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Self-Heating Effects in SiGe Heterojunction Bipolar Transistor with Different Ge Grading Profile

M. R. Jena, A. K. Panda, G. N. Dash

***Abstract:** A comparative account of self heating effect of four SiGe HBTs with different Ge grading profiles, designated as Hybrid Trapezoidal (HT), Symmetrically Triangular (ST), Linear Increasing (LI), and Conventional Trapezoidal (CT) with maximum Ge contents of 20%, is presented. Based on an experimentally validated model of the Silvaco TCAD tool, the properties of the four HBTs are simulated. It is observed that both self heating and local temperature increase due to higher device power dissipation. The effect of energy balance and non iso thermal energy balance effect is observed in SiGe HBT with different Ge base profile have been studied in terms of DC, AC, and RF performances and compared .*

***Keywords:** SiGe HBT, TCAD Tool, Self Heating effect, Ge grading profile*

I. INTRODUCTION

Ge incorporation induced bandgap engineering in the base of silicon bipolar transistors enhances the device performances and becomes more popular in wireless and broadband communications, with the recent record of 505 GHz f_T, 702 GHz f_{max} and a minimum of ring oscillator gate delays of 1.34 ps [1,2]. Different Ge profile is incorporated in the base region for better improvement of device performances [3]. It has high cut off frequency, breakdown voltage, transconductance, low cost, highly integrable with CMOS technology and efficient alternative to III-V group. But this magnificent performance of the device is limited to self-heating effect. Temperature rises due to power dissipation inside the device, as a result self heating effect occurs. Self heating effect mainly due to thermal feedback nature of temperature dependent parameters.

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* Correspondence Author
M. R. Jena*, Department of Electronics and Communication Engineering, Sambalpur University Institute of Information Technology, Jyoti Vihar, Burla, Sambalpur, Odisha - 768019, India, Email-mrjena_etc@vssut.ac.in
A. K. Panda,Department of Electronics and Telecommunication Engineering, National Institute of Science and Technology, Berhampur 761008, Odisha, India, Email-akpanda62@hotmail.com
G. N. Dash, Electron Devices Group, School of Physics, Sambalpur University, Jyoti Vihar, Burla, Sambalpur768019, Odisha, India, Email-gndash@ieee.org

This feedback nature of the device is called thermal run away condition due to self heating. It also affects the reliability of the device during circuit design due to increase of junction temperature [4, 5]. To operate the device in safe mode the self heating and breakdown analysis has to be performed which is called electro-thermal instability and it also important for large signal analysis. To control thermal instability due to high current operation in the device, self-heating characteristics need to be observed [6]. Initially the modelling parameters of Silvaco T-CAD tool are properly tuned to validate with experimental results of [7]. Then SiGe HBTs with different Ge grading profiles are simulated with energy balance and non iso thermal energy and the results obtained are analyzed and compared. The rest of the paper is organised with device structure in Sec. 2, device modelling in Sec.3, result and discussion in Sec 4 and finally conclusion in Sec 5.

II. DEVICE STRUCTURE

The four different Germanium graded SiGe HBTs are based on a fully self aligned with Polysilicon emitter. The polysilicon layer width of 0.06 µm is grown on Si emitter layer which is 0.2 µm and peak doping concentration is $4\times10^{20}/cm^3$. During fabrication the arsenic is doped into the polysilicon layer up to 10 seconds [8] and 15% of arsenic is electrically active which results the uniform doping profile in the emitter region. So, here we have simulated the device using Silvaco T-CAD simulator with a uniform profile in polysilicon layer and half Gaussian profile in the silicon layer of the emitter region. The SiGe HBT has base width of 1µm with doping concentration $5\times10^{18}/cm^3$. The effective area of emitter is $0.2\times10\ \mu m^2$ with single contact at top of the emitter layer. The CT profile is designed with Germanium content of 2% at base emitter junction and 8% at base collector which is shown in fig. 1. HT profile (Ge with 20%) which is linearly graded on both side and uniform on neutral base region, ST profile (20%) which is linearly graded on both side and peak is present on neutral base region, LI profile (20%) in which germanium composition at base emitter junction is 0% and at base collector junction is 20% and linearly graded throughout the base region which are shown in fig .2. All four devices are simulated for both Iso-thermal energy balance model and non Iso-thermal energy balance model.

