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Influence of Heterojunction Position on SiGe HBTs with Graded BC Junctions

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Abstract: The influence of a heterojunction in the vicinity of a graded BC junction on the performance of npn SiGe HBTs is studied. SiGe HBTs differing only in heterojunction position in the vicinity of a graded BC junction are simulated by means of 2D Medici software for DC current gain and frequency characteristics. In addition, the simulated DC current gains and cut-off frequencies are compared at different collector-emitter bias voltages. Through the simulation results, both DC and HF device performance are found to be strongly impacted by degree of confinement of the neutral base in the SiGe layer, even in the absence of a conduction band barrier. This conclusion is of significance for designing and analyzing SiGe HBTs.

Key words: SiGe HBT; BC junction; HBE; relative position; device performance
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1　Introduction

SiGe HBTs have become an important research field because of their good microwave performance and low fabrication cost. Heterojunctions in the vicinity of the BC junction have a significant influence on the performance of HBTs. In npn SiGe HBTs, a heterojunction too far inside the base region causes degradation in both DC current gain and frequency performance[1]. On the other hand, a heterojunction too deep inside the collector region will result in a lower breakdown voltage and worse switching characteristics despite improvement in DC gain and frequency characteristics[2]. As a result, it is important to define a proper heterojunction position in the vicinity of the BC junction in order to optimize device design of SiGe HBTs.

The influence of collector heterojunction position on DC current gain and frequency performance is mainly due to the heterojunction barrier effect (HBE). Yuan and Song discussed this effect and developed physics-based models describing the formation of the parasitic barrier and its dependence on collector doping N_C, junction bias V_{BC}, and collector current density J_C[3]. Mushini and Roenker studied the relationship of parasitic barrier formation and base pushout, and their dependence on device Ge fraction, collector doping, and biasing with analytical doping profiles for emitter and base[4]. Yee and Houston developed a more accurate model[5] than Yuan[3].

In this paper, we simulate SiGe HBTs with different collector heterojunction positions to find the relationship between device performance and heterojunction positions. The doping profiles are obtained from SIMS results of device we have fabricated. So the simulation results could more accurately reveal the actual device performance than analytical doping profiles. The impact of a graded BC junction is also taken into consideration while previous studies[3~5] have paid little attention to it. This is necessary as it captures some of the actual situation.

2　Physical models and device structure

Simulation of SiGe HBTs different only in heterojunction positions in the vicinity of a BC junction have been carried out by means of 2D Medici software based on the drift-diffusion numerical device model. The BGN effect, SRH and Auger recombination, and the high field effect have been taken into consideration, but device self-heating has not been incorporated.

For the SiGe material parameters, we employ a linear energy band gap reduction with Ge[6]. The silicon model for band gap reduction due to heavy doping is used, and the effective densities of states for the conduction and valence bands, N_C and N_V, are calculated following Jain *et al*.[7]. The electron mobility and its doping dependence at high doping levels ($10^{18}cm^{-3}$) and low Ge content (<20%) have been modeled by an analytical model[8] following the re-

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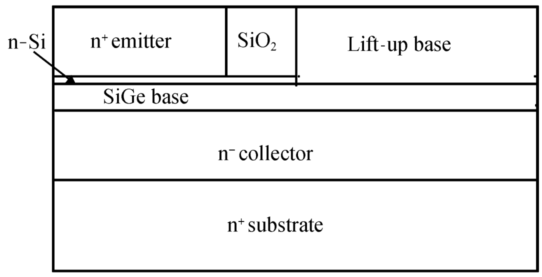

Fig. 1 2D structure of the devices for simulation

sults of Pejcinovic *et al*.[9,10]. For high electrical fields, the Hansch mobility model[11] is employed and its default values in the Medici simulator are used.

