Numerical Evaluation of Junction Temperature Effect on Negative Resistivity at Different Current Densities of Si DDR IMPATT Device at Sub-millimeterwave Region

Arpan Deyasi, Swapan Bhattacharyya

Abstract— **Negative resistivity profile for Si DDR IMPATT device is numerically computed by double-iterative method with incorporation of modified Runge-Kutta method at different junction temperatures and bias current densities for different operating frequency bands in sub-millimeterwave region. Profiles are obtained throughout the depletion layer width for 1-D model consideration and assuming independence of carrier velocities over electric field in avalanche and drift regions; whereas both conduction and displacement current densities are taken into account. Analysis is helpful for comparative study of device performance with different heat sink materials.**

Index Terms— **Current density, Junction temperature, Negative resistance, Small-signal analysis.**

I. Introduction

The generation of microwave power at sub-millimeterwave region is a major problem in microwave electronics, and design of efficient transit-time devices based on different semiconductor materials has now become a field of research in the last decade. IMPATT diode is now one of the premier solid state sources of r.f power compared to other transit-time devices at millimeter and sub-millimeterwave frequency regions. It provides a lot of advantages due to its smaller size, higher accuracy, lighter weight and lower cost, and an improved propagation characteristic at window frequencies. It can effectively be used in RADAR systems and guided missiles, as gigahertz and terahertz domain is now enriched with the immense application possibilities in the fields of Remote Sensing, Imaging and Spectroscopy.

Generation of microwave oscillation is possible due to negative resistance characteristics of the device, as proposed first by Read [1] which can be obtained on the basis of the phase difference being produced between r.f voltage and r.f current due to delay in the avalanche build-up process and the transit time of charge carriers. Works are carried out by several researchers to analyze the negative resistance [2]-[4], and later this work is extended in terahertz regime due to need of the day [5]-[10]. Several different materials are also tried to improve the conversion efficiency and device negative resistance by optimizing bias current density [5], [7]-[12] for DDR structure, but till now, Si is the first choice due to its availability of other important features for fabrication of DDR IMPATT device, and researchers are engaged into exploring its applicability in higher frequency region [13]. Effect of elevated junction temperature plays a big role for analysis of device performance [14]-[16] by calculating high-frequency integrated parameters where mobile space-charge effect is also considered [8] along with contributions of drift and diffusion [17] for near accurate performance evaluation.

In the present paper, double iterative method involving simultaneous solution of Poisson's equation with continuity equation satisfying appropriate boundary conditions is used for simulation of negative resistivity profile of DDR IMPATT structures considering the effect of both drift and diffusion currents, and modified Runge-Kutta method is incorporated for analyzing the effect of elevated junction temperature at optimized bias current densities at different operating frequency regions. Mobile space charge effect is also incorporated with the consideration of 1-D model where saturated carrier velocities are assumed to be independent of electric field throughout the space-charge layer. Si is considered as the material for simulation purpose, but the technique may be adopted for different materials also.

II. Procedure for Paper Submission

Small signal analysis of an IMPATT diode provides insight into the microwave performance of the device. If the ac field in the depletion region is very small compared to the dc breakdown field, the variation of ionization rate with electronic field can be assumed as linear and small-signal solution of the fundamental equations namely, time-varying Poisson equation and continuity equation can be carried out by linearization, which represents the low amplitude limit of large-signal analysis. The present paper contains the method based on Gummel-Blue [18] approach to study the distribution of negative resistivity.

The fundamental equation that governs the avalanche multiplication and the carrier current flow across p-n junction

Manuscript received November 29, 2011.

Arpan Deyasi, Department of Electronics & Communication Engineering, RCC Institute of Information Technology, Kolkata, INDIA, (e-mail: deyasi_arpan@yahoo.co.in).

