An Investigation on Modeling and Statistical Simulation of SiGe Heterojunction Bipolar Transistors for Characterizing Their Dependence on Germanium Content

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ABSTRACT

Although silicon is by far the most widely utilized manufactured semiconductor material, it is very poor in terms of mobilities of holes and electrons, which give rise to unacceptable low operation speeds. Far higher charge-carrier mobilities and saturation velocities have been found in III-V compound materials, for instance GaAs, AlGaAs, and InP. The project undertaken has utilized a novel methodology to achieve enhanced circuit designs using a multiple statistical simulation approach. This methodology has been described in detail elsewhere [1]. The goal of this project is to extend this methodology to characterize SiGe HBTs and elucidate their dependence on germanium content.

Keywords: Modeling, Simulation and Statistical Design of RF ICs, LNA, Wireless Communications, SiGe HBT, Germanium Content

1 INTRODUCTION

The strengths of compound and single element semiconductors have been combined in SiGe HBTs (Heterojunction Bipolar Transistors) since the early 1990's. HBTs are built with a wide band gap material for the emitter and narrow band gap for the base, such that the narrow band gap material for the narrow base region will result in very high gain, high frequency response f_t , but still will have acceptable collector to emitter breakdown voltage [2,3]. This makes SiGe systems very popular today.

HBTs have found applications in medium scale integrated circuits operating at GHz frequencies. Applications include digital phase locked loops for microwave frequency synthesis chip sets, for fiber-optic communications, and analog-digital converters.

The choice of circuit to investigate germanium content dependence on RF IC performance parameters was a 2.4 GHz bipolar low noise amplifiers (LNA) [4]. The LNAs have been widely used in wireless communications applications. LNAs were studied in terms of electrical circuit parameters such as output-gain, noise-figure, and the third order intercept point. Then, dependence of semiconductor device, and silicon processing parameters for implementing the multiple statistical simulation approach methodology was investigated.

The LNAs have been widely used in many applications including wireless personal communication systems. These low noise amplifier circuits were characterized in terms of electrical circuit parameters such as noise figure (NF), and output gain, Table 1.

	Circuit Simulation			*Electrical Goals*		
Parameter	*2.4 GHz*	*2.45 GHz*	*2.5 GHz*	*Min*	*Typ*	*Max*
Av (dB)	17.1	17	16.9	17	20	23
NF (dB)	4.6	4.6	4.6	-	2	3
IP3o(dB_m)	18.2	-	18.6	12	-	-

Table 1: The SPICE circuit simulation data of three output electrical parameters over operation frequency at V_{cc} =2.7 volts. The last three columns shows electrical goals over operation frequency and voltage.

The next step was to obtain the circuit equations for these performance parameters using the small signal model. The output gain A_v , the noise figure (NF) and the third order intercept point (IP3o) for the bipolar LNA (1) can be given by the Equations 1 through 3, respectively,

$$A_v=20\log\left\{\sqrt{\frac{V_p\beta^3V_t^3C_\pi I_{cc}^2+V_p\beta^2V_t^2I_{cc}^3}{(I_{cc}V_t\beta+\beta I_{cc}^2Z_e+I_{cc}Z_e\beta V_tC_\pi+I_{cc}^2Z_e)(2V_t^2\beta C_\pi+2V_tI_{cc})^2}}\right\} \quad (1)$$

$$NF=10\log\left\{\frac{2\beta^2I_{cc}V_t(|Z_y|)^2(R_{in}+r_b+RE)+(|Z_y|)^2(|Z_x|)^2+4R_{in}^2\beta I_{cc}^2(|Z_x|)^2}{2R_{in}\beta^2V_tI_{cc}(|Z_y|)^2}\right\} \quad (2)$$

$$Z_y \_ 2R_{in}\beta V_tC_\pi+2R_{in}I_{cc}+\beta V_t$$

$$Z_x \_ 2R_{in}\beta V_tC_\pi+2R_{in}I_{cc}-\beta I_{cc}Z_e$$

$$IP3o= 9+ 10\log\left\{\frac{Vp'Icc^2}{2(\beta Vt\,|C\pi|+Icc)10^{-3}}\right\} \quad (3)$$

2 STATISTICAL SIMULATIONS AND GERMANIUM CONTENT EFFECT

These electrical performance parameters presented Equations 1 through 3 and effects of silicon processing on

(*) The author is currently with ***Texas Instruments, Inc.***, Dallas, TX. Levent.Sipahi@ti.com these electrical goals of the LNA were separately investigated. Physics-based mathematical models for the each circuit spec output parameter were represented by semiconductor device and processing parameters. After that, micro-level semiconductor device models via MATLAB™ were created. These physics-based device and process models were then coupled with unique statistical simulation software called STADIUM [5] to obtain the dependence of the bandgap (Figure 1) and the beta (Figure 2) on germanium content in Si-Ge HBTs. Furthermore, how much each silicon processing parameter has an effect on the statistical variation of the electrical performance parameters of these Si-Ge HBTs was investigated. STADIUM is a software program which couples computer simulators to a highly strong statistical method so called design of experiments.