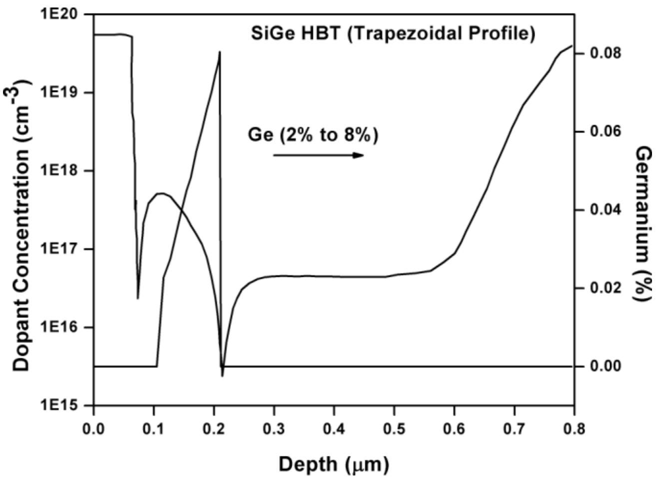

Fig 1: Gaussian doping profile and Conventional Trapezoidal (CT) Ge grading profile.

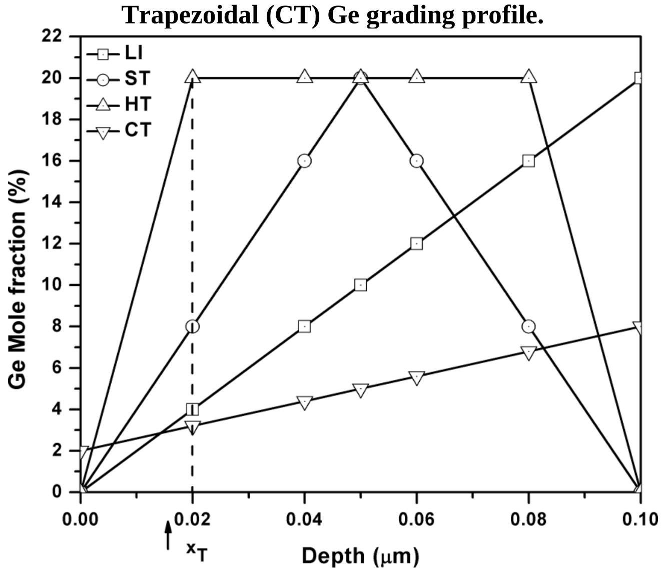

Fig.2: Different Ge grading profiles considered in this paper.

III. DEVICE MODELLING

The models which are selected in ATLAS are derived from continuity equation, Poisson equation, Maxwell's law and the transport equations. The process of generation, recombination of electrons and holes are related to continuity and transport equations. The carrier continuity equation which is explained by

$$\frac{\partial n}{\partial t} = \frac{1}{q} div \vec{J}_n + G_n - R_n \tag{1}$$

$$\frac{\partial p}{\partial t} = \frac{1}{q} div \vec{J}_p + G_p - R_p \tag{2}$$

Where n and p are the electron and hole concentration. $\vec{J}_p$, $\vec{J}_n$ are electron and hole current densities, G_n G_p are the generation rates for electron and holes. R_n , R_p are recombination rate for electron and hole, q is the magnitude of the charge R_n, R_p are recombination rates for electron and holes, q is magnitude of the charge on an electron. The simplest model which is applicable to all device technology is drift diffusion model. This model is used here because it links to change transport model which is responsible for carrier recombination and generation.

$$\vec{J}_n = -q\mu_n n \nabla \phi_n \tag{3}$$

$$\vec{J}_p = -q\mu_p n \nabla \phi_p \tag{4}$$

μ_n and μ_p are the electron and hole mobility $Ø_n$ and $Ø_p$ are Fermi levels of electrons and holes. The model is simulated in ATLAS domains in 300k i.e in room temperature. The Fermi Dirac model is used to simulate the heavily doping material in thermal equilibrium conditions. Band gap narrowing model (BGN) is selected due to heavily doping in the base in the order of 10^{18} cm^{-3} which is most effective in base collector junction. en the doping level increases the bandgap separation between the valence band and conduction band decreases. In bipolar simulation the Klaassen model is taken which includes Klaassen's auger model and Klaassen's concentration depend srh model. Shockley read hall recombination (Srh) model is used to activate the electron and hole life time TAUN and TAUP respectively. During the simulation carrier life time is considered as 1×10^{-7} for silicon and 1×10^{-8} silicon germanium. (Auger) auger recombination model is introduced for reduction of carrier lifetime in high carrier densities. The high electric field in the base collector junction saturates the free electron. So to model the velocity saturation effect on Silicon device parallel electric field dependence (FLDMOB) model is introduced. (PHUMOB) is used for model of difference between majority carrier and minority carrier mobility. We have used the model parameter to best fit for the validation purpose of the device.