Swapan Bhattacharyya, Department of Computer Science & Engineering, Asansol Engineering College, Asansol, INDIA, (e-mail: swapanbhattacharyya@ieee.org).

is the well-known Poisson's equation-

$$\frac{\partial}{\partial x}E(x)=\frac{q}{\varepsilon}[N_D-N_A+\rho(x)] \qquad (1)$$

where ρ(x) is the net density of mobile charge carriers. Continuity equations for electron current is given by

$$\frac{\partial n}{\partial t}=\frac{1}{q}\frac{\partial J_n}{\partial x}+g-U_n \qquad (2)$$

Considering the diffusion current as a perturbation term over the major drift current in the avalanche region, the expressions for hole and electron concentration in the space charge layer can be written as using perturbation technique,-

$$n(x)=\left(\frac{J_n}{qv_n}\right)-\left(\frac{D_n}{qv_n^2}\right)\left(\frac{\partial J_n}{\partial x}\right)+\left(\frac{D_n^2}{qv_n^3}\right)\left(\frac{\partial^2 J_n}{\partial x^2}\right)-\left(\frac{D_n^3}{qv_n^4}\right)\left(\frac{\partial^3 J_n}{\partial x^3}\right)+.. \qquad (3.1)$$

$$p(x)=\left(\frac{J_p}{qv_p}\right)-\left(\frac{D_p}{qv_p^2}\right)\left(\frac{\partial J_p}{\partial x}\right)+\left(\frac{D_p^2}{qv_p^3}\right)\left(\frac{\partial^2 J_p}{\partial x^2}\right)-\left(\frac{D_{pn}^3}{qv_p^4}\right)\left(\frac{\partial^3 J_p}{\partial x^3}\right)+.. \qquad (3.2)$$

Hence the mobile space charge density due to both drift and diffusion component is obtained fro the equation-

$$\rho(x)=\left[\left(\frac{J_p}{v_p}\right)-\left(\frac{J_n}{v_n}\right)+\left\{\left(\frac{D_p}{v_p^2}\right)\left(\frac{\partial J_p}{\partial x}\right)+\left(\frac{D_n}{v_n^2}\right)\left(\frac{\partial J_n}{\partial x}\right)\right\}+\left\{\left(\frac{D_p^2}{v_p^3}\right)\left(\frac{\partial^2 J_p}{\partial x^2}\right)-\left(\frac{D_n^2}{v_n^3}\right)\left(\frac{\partial^2 J_n}{\partial x^2}\right)\right\}+\left\{\left(\frac{D_p^3}{v_p^4}\right)\left(\frac{\partial^3 J_p}{\partial x^3}\right)+\left(\frac{D_n^3}{v_n^4}\right)\left(\frac{\partial^3 J_n}{\partial x^3}\right)\right\}+..\right] \qquad (4)$$

Computation starts from the position of field maximum (x_0) near metallurgical junction and then proceeds towards edges of depletion layer. Double iterations are then carried out over field magnitude (E_0) and position of field maximum (x_0) in depletion region to satisfy boundary conditions for field and current densities. Simultaneous satisfaction of boundary conditions at depletion layer edges gives appropriate solution and d.c field and current profiles are obtained.

Extension of avalanche zone has been defined as the distance between two points (x_1, x_2) on either side of avalanche center. Once the values of maximum electric field(E_m) and it's position (x_0) for which both the boundary conditions are simultaneously satisfied are computed at a given current density, this computer program provides more accurate profiles of electric field and carrier current.

From the DC-field and current profiles, the spatially dependent ionization rates that appear in the Gummel-Blue equations are evaluated, and fed as input data for the small-signal analysis. The edges of the depletion layer of the diode, which are fixed by the dc analysis, are taken as the starting and end points for the small-signal analysis.