Si and Ge are chemically compatible elements. They can be mixed to form a stable alloy ($Si_{1-x}Ge_x$, where x denotes the mole fraction) despite nearly 4% lattice constant mismatch. An empirical band gap curve for unstrained bulk alloys of $Si_{1-x}Ge_x$ based on the literature as a function of Ge content has been reported [6] and utilized in this work as shown in Figure 1. Then, via curve fitting, a polynomial formula based on Germanium percent concentration was determined as shown as the solid line in Figure 1.

The input parameters for the bipolar LNA device simulations are tabulated in Table 2. As for the statistical simulations, the long list of these input parameters in Table 2 have been screened via statistical simulations and then some semi-empirical and random low and high values have been assigned to the highest contributor of seven input variables as shown in Table 2.

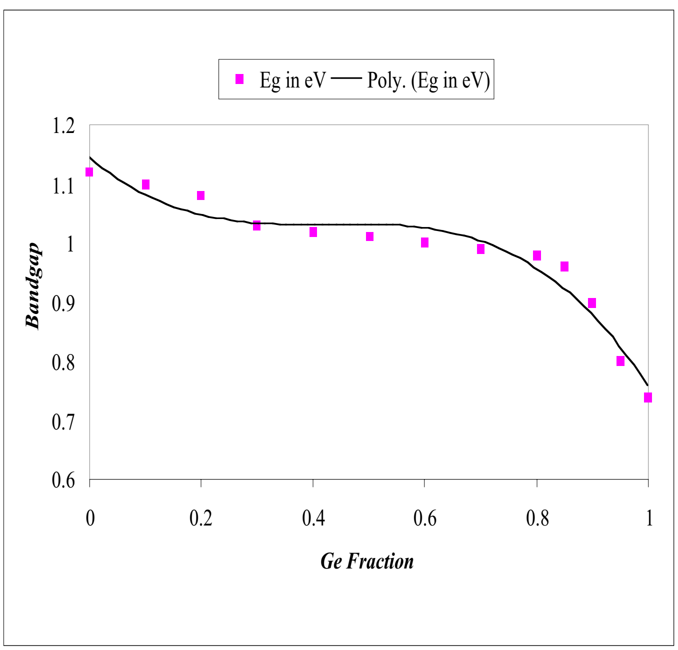

Figure 1. Empirical energy bandgap for unstrained bulk $Si_{1-x}Ge_x$ as a function of Ge content calculated in this work.

Then these first seven influential input variables have been used to run simulations using a statistical technique so called fractional factorial design with resolution III over operation frequency and supply voltage. The factor contributions of these variables for each three output parameters along with mean and standard deviations have been calculated and compared to measurement values. The first selected seven input variables, doping concentration in base, doping concentration in emitter, collector-emitter voltage, emitter resistance, DC operating supply current, emitter width, and emitter and lead inductance as listed in Table 2 have been used to run multiple statistical simulations. Using these assigned low and high values, three output responses were simultaneously simulated over operation frequency and supply voltage. Extraction of simulation data supplied necessary data for mean and standard deviation of each output response, and the individual factor contributions for each input variables along with the prediction equation coefficients. Also, the factor contribution is a number which

Symbol	**Input Parameter**	**Low**	**High**
N_a (cm^{-3})	Doping concentration in Base	6E17	6.2E17
N_{dE}(cm^{-3})	Doping concentration in Emitter	3E18	3.2E18
V_{ce} (V)	CE voltage	0.9	1.0
I_{cc} (mA)	DC operating supply current	15.0	15.2
W_e (μm)	Emitter width	30	35
r_e (Ω.m)	Emitter resistance	25E-6	30E-6
L_e (H)	Emitter and lead inductance	1E-9	1.1E-9
V_{cc} (V)	Supply voltage	2.7 or 3.0 or 3.3	
f (GHz)	Operation frequency	2.4 or 2.45 or 2.5	
Q_B	Bulk charge	not varied	
T	Diffusion time	not varied	
T_d	Diffusion temperature	not varied	
D	Diffusion coefficient	not varied	
N_c	Doping concentration in Collector	not varied	
D_n & D_p	Diffusion constant for electrons & holes	empirically calculated	
τ_n (s)	Life time of electrons	2.5E-3	
τ_p (s)	Life time of holes	2.5E-3	
x_{jB}	The Collector-Base junction depth	0.433E-4	
x_{jE}	Emitter junction depth	0.316E-4	
C_{je}	Emitter-Base junction depletion cap	2.9E-9	
r_b	Transistor noise base resistance	616E-6 (Ω.m)/We	
T	Operation temperature	25 °C	

