Research Program Project Report

Simulation and Calibration of HBT

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June 5, 1998

Contents

1 Introduction

CMOS is presently the preferred VLSI technology due to its low power dissipation and high packing density. BJT, however, can supply several times higher drive current of an equal size MOS transistor, thus larger drive current translates into faster switching of large capacitive loads. In real world, the ideal characteristics of BJT should be deviated from the ideal that were associated with base doping. In particular, base-width modulation, the extrinsic base resistance and the voltage drop across the emitter leading to current crowding are all decreased by increasing the base doping. Unfortunately, increasing the base doping also decreases the emitter efficiency, in turn reduces the gain of a standard transistor, that is a trade-off between in designing a standard BJT [1]. The situation is different in HBT where the base is the most heavily doped region and the emitter is made from a wider bandgap semiconductor than the base.

The Si/SiGe heterojunction recently has been extensively accepted due to its high compatibility with conventional silicon process technologies, such as HBTs [2], SiGe heterojunction p-channel MOSFETs [3] and SOIs [4], [5]. Since silicon and germanium are atoms from column IV, the processing of SiGe is potentially compatible with existing silicon technology, and implanted germanium is commonly used to reduce boron diffusion in boron-implanted silicon without side effects. The application of Si/SiGe heterojunction device has focused mainly on both bipolar and field-effect transistors. Recently, this has also been applied to SOI devices.

In this report

1. DC and AC characteristics of BJT and SiGe HBT are shown and compared using device simulation [6]-[7]

2. Calibration of device parameters is performed for the real measured Gummel plot of $In_{0.52}Al_{0.48}As$ / $In_{0.53}Ga_{0.47}As$ / $In_{0.53}Ga_{0.47}As$ III-V compound HBT provided by Hewlett-Packard Laboratories.

2 Advantages of HBT

In HBTs, the germanium exponentially alters the collector current for high-speed digital and microwave applications. A typical HBT's emitter has a bandgap that is wider than the bandgap in the base. The potential barrier formed at the emitter-base junction under such condition reduces the minority carrier injection from the base into the emitter to a significant level. This results in improved emitter efficiency and higher current gain. In addition to high injection efficiency, the base spreading resistance is small due to the high base doping. Also, the emitter-base capacitance can be quite small by the relatively low doping of emitter region [8].

HBTs have been fabricated by using molecular-beam epitaxy (MBE) and chemical-vapor deposition (CVD), as well as limited-reaction processing (LRP) [2]. In field-effect transistors, lots of interest is given to high-mobility p-channel MOSFETs to overcome the inferior performance of p-channel MOSFETs in CMOS applications caused by the lower hole mobility, typically two to three times less than the electron mobility [3].

Since the bandgap of the germanium is lower than that of the silicon, a discontinuity in the valence band is created in the Si/SiGe heterostructure, which can be effectively used to confine the mobile holes in the SiGe channel. As a result, the holes in the quantum well can have a higher mobility since the surface scattering effect in conventional MOS transistors has been avoided. It is also applied to SOI devices in order to either improve channel mobility of PMOS [5] or eliminate the parasitic bipolar effect by adding it in the source region [4].

The advantages of HBT are summarized as follows [9]:

- High current gain (β) independent of emitter and base doping. High current gain can be obtained irrespective of the emitter and the base doping concentration. Because of the different intrinsic carrier density in emitter and base material, emitter to base doping ratio is not the dominant factor to determine the current gain. In addition, the different potential barrier of valence band in emitter base junction blocks the carrier injection into the emitter from the base, very high emitter efficiency can be achieved.

- Reduced base resistance, contact resistance and Early effect. High base doping reduces base resistance, contact resistance, and Early effect. Using high base doping structure, many parasitic effects in conventional homojunction BJT can be reduced without sacrificing emitter efficiency. Also, less emitter current crowding effect is incurred because of a low voltage drop along the emitter-base junction, so current flows uniformly compared with BJT structure.

- Smaller emitter-base and collector-base capacitances. Emitter and base, base and collector junction capacitance are small due to low emitter and collector doping concentration. Relatively low doping in emitter and collector region enable to lower the junction capacitance for E-B and E-C junctions. Therefore emitter delay charging time and collector RC time can be lowered.