Assuming 1-D model and carrier velocities are independent of electric field in avalanche and drift regions, total surface current density J0 at any space point is the sum of conduction current density and displacement density. Thus J_0 is given by

$$J_0=J_{cond}+J_{disp}=q(v_{sn}n+v_{sp}p)+\frac{\partial}{\partial t}(\varepsilon E) \qquad ....(5)$$

where v_{sn} and v_{sp} are the saturated drift velocities of electron and holes respectively. Thus surface current density may be re-written as-

$$J_0=q(v_{sn}n+v_{sp}p)+\frac{\partial}{\partial t}(\varepsilon E) \qquad ....(6)$$

So our fundamental dynamical equation can be obtained as

$$\left[\frac{\partial^2}{\partial x^2}-\frac{1}{v_m^2}\frac{\partial^2}{\partial t^2}+(\beta_n-\alpha_p+2r\_k)D+2\bar{\alpha}k\right]E_{sc}=\frac{1}{v_m\varepsilon}[(2\bar{\alpha}-k)J_0] \qquad ....(7)$$

where v_m, $\bar{\alpha}$, $r\_$ are functions of material parameters, and we neglect the effect of stochastic generation rate.

Equation (5) is nonlinear in E as the ionization coefficients are the functions of electric field. Llinearizing the equation for small signal condition, differential equation for resistive impedance may be written in the following form:

$$\frac{\partial^2}{\partial x^2}\tilde{X}-(\beta_n-\alpha_p)\frac{\partial}{\partial x}\tilde{X}-2\frac{r\_\omega}{v_m}\frac{\partial}{\partial x}\tilde{R}+\left(\frac{\omega^2}{v_m^2}-H\right)\tilde{X}+2\bar{\alpha}\frac{\omega}{v_m}\tilde{R}+\frac{\omega}{v_m^2\varepsilon}=0 \qquad ....(8)$$

where the operator H contains derivatives of ionization coefficients w.r.t electric field. From the d.c field and current profiles, the space-dependent quantities for a given doping profile and d.c current are evaluated and fed in as input data for small signal analysis. The boundary conditions for R is given by

$$D\tilde{X}+\left(\frac{\omega}{v_{sp}}\right)\tilde{R}=0 \qquad ....(9.1)$$

and

$$D\tilde{X}-\left(\frac{\omega}{v_{sn}}\right)\tilde{R}=0 \qquad ....(9.2)$$

at the boundaries of n-side & of p-side respectively.

Equation (8) can be numerically solved subject to the boundary conditions given by equations (9.1) and (9.2) using double-iterative simulation scheme incorporating modified Runge-Kutta method. The solution provides spatial distribution of the small-signal integrated parameter high-frequency negative resistivity per unit length in the depletion layer of the device. The negative resistance of IMPATT diode can be obtained from numerical integration of R profile over the entire depletion layer of the device.

Thus

$$\tilde{R}=\int_{-X_1}^{X_2}R(x)dx \qquad ....(10)$$

The devices can be subjected to fine structure optimization through variation of diode structural parameters in order to optimize the value of RF negative resistance which can be achieved when the values of avalanche phase delay and transit phase delay are close to π/2 each and the peaks of the R(x) profile in the drift zones are located to the close to the centre of the drift zone in both 'n' and 'p' regions.

ISSN: 2231-2307, Volume-1, Issue-6, January 2012

III. Numerical Analysis

From the small-signal analysis, it is observed that in negative resistivity profile, two peaks are occurred at either side of junction correspond for both the type of carriers, when simulated at 34 GHz for specified junction current density. It can be concluded that negative resistance increases with lowering of temperature. Fig 1 shows negative resistivity profile at three different junction temperatures, where peak for both the carriers are originated almost at the same position of the metallurgical junction. From the profile, it can be observed that negative resistance increases with lowering of junction temperature. This is important as far design of suitable heat sink is concerned when the device is biased in proper region at a particular window frequency.