The devices for simulation are single emitter finger and base finger 2D structure, as shown in Fig. 1. The n^+ emitter width is 0.5μm and the lift-up base width is 0.7μm, and they are separated by a 0.2μm wide oxide. The lift-up base and external SiGe base are both highly doped to achieve a smaller external base resistance. The collector contact is defined at the bottom. Figure 2 shows the doping and Ge profiles of the SiGe HBTs structures for simulation, in which the emitter and base doping is from the SIMS result of a SiGe HBT fabricated by Tsinghua Microelectronics Institute, and the collector is doped with a uniform phosphorus concentration of 1×10^{16} cm^{-3} over a thickness of 500nm. As denoted in the figure, the quantity d stands for the location of the heterojunction relative to the metallurgical BC junction position, with $d < 0$ indicating that the heterojunction falls into the base side of the BC junction and $d > 0$ defining heterojunctions in the collector region while $d = 0$ implies coincidence of the two.

3 Simulation results and analysis

3.1 Influence of heterojunction position on DC current gain

Figure 3 shows the simulation results of β-I_c characteristics of HBTs with various d values. The current

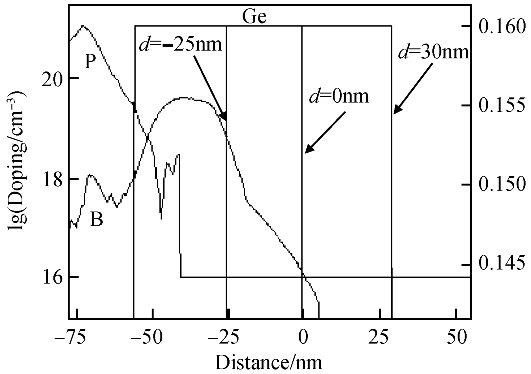

Fig. 2 Doping and Ge profiles of the SiGe HBTs for simulation

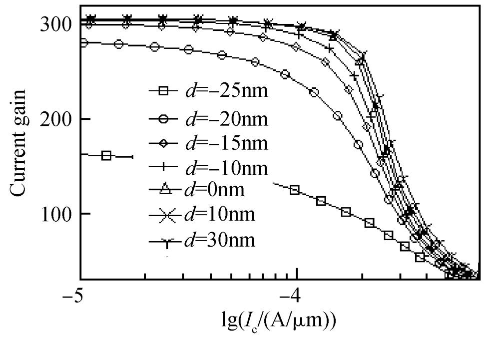

Fig. 3 β-I_c characteristics of HBTs with various d values at V_{ce} = 2V

gain is very low at $d = -25$nm and grows higher at $d = -20$nm. The current gains continue incveasing but tend to saturate when d is further increased.

Figure 4 shows the conduction band bottom of HBTs with various d values at $V_{ce} = 2$V, $V_{be} = 0.71$V, and I_c of about 10^{-5} A/μm, where the Kirk effect is not apparent. There exists an apparent conduction band barrier in the case of $d = -25$nm. When pushing the heterojunction toward the collector with d approaching -20nm, the conduction band barrier disappears, but the band is still higher than those of other d values. When d becomes large enough, the conduction bands for different d values start to converge, exhibiting nearly no differences.

When $d = -25$nm, the conduction band barrier is the main cause for the current gain decrease. On one hand, it introduces a reverse electrical field that retards the flow of electrons to collector from base and results in a low collector current. On the other hand, the accumulation of electrons in the base region caused by the retarding filed will give rise to a growth of base recombination current. As a result, the current gain is considerably reduced by the presence of the conduction band barrier. When $d = -20$nm, though with no barriers, the conduction band is still raised because of the existence of a partially depleted area, especially for a graded BC junction[12]. This lift-up conduction band decreases the base electron current

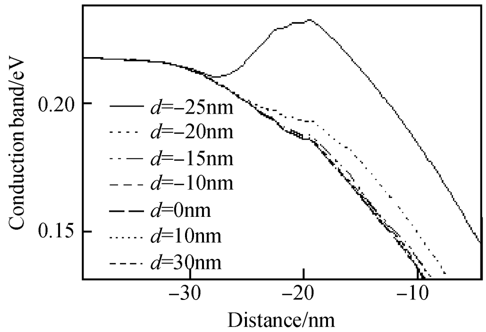

Fig. 4 Conduction band of HBTs with various d values at V_{ce} = 2V ($V_{be} = 0.71$V, $I_c \approx 10^{-5}$ A/μm)