- Graded base and built-in electric field can be realized without compromising on base doping. By the bandgap engineering,the gradual change of mole fraction for heterojunction can induce the built-in field in the base region and this enhances the base transit time for the injected carriers. Thus frequency response is much improved than homo-junction BJT.

- Higher breakdown voltage and ballistic injection as well as wider operating temperature ranges when wide bandgap material is used.

3 Current gains (β) of BJT and HBT

The current gain (β) of a bipolar junction transistor can be expressed as [10]:

$$\beta \cong \frac{N_E D_{nB} W_E}{N_B D_{hE} W_B}\, e^{-\Delta Eg/kT} \tag{1}$$

where ΔEg is the bandgap difference between the base and the emitter, D_{nB} is the electron diffusion constant in the base region, and D_{hE} is the hole diffusion constant in the emitter region. N_E and N_B are the doping concentrations in the emitter and the base regions, and W_E and W_B are the emitter and base width, respectively. Fig. 1 shows the energy diagram of n$^+$/p-SiGe/n$^+$ structure and the conduction bandgap reduction is

$$\Delta E_{C(Si/SiGe)} = \chi_{Si} - \chi_{SiGe} \tag{2}$$

where χ is the electron affinity. For Si/SiGe structure, since $\chi_{Si} \cong \chi_{SiGe}$ and the conduction bandgap reduction at Si/SiGe is less than 0.02 eV, most of the bandgap reduction occurs at the valence band

$$\begin{aligned}\Delta E_{V(Si/SiGe)} &= \Delta E_C - [\Delta Eg_{(Si)} - \Delta Eg_{(SiGe)}] \\ &\approx -[\Delta Eg_{(Si)} - \Delta Eg_{(SiGe)}] \\ &= -\Delta Eg_{(Si/SiGe)} \end{aligned} \tag{3}$$

Thus, the difference in the electron barriers between the base and the emitter becomes -ΔE_V [2], and eq. (1) can be written as

$$\beta \cong \frac{N_E D_{nB} W_E}{N_B D_{hE} W_B}\, e^{\Delta E_V/kT} \tag{4}$$

Therefore, the current gain of the bipolar transistor in a SiGe HBT can be improved exponentially as $\exp(\Delta E_V/kT)$.

As a practical matter, however, it should be noted that current gain in actual HBTs tend to be lower than computation with the above equation by the significant generation-recombination current from the emitter-base junction. Though the proper surface passivation poses more of a problem than in silicon devices, HBTs are now produced with being very respectable as high-frequency devices.

4 Simulation and Analysis for BJT and SiGe HBT

The characteristics of SiGe HBT are analyzed by the heterojunction analysis module [6]. This module handles the properties of materials that meet at the heterojunction by including the energy bandgap parameters, electron affinity, density of state, various parameters for describing recombination, and mobility. Since intrinsic Fermi potential is not the general solution to Poisson's equation when solving for structures that contain heterojunction

Table 1. Simulation results of BJT and SiGe HBT

item	BJT	SiGe HBT
N_e	$5.0\times10^{19}/cm^3$	$1.0\times10^{20}/cm^3$
N_b	$1.0\times10^{18}/cm^3$	$4.0\times10^{19}/cm^3$
N_c	$5.0\times10^{15}/cm^3$	$2.0\times10^{16}/cm^3$
τ_b	0.1μs	0.01μs
W_b	0.1 μm	0.1 μm
β(V_{be}=0.5V,V_{ce}=2V)	30	900
I_c(I_b=5μA,V_{ce}=5V)	0.2 mA	0.45 mA
C_{jbase}(freq=1MHZ)	8.2 fF/μm	7.9 fF/μm
g_m (freq=1MHZ)	900	2000

due to the property differences of adjacent materials, Poisson's equation must be written as [7]

$$\nabla^2(\psi - \theta) = \frac{\rho_s}{\epsilon} \tag{5}$$

where θ is band structure parameter given by

$$\theta = \chi + \frac{E_g}{2q} + \frac{kT}{2q}\ln\frac{N_C}{N_V} \tag{5}$$

where χ is the electron affinity and N_C and N_V are effective density of states in the conduction band and valence band.