Table 2: Overview of input parameters and their randomly selected low and high values for STADIUM statistical simulations.

is used to determine the effect of the input variables on the variability of the each output response. Thus, the important factors to the output parameter can be easily attained by the factor contribution of each individual input.

Since the common emitter current gain or beta, _, is strongly process dependent through emitter injection efficiency _, a macro circuit electrical parameter model in conjunction with using semiconductor device parameters and associated manufacturing process parameters for the circuit parameters was generated as follows.

$$\_ = \frac{\alpha}{1-\alpha} = \frac{\gamma\beta_T}{1-\gamma\beta_T} \qquad (4)$$

The injection efficiency was a direct function of electron and hole diffusion constants, doping concentrations in base and emitter and base and emitter widths as,

$$\_ = [1+ \frac{D_p N_a x_B}{D_n N_{dE} x_{jE}}] \qquad (5)$$

but now in Si-Ge HBTs, the injection efficiency will have another form as shown in the following equation

$$\_ = [1+ \frac{D_p N_a x_B}{D_n N_{dE} x_{jE}} \exp{(-\frac{\Delta E_g}{kT})}]^{-1} \qquad (6)$$

where ΔEg, emitter to base band gap difference of a HBT system. The band gap of the alloy system such GaAlAs is a function of AlAs mole fraction and can be given by Eg=1.424+1.247x for x<0.45 [7]. However, there is no such direct clean expression for $Si_{1-x}Ge_x$ system and Ge content determines the bandgap of this system as shown in Figure 1 and needs to be empirically calculated.

3 RESULTS AND CONCLUSIONS

For 0% germanium content (i.e. pure Si), the output gain simulation results for bipolar LNA displayed that the highest impacting input parameter was the doping concentration in emitter, n_{de} , as 65.53%. The remaining others from high to low were the doping concentration in base, n_a , and the collector emitter voltage V_{ce} nearly 15% each, the emitter inductance, l_e , 3.2%, the supply current, I_{cc} , 1.44% and almost negligible emitter resistance and width factor contribution. However, the noise figure simulations showed that the largest impacting input parameter was now the emitter width, W_e , rather than doping concentration in emitter, n_{de} , as was the case for the voltage gain. The factor contribution for the emitter width is 63.23 %. The other six parameters, high to low, were the emitter resistance, the doping concentrations in emitter and base, the DC operating supply current, the emitter inductance and the collector emitter voltage.

To investigate the effect of material variations on the output of the LNA, the germanium content was varied by one percent increments and simulations were run. For this part, the other previously studied input parameters were the same

Factor	*0% Ge Content Mean*	*0% Ge Content σ*	**Si-Ge system**	*Si-Ge σ*	*Ge Content %*
Av (dB)	16.39	0.24	18.45	0.68	
NF (dB)	3.79	0.07	3.27	1.04	1% to 2%
IP3o (dB_m)	16.39	0.20	14.64	0.60	
Av (dB)	16.39	0.24	19.69	0.65	
NF (dB)	3.79	0.07	3.57	0.07	2% to 3%
IP3o (dB_m)	16.31	0.20	13.52	0.59	
Av (dB)	16.39	0.24	20.91	0.62	
NF (dB)	3.79	0.07	3.52	0.07	3% to 4%
IP3o (dB_m)	16.31	0.20	12.40	0.58	
Av (dB)	16.39	0.24	22.00	0.59	
NF (dB)	3.79	0.07	3.49	0.07	4% to 5%
IP3o (dB_m)	16.31	0.20	11.38	0.56	
Av (dB)	16.39	0.24	23.06	0.57	
NF (dB)	3.79	0.07	3.46	0.07	5% to 6%
IP3o (dB_m)	16.31	0.20	10.37	0.54	
Av (dB)	16.39	0.24	27.55	0.45	
NF (dB)	3.79	0.07	3.40	0.06	10% to 11%
IP3o (dB_m)	16.31	0.20	6.0	0.44	
Av (dB))	16.39	0.24	30.83	0.36	
NF (dB)	3.79	0.07	3.37	0.06	15% to 16%
IP3o (dB_m)	16.31	0.20	2.75	0.35	

Table 3: Comparison of mean and standard deviation values of three output parameters of the bipolar LNA 0% Germanium content versus varying Ge content at V_{cc} = 3.3 V and at f = 2.45 GHz.

and the variations as listed in Table 2. Only the supply current was deactivated from the input variable list and germanium content was added as an input variable. These results are tabulated in Table 3

Increasing the germanium content results in a decrease in the bandgap. Thus, this decrease in the bandgap gives rise to significant increase in the common emitter current gain or the beta, as shown in Figure 2. An increase in the beta results in a voltage gain increase as predicted by the theory explained above, as tabulated in Table 3 and as shown in Figure 3.