Non local transport effects such as velocity overshoot, diffusion due to carrier temperature and impact ionization rate on carrier are neglected in drift diffusion model. To signify those properties, ATLAS offers two non local models of charge transport like energy balance model and hydro dynamic model. Energy balance (EB) model is derived from Boltzmann Transport equation and it adds continuity equation for the carrier temperatures. In energy balance model mobilities and impact ionization coefficients are treated as function of carrier temperature rather than function of local electric field. Carrier temperature for electron T_n and for hole T_P are two new independent variables introduced in EB model. The energy balance equations consist of an energy balance equation with associated equation for current density and energy flux $S_{n,p}$. The equations are

$$div\vec{S}_n = \frac{1}{q}\vec{J}_n.\vec{E}\_W_n - \frac{3K}{2}\frac{\partial}{\partial t}(\lambda_n^{*} nT_n) \tag{5}$$

$$\vec{J}_n = qD_n\nabla_n - q\mu_n\nabla_{\psi} + qnD_n^{T}\nabla T_n \tag{6}$$

$$\vec{S}_n = -K_n \vec{\nabla} T_n - (\frac{k\delta_n}{q})\vec{J}_n T_n \tag{7}$$

Where $\vec{S}_n$ the energy flux density associated with electrons, μ_n is the electron mobility, D_n is the thermal diffusivities for electron, W_n is the energy density loss rate for electron, K_n is the thermal conductivity of electron. In our simulation energy balance transport model is used and the hot carrier transport equations are activated by the parameter HCTE.EL in model statement for electron temperature will be solved. The self heating effect is carried in SiGe HBT using GIGA, which is responsible for lattice heat flow and general thermal environments.

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GIGA implements Wachutka's thermo dynamically rigorous model of lattice heating which accounts for joule heating, cooling due to carrier generation and recombination. Heat flow equation in GIGA that are solved by ATLAS.

$$C\frac{\partial T_L}{\partial t} = \nabla(k\nabla T_L) + H \tag{8}$$

C is the heat capacitance per unit volume, k is the thermal conductivity, H is the heat generation, T_L is the local lattice temperature. LAT.TEMP statement is specified in model section for stimulated lattice Heat flow equation in ATLAS simulation. HCTE and LAT.TEMP parameters are included in model statement for simulation of non Iso thermal energy balance model which causes self heating effect. Both energy balance transport model and energy non balance transport model are activated by electron and hole relaxation time TAUREL.EL AND TAUREL.HO respectively. Carrier mobility for electron TAUMOB.EL and for hole TAUMOB,HO are specified in model statement.

In the device simulation of Si/SiGe/Si HBT heat capacity of SiGe alloys is taken to same as Si. The value of thermal conductivity k for Si and SiGe are specified in material statement. TC.A, TC.B, TC.C are the user specified thermal conductivity coefficient parameter which were included in Model statement. TC.A for Si and SiGe was taken as 0.7 and 2.5 respectively. TC.B and TC.C were taken as zero for Si and SiGe. THERMOCONTACT statement is used for self heating effect in ATLAS in simulation. Thermo contact was given in the bottom layer of the device. ALPHA is the inverse value of thermal resistance which is user definable on the THERMOCONTACT statement. In our simulation ALPHA is taken as 1500.

IV. RESULT AND DISCUSSION

The simulated Gummel plots of the CT graded (2 to 8%) device with Gaussian doping profile along with those from the experimental measurements of the fabricated device of Ref [7] are shown in Fig. 3. Excellent agreements between the two sets of plots stand testimony to the fact that our model is strongly validated.

