Mechanically Strained Si–SiGe HBTs

F. Yuan, S.-R. Jan, S. Maikap, Y.-H. Liu, C.-S. Liang, and C. W. Liu

***Abstract*—The current gain ($\beta = I_C/I_B$) variations of the mechanically strained Si–SiGe heterojunction bipolar transistor (HBT) and Si bipolar junction transistor (BJT) devices are investigated experimentally and theoretically. The β change of HBT is found to be 4.2% and -7.8% under the biaxial compressive and tensile mechanical strain of 0.028%, respectively. For comparison, there are 4.9% and -5.0% β variations for BJT under the biaxial compressive and tensile mechanical strain of 0.028%, respectively. In HBT, the mechanical stress is competing with the compressive strain of SiGe base, inherited from the lattice misfit between SiGe and Si. The current change due to externally mechanical stress is the combinational effects of the dependence of the mobility and the intrinsic carrier concentration on strain.**

***Index Terms*—Bipolar junction transistor (BJT), heterojunction bipolar transistor (HBT), mechanical strain.**

I. Introduction

THE CURRENT gain ($\beta = I_C/I_B$) of bipolar transistors can be changed upon externally mechanical stress. The saturation current characteristics of an Si bipolar junction transistor (BJT) device with mechanical stress (uniaxial strain) have been studied [1]. However, the effect of mechanical strain on the heterojunction bipolar transistors (HBT) has not yet been reported. In this letter, we will report the performance of Si–SiGe HBT under the biaxial compressive and tensile mechanical stress with the comparison of BJTs. To obtain the similar biaxial strain of SiGe on Si due to the lattice misfit, a new mechanical setup is used to produce biaxial strain.

II. Experiment

A silicon (100)-wafer was processed in the standard bipolar process and the vertical npn transistors were realized. In the case of HBT, the base region was grown by ultrahigh-vacuum chemical vapor deposition (UHVCVD) using SiH_4 and GeH_4 precursors. The SiGe base consists of an unintentionally-doped 30-nm Si layers, a 30-nm SiGe graded layer with Ge = 0% to 20% and a boron concentration of 10^{19} cm^{-3}, and an unintentionally doped 30-nm $Si_{0.8}$ $Ge_{0.2}$ space layer. The base of BJT is formed by conventional high-temperature epitaxy with a boron concentration of 5×10^{18} cm^{-3}. Both devices have poly-Si emitters with the single-crystalline Si layer after the emitter drivein process.

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F. Yuan, S.-R. Jan, S. Maikap, and C. W. Liu are with the Department of Electrical Engineering and Graduate Institute of Electronics Engineering, National Taiwan University, Taipei, Taiwan, R.O.C.

Y.-H. Liu, C.-S. Liang, and C. W. Liu are with the Electronics Research and Service Organization (ERSO), ITRI, Hsinchu 300, Taiwan, R.O.C. (e-mail: chee@cc.ee.ntu.edu.tw).

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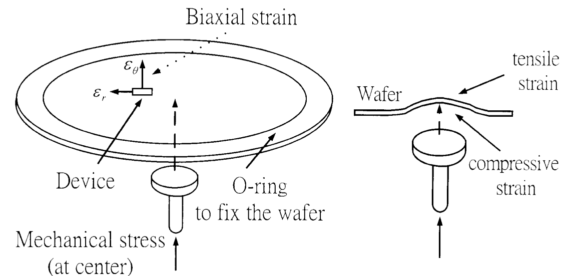

Fig. 1. Schematic diagram of the externally applied mechanical stress on the wafer. The biaxial strain can be considered as the arithmetic average of the strain along the azimuthal direction ($\hat{\theta}$) and the radial direction ($\hat{r}$).

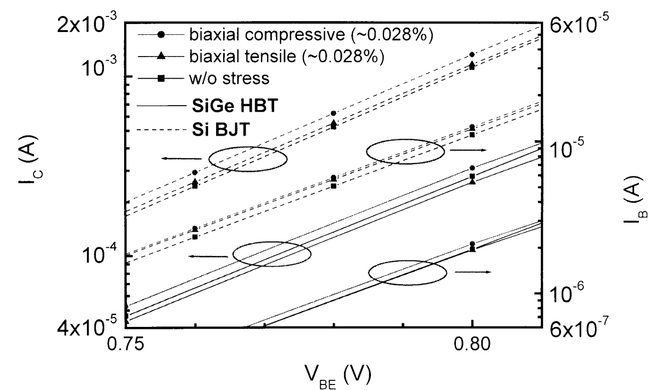

Fig. 2. Gummel plot of the Si BJT and the SiGe HBT devices without and with mechanical stress (biaxial strain $\sim 0.028\%$). The base–collector bias is 0 V.