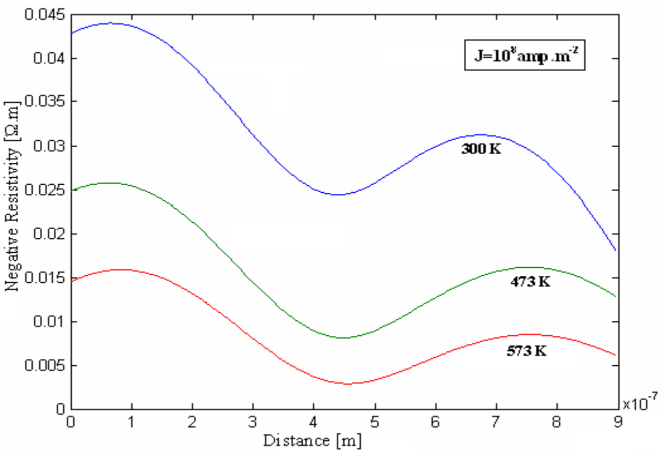

Fig1: Negative resistivity profile of DDR IMPATT at specified current density at different junction temperatures at 34 GHz

By increasing current density and operating frequency also, a shift of peak is observed away from the junction as temperature is lowered. Another interesting feature may be noted down in this context that though negative resistance is higher for lower junction temperature, but far away from the junction, the trend is going to reverse. This effect is profiled in fig 2, simulated at 94 GHz. Here current density is considered higher which is due to the higher operating frequency region.

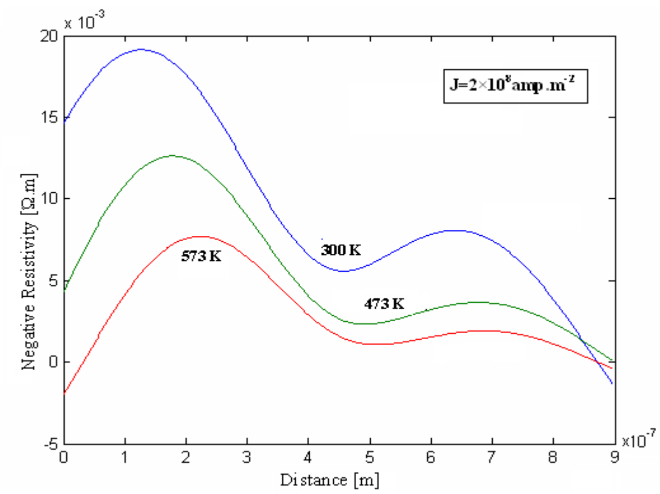

Fig2: Negative resistivity profile of DDR IMPATT at specified current density at different junction temperatures at 94 GHz

When negative resistance is plotted against bias current density for different junction temperature, a constant profile is observed when current density is in the range of 0.8-1.0 amp.m^{-2} for lower values of junction temperature. This effect is absent as the device is heated up, and sharp peak can be observed for sufficiently high temperature, shown in fig 3.

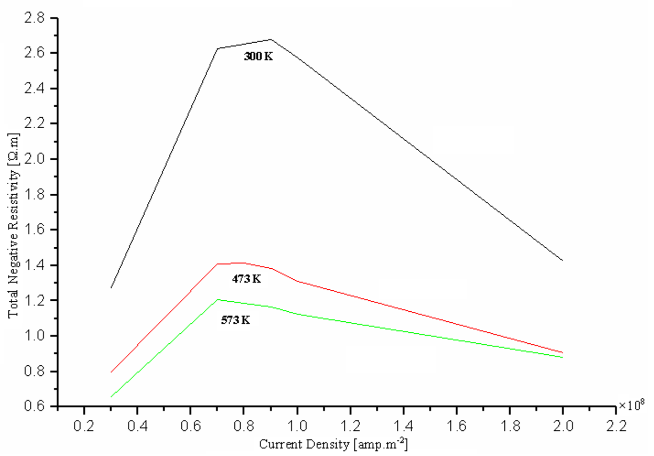

Fig 3: Total negative resistivity profile with bias current density for different junction temperatures

When frequency of operation is varied in sub-millimeterwave region at different junction temperatures, higher peak is obtained at lower frequency regions for higher temperature, and this combined effect is less when junction temperature is reduced. It may also be concluded that peak of negative resistance profile occurred at particular value of junction temperature depending on the operating frequency region. This is depicted in fig 4.