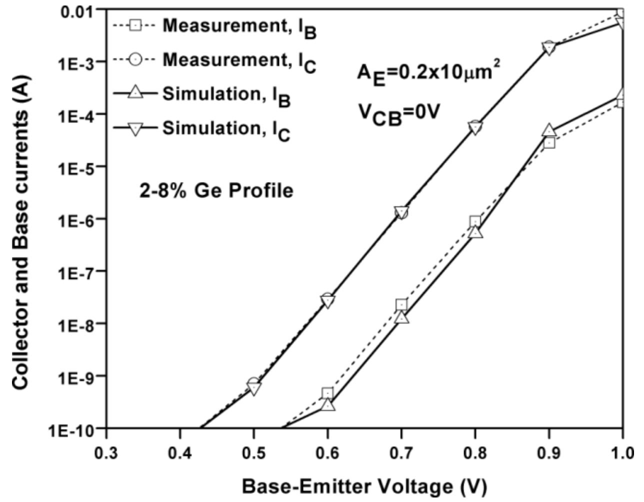

Fig 3: Gummel plots of conventional trapezoidal (CT) SiGe grading profile compared with the measurements of Ref [7].

It is observed form the figure that the DC current gain decreases from HT, to ST, then to LI, and finally to CT profiles recording the maximum values (β_{max}) of 294,225,156, and 56 respectively. It is observed that the Ge induced band grading is the highest for HT followed by the ST, then the LI and at last that for CT profile. The collector current density as a function of the Ge grading for the different grading profiles in SiGe HBT is given by [9,10]

$$J_{C,SiGe} = \frac{qD_{nb}}{N_{ab}{}^{-}W_b}(\exp^{\frac{qV_{BE}}{kT}} - 1)n_{io}{}^2(\exp^{\frac{\Delta E_{gb}{}^{app}}{kT}})\{\tilde{\gamma}\tilde{\eta}\frac{(\frac{\Delta E_{g.Ge(\text{grade})}}{kT})\exp(\frac{\Delta E_{g,Ge(0)}}{kT})}{1-\exp(-\frac{\Delta E_{g,\text{Ge(grade)}}}{kT})}\}$$

(9)

where, $\tilde{D}_{nb} = \frac{\int_0^{W_b}\frac{dx}{n_{ib}{}^2(x)}}{\int_0^{W_b}\frac{dx}{D_{nb}(\mathrm{x})\,\mathrm{n}_{ib}{}^2(\mathrm{x})}}$ is the position dependent diffusion constant, $\tilde{\eta} = \frac{(\tilde{D}_{nb})_{SiGe}}{(\mathrm{D}_{nb})_{Si}}$ is the minority electron diffusivity ratio, and $\tilde{\gamma} = \frac{(\mathrm{N}_C\mathrm{N}_V)_{\mathrm{SiGe}}}{(N_C\,\mathrm{N}_V)_{Si}}$ is the effective density-of-states ratio between SiGe and Si. $\Delta E_{g,Ge(\text{grade})} = \Delta E_{g,Ge}(\mathrm{W}_b) - \Delta E_{g,\mathrm{Ge}}(0)$ is the band offset difference across the neutral base region. Assuming $\Delta E_{\mathrm{g.Ge(grade)}} \gg kT$ the exponential term in the denominator of Eq. (9) reduces to zero leaving behind a directly proportional collector current with $\Delta E_{\mathrm{g.Ge(grade)}}$. This leads to the observed behaviour of β with different Ge grading profiles. Now The DC current gain for those different profiles again simulated in the presence of for both Iso-thermal energy balance model and non Iso-thermal energy balance model, which are shown in fig.4 ans fig.5 respectively. Peak gain is decreased drastically from 294 to 258 and 225 to 213 for HT and ST profile with 20 % Ge respectively. Peak gain is inversely related to temperature which can be observed from eq. 10. Due to self heating when temperature is gradually increased from 300 K to 323 K, gain of the corresponding device drastically decreased exponentially.