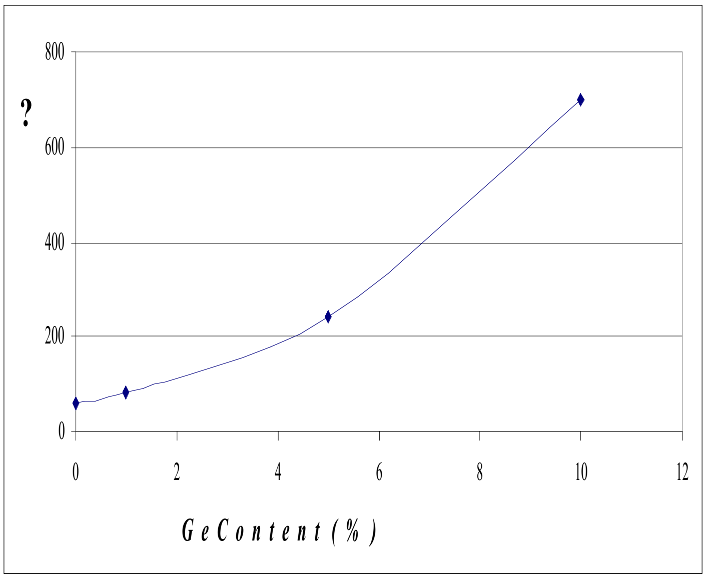

Figure 2: The beta versus germanium content in % calculated in this work.

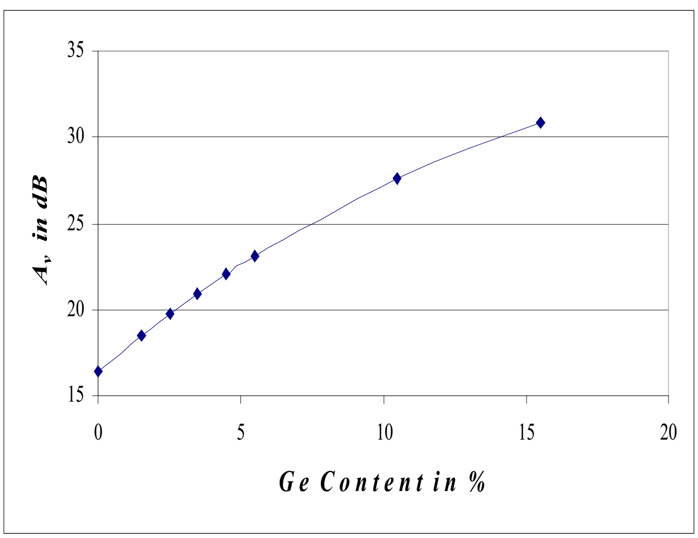

Figure 3: Germanium content effect on the output gain in SiGe system.

The factor contribution to the variation of the voltage gain for this case is dominated by the germanium content (nearly 88%) followed by doping concentration in emitter 8% and then by doping concentration in base 2%. Better and lower noise figure numbers were obtained but this decrease was not linear. The standard deviation remained constant unlike the increase in standard deviation values of the voltage gain. The most striking observation was the factor contributions were almost evenly split among all seven variables. But still the emitter width with 17% was the highest followed by the emitter resistance with 16.1% and Ge content with 15.8 %.

Since the gain increase observed in Table 3 was so dramatic, the linearity of the transistor rapidly deteriorated and resulted in unacceptable third order intercept point numbers after the 5% Ge content.

CONCLUSIONS

The unique novel statistical approach for analyzing and understanding associated manufacturing process parameters for the electrical circuit parameters was successfully extended to SiGe HBTs. Furthermore, output gain improvement of Si-Ge LNAs have been clearly explained by means of device physics theory and statistically simulated in terms of bandgap modeling and bandgap engineering. Thus, these results of this analysis give the statistical dependence of these output parameters on the semiconductor device and silicon processing parameters and resulted in optimum solutions for any circuit design and systematic high volume IC manufacturing.

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