Fig.2 (a) and (b) shows simulation structures for BJT and SiGe base HBT, respectively. The base-collector of HBT is linear grade junction with Ge mole fraction of 23 % and the base width of approximately 0.1μm. The base doping of HBT (4.0×10^{19}cm^{-3}) is higher than that of BJT (1.0×10^{18}cm^{-3}) such that reduced base resistance and Early effect are expected. Emitter doping concentrations of BJT and HBT are 5.0×10^{19}cm^{-3} and 1.0×10^{20} cm^{-3}. Collector doping concentrations are 5.0×10^{15}cm^{-3} and 2.0×10^{16}cm^{-3} for BJT and HBT, respectively. Fig. 3 illustrates simulated device structures of BJT and HBT as well as their internal doping profiles.

Fig. 4 shows electrical characteristics for both devices. Current gain of HBT is higher than BJT (β_{HBT}=900, β_{BJT}=30) due to the narrow band gap of base region, as shown in Gummel plots, Fig. 4 (a), (b) and (c). Also, higher collector current with respect to collector bias is obtainable in HBT, as shown in Fig. 4 (d) and (e) ($I_{c,HBT}$ = 0.45 mA, $I_{c,BJT}$ = 0.20 mA at I_b=5μA, V_{ce}=5V).

The Base junction capacitance of HBT as a function of frequency is less than BJT, as shown in Fig. 5 (a), such that faster device operation is achievable. Furthermore, the transconductance of HBT is higher than BJT as shown in Fig. 5 (b). Table 1 summarizes the device specs and simulation results of BJT and HBT.

5 Calibration of III-V Compound HBT

The viability of III-V compound HBT for low-noise, wireless RF front-end application is emerging due to the higher gain and lower noise figure (lower base resistance) in GHz frequency range compared to silicon bipolar transistors. In this section, device simulation and calibration are devoted for $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/In_{0.53}Ga_{0.47}As$ HBT device and its measured Gummel curve.

Fig. 6 and 7 show a cross-section of $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/In_{0.53}Ga_{0.47}As$ HBT where a linear graded junction is built between the emitter-base junction with InAlGaAs. Fig. 8 (a) and (b) show the band diagram of the HBT at the zero bias and $V_{ce} = V_{be} = 1$V condition, respectively. The energy gaps of emitter ($In_{0.52}Al_{0.48}As$) and base ($In_{0.53}Ga_{0.47}As$) regions are 1.46 and 0.7 eV, respectively. Fig. 9 shows flowline of current at bias of $V_{ce} = V_{be} = 1$V.

In practice, however, the current gain in actual HBTs tends to be lower than that from the calculation because of the significant surface recombination current at the emitter-base junction. The measured collector-base current in Fig. 10 clearly shows this effect. The bias condition is $V_{bc} = 0$V while V_e sweeps from 0 to -1V. The current gain at $V_{ce} = 1$V is around 50, which is much lower than that from the calculation.

Calibration is performed by modifying parameters for the surface recombination velocity and the carrier lifetime. The solid curves show the simulated results after calibration when surface recombination velocity parameters of emitter, base, and collector are 1.0×10^5, 1.0×10^4 and 1.0×10^6 cm/s, respectively. As a result, closer agreement can be obtained between the measured and simulated collector and base currents. At the low current, recombination dominates so that n of $qV_a/(nk_BT)$ approaches to '2'. The lifetime of InGaAs and InAlAs are both 0.2 ns in the case. Fig. 11 demonstrates $I_{ce} - V_{ce}$ characteristics for various I_b's with the calibrated parameters from the Gummel curve.

6 Conclusions

Higher current gain and reduced base resistance are achievable in SiGe HBT, because the potential barrier formed at the emitter-base junction under such condition reduces the minority carrier injection from the base into the emitter to a significant level, resulting in improved emitter efficiency and higher current gain. In addition to the high injection efficiency, the base spreading resistance is small due to the high base doping in HBT. Also, since the emitter-base capacitance is smaller than BJT, HBTs are suitable for the high-frequency devices. However, it is shown that the current gain becomes degraded than the ideal calculation value due to the effect of surface recombination base current, through the calibration of the real III-V compound HBT, $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As/In_{0.53}Ga_{0.47}As$.

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