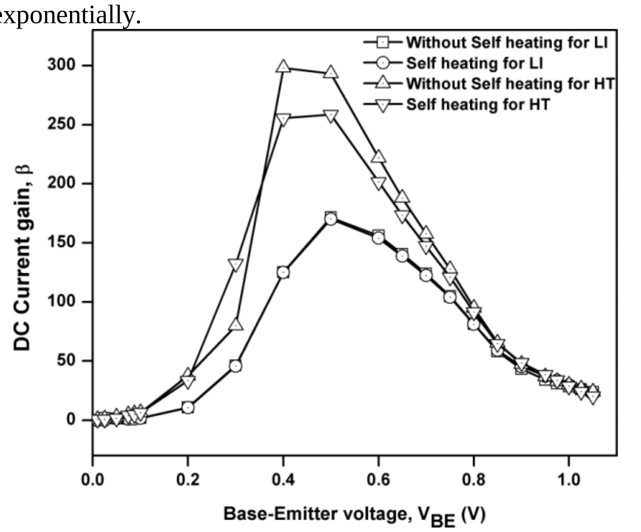

Fig 4: Variation of DC current gain (β) with base-emitter voltage for LI and HT

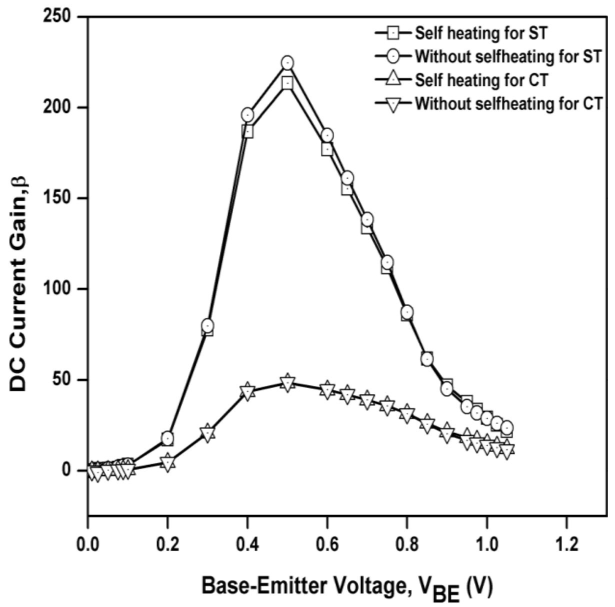

Fig 5: Variation of DC current gain (β) with base-emitter voltage for CT and ST

$$\frac{\beta_{SiGe}}{\beta_{si}} = \frac{\dfrac{(N_C N_V \overline{D}_{nb})_{SiGe}}{(N_C N_V D_{nb})_{si}} \dfrac{\Delta E_{G(\text{grade})}}{KT} \exp^{\frac{\Delta E_{G(0)}}{KT}}}{1 - \exp^{\frac{-\Delta E_{G(grade)}}{KT}}} \qquad (10)$$

However gain remains same for device with LI (20 % Ge) and CT (2 to 8 % Ge) graded profile under self heating condition.From the analysis peak gain of devices with linear and trapezoidal grading profiles are less affected by self heating characteristic. The reason behind this is due to more $\Delta E_{G(Grade)}$ which is nearly compensated with the variation of temperature.

Output characteristic V_{ce}-I_c of SiGe HBT due to self heating effect observed by controlled the base current I_B. fig.6 shows the output characteristic of the device with different grading profile for self heating effect and without self heating at fixed I_B of 3 μA. Due to thermal run away, when temperature is increased from 300 K to 323 K, the saturate collector current is gradually varying with output voltage rather to fix at constant value. As a result DC operating point is shifted. For device with HT profile output collector current is increased from 0.00189 A to 0.0023 A at 3 V of V_{CE} due to self heating effect. Increased percentage of output current after thermal run away with respect to energy balance transport model simulation is 21.69%. Similarly increased percentage of output collector current at 3V of V_{CE} for ST (20 % Ge), LI (20 % Ge), CT (2 % to 8 % Ge) graded profile device are of 23.86%, 22.61%, 11.18% respectively. So more self heating effect observed in ST (20 % Ge) graded device and less self heating effect observed in CT profile (2 to 8 % Ge). Less Germanium composition device exhibits less self heating effect [11]. From previously reported result early voltage of SiGe HBT degrades due to self heating effect [11]. It is observed that degradation of early voltage due to self heating effect as compared to without self heating effect.

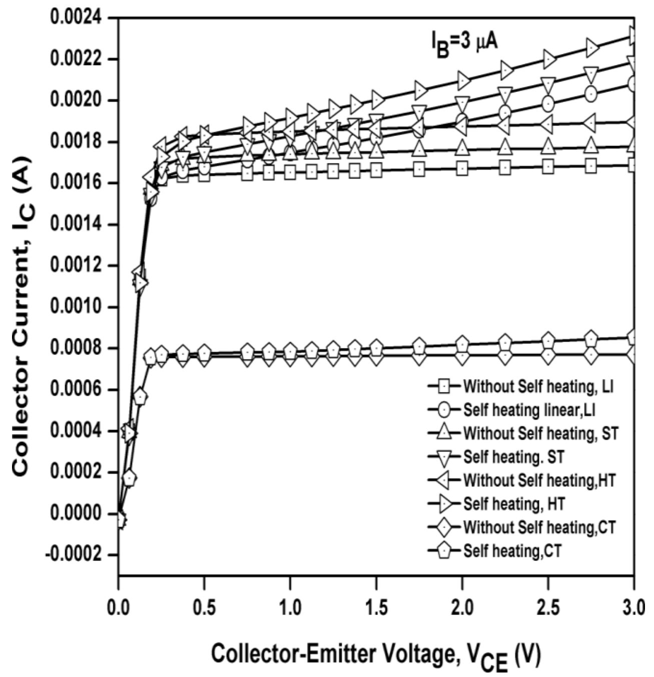

Fig 6: Plots of collector current as function of collector-emitter voltage.