We have applied externally a uniform mechanical displacement at the center with the diameter of 13 on 100 mm wafers for both SiGe HBT and Si BJT devices (Fig. 1). The finite element simulation by ANSYS has been performed to verify the strain distribution [2]. The strain at 13 mm from the center is ~0.033% and ~0.024% along azimuthal and radial directions, respectively. The average biaxial strain used in this study is 0.028%.

III. Results and Discussion

Fig. 2 shows the Gummel plots of the SiGe HBT and Si BJT devices under the biaxial tensile or compressive mechanical strain of ~0.028%. The current changes under the biaxial tensile strain are found to be -7.8% and -0.1% for I_C and I_B, respectively, at $V_{BE} = 0.8$ V. For the biaxial compressive stress, there are 11.6% and 7.1% changes on I_C and I_B, respectively. The β improvement under the compressive stress is due to the higher I_C enhancement than I_B. In contrary, the device under tensile stress has the decrease of β due to the severe decrement

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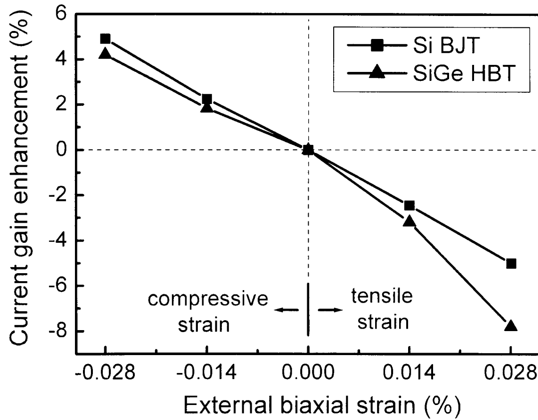

Fig. 3. Current gain changes of SiGe HBT and Si BJT device as a function of stress level. It shows a good linear dependence on the strain field.

TABLE I
SIMULATED AND MEASURED CURRENT CHANGE OF BOTH SiGe HBT AND Si BJT DEVICES AT $V_{\rm BE} = 0.8$ V

Percentage change with ε_{ave} = 0.028%	μ_B	n_{iB}^2	Theoretical data			Experimental data			Simulation data
			I_C ($n_{iB}^2 \cdot \mu_B$)	I_B ($\sim n_{iE}^2$)	gain	I_C	I_B	gain	gain
SiGe HBT tensile	0.1	-9.3	-9.2	5.1	-13.6	-7.8	-0.1	-7.8	-7.2
SiGe HBT compressive	-0.1	9.3	9.2	6.6	2.4	11.6	7.1	4.2	4.7
Si BJT tensile	-4.5	11.0	6.0	7.3	-1.2	4.1	9.5	-5.0	-5.0
Si BJT compressive	2.6	14.1	17.1	9.4	7.0	18.1	13.1	4.9	5.0

of I_C than I_B. The current gain changes have also a linear dependency on external biaxial mechanical stress (Fig. 3).

For HBTs, the strained-SiGe base on relaxed-Si wafer has a compressively biaxial strain without any mechanical stress due to the lattice misfit between Si and SiGe. The biaxial compressive/tensile mechanical strain increases/decreases the original compressive strain. The mechanical strain is competing with the strain of SiGe base due to the lattice misfit. Table I summarizes the measured changes of I_C and I_B of both devices with the externally mechanical stress. At moderate current level of the Gummel plot, the collector current density is characterized by [3]

$$J_C = \frac{qn_i^2}{G_B}\exp\left(\frac{qV_{BE}}{kT}\right), \quad G_B = \int_0^{W_B} \frac{n_i^2}{n_{iB}^2}\frac{p_p}{D_{nB}}dx \quad (1)$$