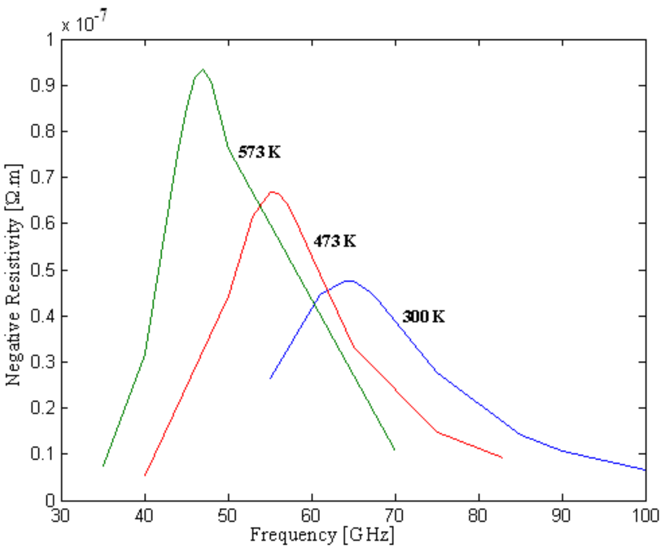

Fig 4: Negative resistivity profile with operating frequency in sub-millimeterwave region for different junction temperatures

IV. Conclusion

The analysis provides overall information about the variation of negative resistance with junction temperature and current density for different range of operating frequency. Obtained profiles are important for design of proper heat sink materials to nullify the effect of elevated junction temperature. Effect of mobile space charge is considered to make the analysis more realistic. The model adopted for simulation purpose can be fit for different semiconductor materials also, which speaks in favor of experimental processes with novel materials; thus make a wider possibility of applications.

REFERENCES

[1] W.T.Read, "A Proposed High-Frequency Negative Resistance Diode", Bell System Technical Journal, Vol.37, pp. 401-446, 1958.

[2] H.C.Bowers, "Space-Charge-Induced Negative Resistance in Avalanche Diodes", IEEE Transactions on Electron Devices, Vol. ED 15, No.6, June 1968.

[3] T.E.Seidel, R.E.Davis and D.E.Iglesias, "Double-Drift-Region Ion-Implanted Millimeter-Wave IMPATT Diodes", Proceedings of the IEEE, Vol.59, No.8, pp-1222-1228, 1971.

[4] S.K.Roy, J.P.Banerjee and S.P.Pati, "A Computer analysis of the distribution of high frequency negative resistance in the depletion layer of IMPATT Diodes", NASECODE-IV, p. 494, 1985.

[5] M.Mukherjee, S.Banerjee and J.P.Banerjee, "Dynamic Characteristics of III-V and IV-IV Semiconductor Based Transit Time Devices in the Terahertz Regime: A Comparative Analysis", Terahertz Science and Technology, Vol.3, pp 97-109, 2010.

[6] M.Mukherjee and J.P.Banerjee, "DDR Pulsed IMPATT Sources at MM-Wave Window Frequency: High-Power Operation Mode", International Journal of Advanced Science and Technology, Vol. 19, pp 1-11, 2010.

[7] S.Banerjee, M.Mukherjee and J.P.Banerjee, "Bias current optimization of Wurtzite-GaN DDR IMPATT diode for high power operation at THz frequencies", International Journal of Advanced Science and Technology, Vol. 16, pp 11-20, 2010.

[8] M.Mukherjee, S.Banerjee and J.P.Banerjee, "Mobile space-charge effect on Terahertz properties of Wz-GaN based DDR IMPATT oscillators", CODEC 2009.