Significant degradation in maximum operating frequency (f_{max}) and maximum cut-off frequency (f_T) of the devices is observed due to increase of base transit time. Base transit time increases due to poor thermal conductivity during self heating in the device [12]. The maximum cut off frequency is inversely related to base transit time and base transit time is increased due to degradation of mobility in base region which is already reported [13]. The relation between [13] τ_b and temperature (T) is given below.

$$\frac{\tau_b(T)}{\tau_b(300K)} = \left(\frac{300K}{T}\right)\frac{\mu_n(300K)}{\mu_n(T)} = \left(\frac{T}{300K}\right)^{\frac{1}{2}} \qquad (11)$$

Similarly operating frequency is also degraded like cut off frequency. Relation between f_T and f_{max} can be described in in eq.12 [13]

$$f_{MAX} = \sqrt{\frac{f_T}{8\pi R_B C_{jc}}} \qquad (12)$$

From the simulation result reduction of f_T and f_{max} for all the four profile can be observed in Table.1. The frequency at which unity power gain is observed is called maximum frequency of oscillation (f_{max}) and the frequency at which unity current gain is observed is called cut off frequency (f_t). The variation of power gain and current gain with respect to frequency for CT, HT, LI, and ST profiles. f_t and f_{max} are shown in Fig.7, Fig.8, Fig.9, and Fig.10 respectively. The detailed values of the f_t and f_{max} is given in the table1.

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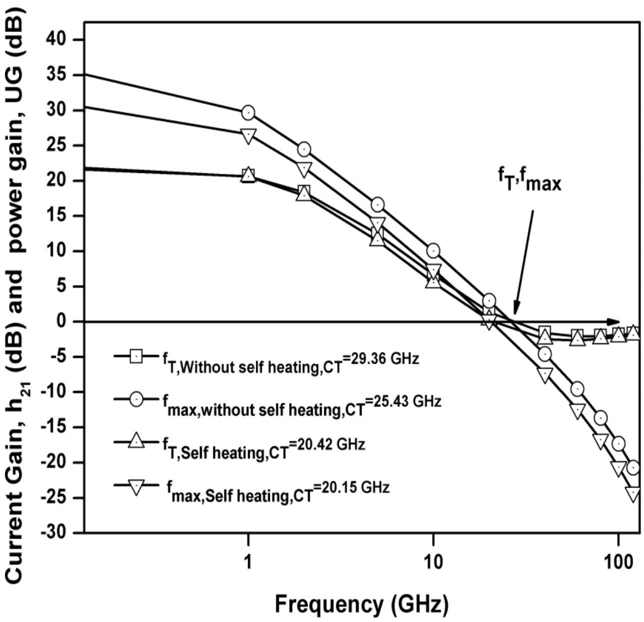