Because of Einstein relations $D = \mu \cdot kT/q$, the I_C and I_B are basically proportional to $\mu_B n_{iB}^2$ and $\mu_E n_{iE}^2$, respectively, where μ and n_i are the minority-carrier mobility and the intrinsic carrier concentration, respectively. Although the effective densities of states $(N_C N_v)$ are quite different between SiGe and Si, we have compared the $N_c N_v$-product of the SiGe HBT device itself, with and without external mechanical stress. The change of $N_c N_v$-product is within 1% in our mechanical strain conditions. Therefore, the n_i^2 is proportional to $\exp(-E_g/qV_T)$, where V_T is thermal voltage and E_g is the bandgap. The 0.0417% biaxial compressive strain is equivalent to strained-$\mathrm{Si_{0.99}Ge_{0.01}}$ on relaxed-Si condition (100% Ge = 4.17% biaxial compressive strain). And ΔE_g of biaxial mechanical stress can be estimated as ± 7.4 meV per 0.0417% strain (=1% Ge) [4]. However, this value of ΔE_g is the combinational effect of both strain and Ge concentration. To obtain the bandgap change due to only Ge content, the bandgap difference between relaxed-SiGe and relaxed-Si is estimated to be -4 meV per 1% Ge [4]. Therefore, ΔE_g due to the strain only is estimated to be -3.4 meV per 0.0417% strain, and is used for both biaxial tensile and compressive mechanical strain. Note that the compressive strain in the SiGe base due to the misfit is still larger than the externally mechanical strain, and the net strain in SiGe base is still compressive. The n_{iB}^2 change can be obtained from ΔE_g (Table I). For HBT devices, the biaxial tensile mechanical strain yield bandgap increase of the base and consequently the I_C reduction.

The vertical mobility change due to the combinational effects of strain and Ge concentration can be estimated from [5]. The mobility changes due to Ge concentration only can be obtained by the relaxed-SiGe [6]. For the first-order assumption, these two effects can be regarded as additive. Therefore, the mobility change due to the external biaxial mechanical strain can be approximately given in Table I. Then, the change on $I_C(\sim \mu_B n_{iB}^2)$ can be obtained, it shows a qualitative agreement between measurement and theoretical value.

In the case of Si BJT, the 0.0417% biaxial tensile strain is equivalent to strained-Si on relaxed-$\mathrm{Si_{0.99}Ge_{0.01}}$ condition. The ΔE_g of biaxial tensile mechanical stress can be estimated as -4 meV per 0.0417% strain (=1% Ge of the relaxed SiGe) [4], [5], [7]. Furthermore, ΔE_g of biaxial compressive mechanical stress was reported as -5.1 meV per 0.0417% strain [7]. Therefore, the changes of n_i^2 and mobility [5] in the base regions of Si BJT can be obtained to get the $I_C$change of BJTs (Table I).

Both the SiGe HBT and Si BJT devices have poly-Si emitter regions, and the mechanical strain presumably has no effect on poly-Si regions. However, the emitter is also extended to the single-crystalline Si layer by the emitter drive-in process. The hole minority mobility was relatively constant in the heavily doped emitter region (5×10^{20} cm^{-3}) [8], and the hole mobility variation due to the biaxial mechanical strain of 0.028% is also very small ($<$0.1%) [5], [7]. Therefore, the I_B change of BJT at fixed $V_{\rm BE}$ due to the mechanical stress is [3]

$$\frac{\Delta I_B}{I_B} \approx \frac{W_E}{W_E + L_{pE1}\tanh(W_{E1}/L_{pE1})} \times \left(\frac{\Delta n_{iE}^2}{n_{iE}^2}\right)_{\rm single-crystal}. \quad (2)$$

Using $W_E = 80$ nm, $W_{E1} = 300$ nm, and $L_{\rm pE1} = 40$ nm, the theoretical I_B change is listed in Table I. The I_B change of HBTs is obtained in similar way, but the smaller $W_E = 35$ nm is used due to the low thermal budget of the emitter drive-in. However, the secondary ion mass spectrometry analysis (not shown here) shows that the emitter region also extends to the graded Ge epi-region. This SiGe region in the emitter is not taken into account in the theoretic calculation of Table I, since too many

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parameters can be adjusted to fit the data. Furthermore, the current gain for both SiGe HBT and Si BJT devices are simulated by commercial device simulator ISE [9], (Table I). The deformation potential model to calculate n_i^2 and piezoresistive model [10], [11] to calculate mobility are used to simulate the change in the band structure and the mobility, respectively, in the simulation. The current gains from the simulation are showing the similar trend, but the values are slightly different.

IV. Conclusion

The mechanic strain can change the intrinsic carrier concentration, and electron minority mobility, but has little effect on hole minority mobility. These combination effects determine the I_C, I_B, and β change for HBTs and BJTs under the biaxial mechanical strain. The biaxial compressive strain can enhance the current gain, and it seems to be useful for the BJT and HBT circuit design.

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