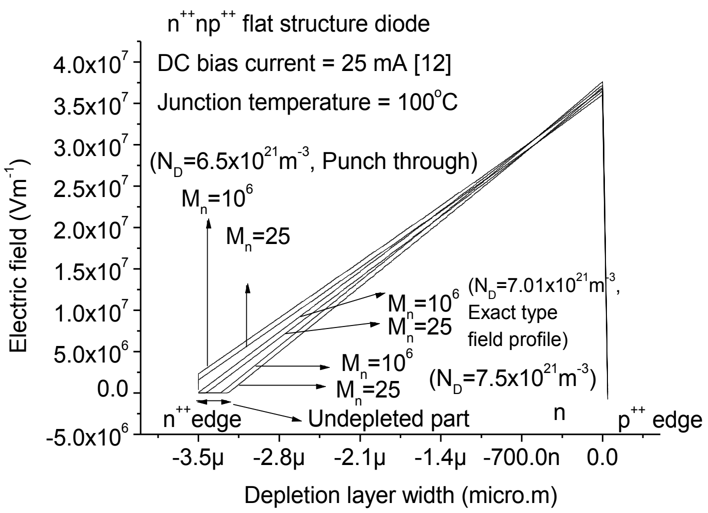

Figure 1 Electric field distributions in the depletion layer of $n^{++}np^{++}$ flat structure X band IMPATT diodes under different doping levels and multiplication factors.

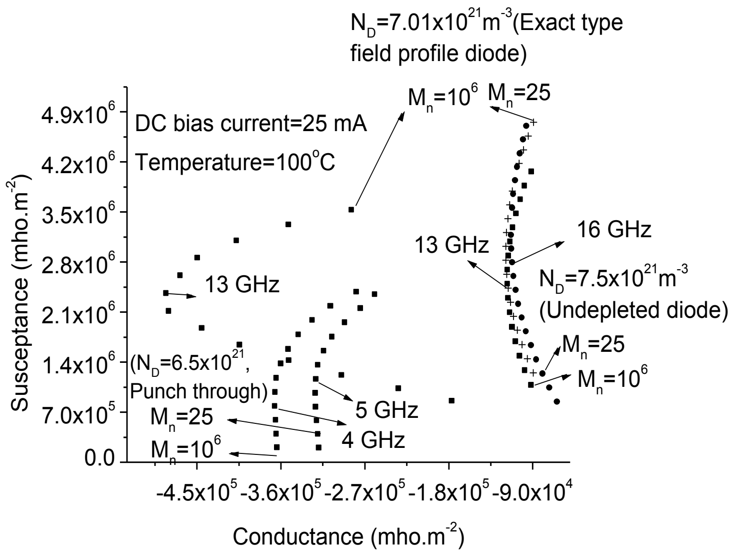

Figure 2 Admittance characteristics of $n^{++}np^{++}$ Si flat structure X band IMPATT diodes under different doping levels and multiplication factors.

Fig. 2, indicates that the effect of leakage current on the change of negative conductance(G) is negligible for the diodes having undepleted region. Also, the value of negative conductance is small with higher center frequency, deviating from the X band. But, the upward shift in the center frequency is comparatively more and is from 13 to 16 GHz, as the multiplication factor decreases from 10^6 to 25 with the increase of illumination.

Fig. 2, indicates that the values of center frequency decreases from the X band (4 & 5 GHz) for punch through diode with lower value of optimum negative conductance compared to the diode with exact type, operating even under dark condition. The conductance-susceptance (G-B) characteristics with higher leakage currents (for M_n=25) for all doping levels indicate wider tuning range around the center frequency, for which the variation of G with frequency is small.

The negative resistivity profiles shown in Fig. 3, simulated at the corresponding center frequencies (given in Table 1) of the diodes under study, indicate the contribution of microwave power from different portions of the depletion region. In which the punch through diode yields maximum negative resistance (R) contribution (profile a1, b1). The value of negative resistance decreases with the increase of leakage currents (for M_n=25) for all types of diodes under study (profile b1, b2 & b3). It is also clear that the undepleted diode results very smaller negative resistance even under very low leakage current. The diode with exact field profile yields higher appreciable negative resistance in the drift region under low leakage current ($M_n=10^6$) within the X band (profile a2). But the same for exact diode decreases drastically with the increase of leakage current (profile b2).

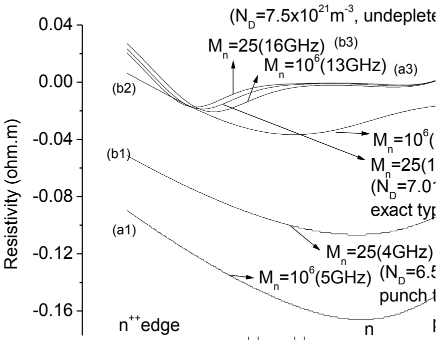

Figure 3 Negative resistivity profiles in the depletion region of $n^{++}np^{++}$ flat structure X band IMPATT diodes under different doping levels and multiplication factors.

The measured values of series resistance (R_s) at the center frequencies are given in Table 1. The values of R_s increases for both punch through and undepleted diodes compared to its exact type counterpart as per expectation. The value of R_s satisfies device data [12] for only exact type of diode (doping=7.01×10^{21} m^{-3}), which is 0.801 Ω at 13 GHz for un-illumination. For each doping level the value of R_s increases with the increase of leakage current within the realistic limit of 2 Ω for X band diode [12]. In all cases the values of negative resistance (R, given in Table 1) is less than the series resistance that is the required condition for sustained oscillation.

Table 1 Microwave properties of $n^{++}np^{++}$ X band Si IMPATT diodes under different optical illuminations i.e on different values of electron multiplication factors (M_n).

Doping level (10^{21} m^{-3})	M_n	(-R) Ω	(-G) 10^4 $\Omega^{-1}m^{-2}$	B $10^5\Omega^{-1}m^{-2}$	R_s Ω	f_c GHz
6.5(Punch through)	(i)10^6	29.6	36.53	7.71	1.24	4
	(ii)25	28.5	32.21	9.53	1.69	5
7.01(Exact type)	(i)10^6	11.55	48.21	23..49	0.801	13
	(ii)25	1.79	11.89	30.19	1.19	15
7.5(Undepleted)	(i)10^6	2.23	11.61	26.76	1.27	13
	(ii)	1.54	11.22	31.62	1.45	16

The effect of optical illumination is significantly remarkable in case of diodes having punch through and exact field distribution. In respect of negative resistance, negative conductance, series resistance and operating frequency, the present analysis also confirms that for optimization, the doping density for a $n^{++}np^{++}$ diode should be so that the field profile is approximately punch through at breakdown.

Acknowledgement

The author acknowledges University Grants Commission, ERO, India, for Minor Research Project and financial support.

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