Fig 7: Determination of f_T and f_{max} for CT profile

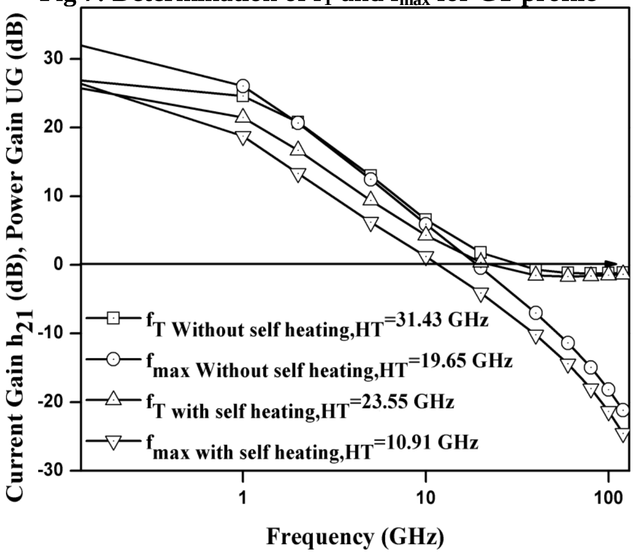

Fig 8: Determination of f_T and f_{max} for HT profile

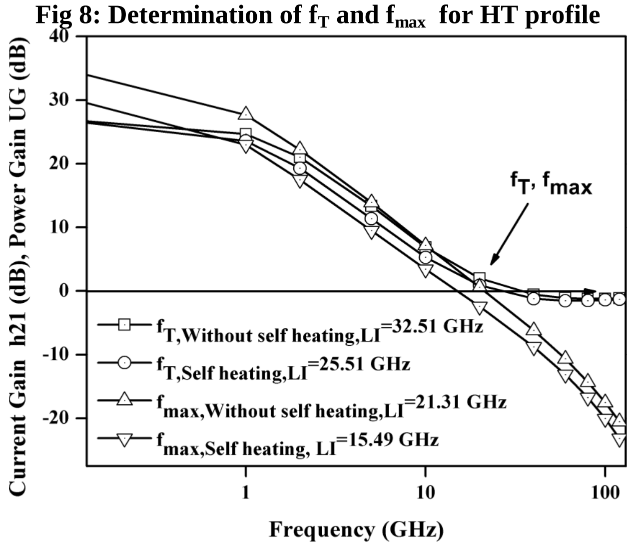

Fig 9: Determination of f_T and f_{max} for LI profile

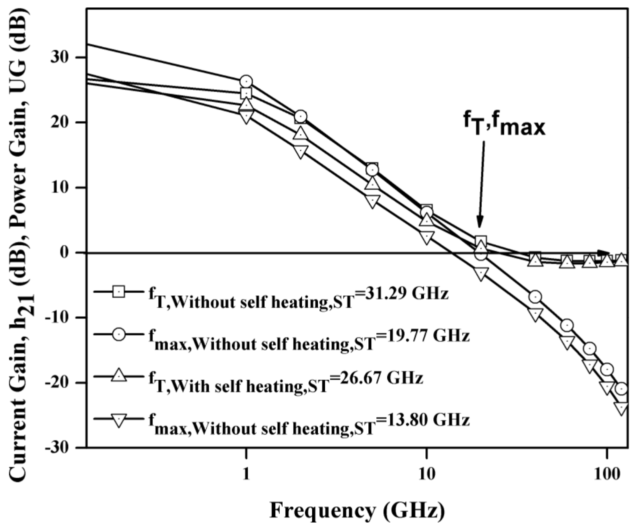

Fig 10: Determination of f_T and f_{max} for ST profile

Table 1: f_t an f_{max} for different condition of the devices.

Profiles(% Ge)	Without self-heating f_T in GHz	With self-heating f_T in GHz	Without self-heating f_{max} in GHz	With self -heating f_t in GHz
CT(2 to 8 % Ge)	29.36	20.42	25.43	20.15
HT(20% Ge)	31.43	23.55	19.65	10.91
ST(20% Ge)	31.29	26.67	19.77	13.80
LI (20 % Ge)	32.51	25.51	21.31	15.49

When the transistor is used in circuit for power amplification purpose, it depends upon transistor characteristics with source and load impedance of the circuit. So the stability factor can be described as in terms of S- parameter by Rollet stability factor (K).

$$K = \frac{1-|s_{11}|^2 - |s_{22}|^2 + |\Delta s|^2}{2|s_{12} \cdot s_{21}|} \tag{13}$$

Where $\Delta s = s_{11} \cdot s_{22} - s_{12} \cdot s_{21}$

When K > 1 there is a conjugate matching between source impedance and load impedance i.e. circuit is inherently stable. The circuit is potentially unstable when K < 1 [14]. The stability criteria of all grading profiles for energy balance model and energy non balance model are observed. From the observation the devices with different Ge garding profile Self heating effect achieve potentially unstable at below 1 GHz as K<1 and above which all are inherently stable. It may be occurd due to degradation of gain as compared to without self heating effect.

During high frequency operation exact short circuit and open circuit condition are difficult to achieve due to inherent inductances and capacitances. During device under test (DUT) it oscillates at open circuit and short circuit condition. So some difficulties occur during wavelength testing of devices. Therefore, to overcome those difficulties, S-parameter were developed and it is exclusively used in RF performance.