[9] M.Mukherjee, S.Banerjee and J.P.Banerjee, "MM-wave performance of DDR IMPATT's based on cubic SiC", XVth IWPSD-2009.

[10] S.Banerjee, M.Mukherjee and J.P.Banerjee, "Studies on the performance of Wz-GaN DDR IMPATT diode at optimum bias current for THz frequencies", 3rd IEEE MiNDSS-2010.

[11] M.Mukherjee and N.Mazumder, "Modeling of high power 0.3 THz IMPATT oscillator based on 3C-SiC and growth of 3C-SiC on Si <100> substrate for possible IMPATT fabrication", ICMMT 2008.

[12] M.Mukherjee and N.Mazumder, "Effects of Charge Bump on High-Frequency Characteristics of α-SiC-based Double-drift ATT Diodes at Millimeter-wave Window Frequencies", IETE Journal of Research, Vol. 3, pp. 118-127, 2009.

[13] X.Bi, J.R.East, U.Ravaioli and G.I.Haddad, "Analysis and Design of Si Terahertz Transit-Time Diodes", 16th International Symposium on Space Terahertz Technology, pp 271-275, 2005.

[14] M.Mukherjee, P.Tripathi and S.P.Pati, "Effects of Mobile Space-Charge on Dynamic Characteristics and Parasitic Resistance of InP Terahertz IMPATT Oscillator Operating at Elevated Junction Temperature, Applied Science Research, Vol. 2(3), pp 42-52, 2010.

[15] M.Mukherjee, J.Mukherjee, J.P.Banerjee and S.K.Roy, "MM-wave properties of photo-illuminated double drift Indium Phosphide IMPATT's at elevated temperature", Proceedings of Int. Conf. IEEE-ICMMT, 2008.

[16] U.C.Ray, A.K.Gupta and M.N.Sen, "Frequency response of W-band pulsed IMPATT's operating over extended ambient temperature", International Journal of Infrared and Millimeter Waves, Vol. 10, pp 1165-1179, 1989.

[17] S.P.Pati and P.R.Tripathy, "Design Consideration for Sub-mm Wave Silicon DDR's including Drift, Diffusion and Tunnel Currents", XIIIth IWPSD, 2005.

[18] H.K.Gummel and J.L.Blue, "A Small Signal Theory of Avalanche Noise on IMPATT Diodes", IEEE, Transaction Electron Devices, Vol. 14, pp. 569-580, 1967.

Arpan Deyasi is an Assistant Professor in the Department of Electronics & Communication Engineering in RCC Institute of Information Technology under West Bengal University of Technology, Kolkata West Bengal, INDIA. He received B.Sc in Physics with Hons, B.Tech in Radio Physics & Electronics and M.Tech in Radio Physics & Electronics, all from University of Calcutta in 2000, 2003 & 2005 respectively. Currently he is working in the area on semiconductor nanostructure from University of Calcutta. He has published a few papers in national & international journals and conferences.

Swapan Bhattacharyya received his B.Sc. (Hons.) degree in physics from the University of Calcutta in 1982, the integrated M.Tech. Degree in Radio Physics and Electronics from the University of Calcutta, in 1987. In 1988, he joined TGC as a Senior Customer Support Engineer, where he became the Branch Manager (Customer Support) in 1998 and in the next year he joined the as Corporate Manager (Customer Support). In May 2004, he joined the Asansol Engineering College (India) as a System Manager, where he is the Head of the department of Computer Science and Engineering since December, 2004. His field of research in the area of Semiconductor nanostructures with special focus on Quantum dots for information and communication applications. He also worked as a visiting faculty at ICFAI Institute, India. He has published many technical research papers in national and international journals and in conference proceedings. He also served as a conveyer of technical committee for several national conferences and seminars. He is a member of IEEE, LEOS Chapter and life member of IE (Institute of Engineers, India).