In S-parameter dependent variables are Voltages waves. These combinations are chosen for parameter measurement in high frequency operation. Consider the wave variables a_1, a_2, b_1, b_2. Where a_1 and a_2 indicates incident scattering, b_1 and b_2 reflection scattering. The scattered wave can be written in a linear equation in terms of incidence and reflection scattering parameter [14].

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} \quad (14)$$

$S_{11} = \frac{b_1}{a_1}$ Reflection co-efficient corresponding to input imepedance

$S_{11} = \Gamma_{in}$; for practical application Γ_{in} should be less than 0.33. In this condition circuit does not need any matching network.

$|S_{12}|^2 =$ Reverse transducer Gain

$|S_{21}|^2 =$ Transducer gain

$S_{22} = \frac{a_2}{b_2}$ Reflection co-efficient corresponding to output impedance

$$\Gamma_{in} = \sqrt{\mathrm{Re}(S_{11})^2 + \mathrm{Im}(S_{11})^2} \quad (15)$$

Reflection Coefficient for CT is less than 0.33 in the frequency range of 2 GHz. Reflection coefficients of HT, ST and LI device have less than 0.33 in the frequency range of 40 GHz, 50 GHz and 70 GHz respectively in case of self heating effect. In this frequency range circuit does not require any matching network because no reflection of the signal occurs at the input port.

V. CONCLUSION

Thermal effect inside the device which results self heating of the lattice degrades the device characteristic drastically. Electrical performance such as Gain (β), output characteristic, Maximum operating frequency (f_{MAX}), cut-off frequency (f_T), early voltage (V_A), and Stability criteria of the device degrades due to self heating effect inside the device. The built in potential of the devices before self heating is lesser than the built in potential after self heating. So turn-on voltage increases after self heating effect which affects the device performance.

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AUTHORS PROFILE

Manasa Ranjan Jena obtained his B.E. degree in 2004 in the branch of Electronics and Instrumentation Engg. from National Institute of Science and Technology (NIST), Berhampur, odisha. From 2006 to 2009 joined as a faculty in ITER, SOA University in the department of Electronics and Instrumentation Engg. Received M.Tech. degree from IIT Kharagpur (2009-2011) in the field of Micro Electronics and VLSI design. Again Joined in ITER, SOA University from 2011 December to 2014 May as an Assistant Professor in the department of Electronics and Instrumentation Engg.. Currently as an Assistant Professor in the department of Electronics and Telecommunication Engg. in Veer Surendra Sai University of Technology, Burla, Odisha. Currently working in the physics of devices and modelling of transistors.

Ajit Kumar Panda obtained his PhD degree in 1996 in the field of microelectronics from Sambalpur University, India and is working now as a professor in National Institute of Science and Technology, India. He was a BOYSCAST fellow of Government of India to Department of Electrical Engineering and Computer Science of University of Michigan in the year 1999–2000 and work with Prof. D. Pavlidis. He is a regular associate of Microprocessor Laboratory of ICTP, Trieste, Italy. He is a life member of IETE, ISTE, member of VLSI Society of India and is senior member of IEEE. He has published more than 60 papers in the journals of repute and has presented his work in more than 80 national/international conferences. He is handling the DST-FIST programme of NIST with a grant of 1 crore. He is also recently assigned as the TIFAC CORE coordinator for the Center of Excellence in "3G/4G Communication Technologies" at NIST, Berhampur. His research interest includes modelling of homo/heterostructure semiconductor devices to operate at high frequency, VLSI circuits and FPGA implementation for communication, DSP and electrical engineering applications. He has given more than 15 popular talk/inspire talk.

G. N. DASH was born in 1955. He received the M.Sc., M.Phil., and Ph.D. degrees in 1977, 1983, and 1992, respectively. He joined G.M. College, Sambalpur, India, under the Government of Odisha as a Lecturer in physics in 1978 and subsequently he moved to the School of Physics, Sambalpur University, Sambalpur, India, in the same post. There he became a Reader in 1993 and since 2001, he is working as a Professor. He has published over 170 papers in journals of repute and proceedings national and international conferences. He has guided 35 scholars for the award of M.Phil. degrees and seven for the award of Ph.D. degrees in physics and engineering. Some ten more scholars are pursuing Ph.D. degrees under his guidance. He is a fellow of the IET (U.K.) and a Life Fellow of the IETE (India). He is also a Distinguished Lecturer of the IEEE Electron Devices Society. His research interests include 2T microwave devices, HEMT, graphene-based devices, and new emerging materials