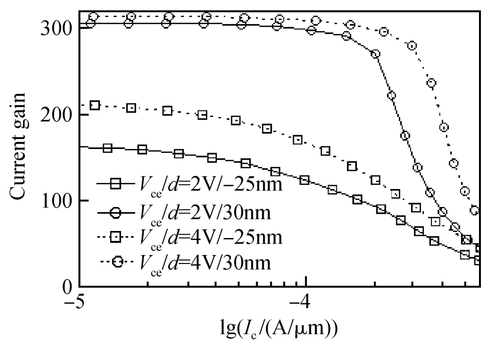

Fig.5 Comparison of β-I_c characteristics for HBTs with $d = -25$nm and $d = 30$nm at $V_{ce} = 2$V and $V_{ce} = 4$V

to the collector and increases the base transit time, which results in a current gain decrease, but not as seriously as the barriers. When d varies from -10 to 30nm, the conduction band and thereby the current gain change little at medium current level, which means that the conduction band in the vicinity of the BC junction will be influenced little and the current gain approaches its maximum value when the heterojunction is located far enough from the neutral base.

Figure 5 shows a comparison of β-I_c characteristics at $V_{ce} = 2$V and $V_{ce} = 4$V. When $d = -25$nm, the current gain at $V_{ce} = 4$V is larger than that at $V_{ce} = 2$V. This is because that a higher V_{ce} pushes the BC junction depletion edge more towards the inner base and results in a lower conduction band barrier, as shown in Fig. 6. So the lowered barrier by higher V_{ce} will be responsible for the increase of current gain.

3.2 Impact of heterojunction position on cutoff frequency

The heterojunction position has an important impact on the cutoff frequency. Figure 7 shows the f_T-I_c characteristics of HBTs with various d values at $V_{ce} = 2$V while Figure 8 is the corresponding conduction bands. It can be divided into three regions based on the f_T-I_c characteristics: (1) The heterojunction is too close to the neutral base and the conduction band barrier exists before f_T reaches the peak value (Heterojunction Barrier Effects occurring[3]). This will seriously increase the base transit time and decrease the peak cutoff frequency; (2) The heterojunction locates at a certain distance from the neutral base and there is no conduction band barrier before the f_T peak, but conduction band differs apparently at different d values. At this time, the peak cutoff frequency still varies for different d values though the frequency characteristic is much better than under the above condition. The cutoff frequencies do not have much difference at low I_c but do at high I_c. The conduction band now changes with different d values because the BC junction is graded and partially depletion. Comparing Fig. 8 and Fig. 4, the difference between them is that now SiGe HBTs operate at higher I_c currents, which introduces Kirk effects. As shown in Fig. 7 and Fig. 8, if the heterojunction leaves the neutral base further, the accelerating field around the BC junction will strengthen due to less conduction band lift-up and eventually result in a smaller base transit time and higher cutoff frequency; (3) The heterojunction is far enough from the neutral base and has little impact on the conduction band before peak cutoff frequency. As a result, the conduction band differs little at different d values. So condition (3) is the best with respect to cutoff frequency.

As shown in Fig. 7, when $d = -25$nm, the con-

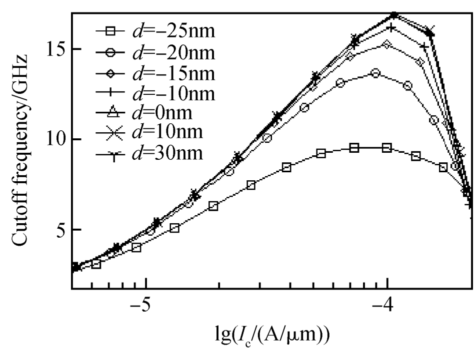

Fig.7 f_T-I_c characteristics of HBTs with various d values at $V_{ce} = 2$V

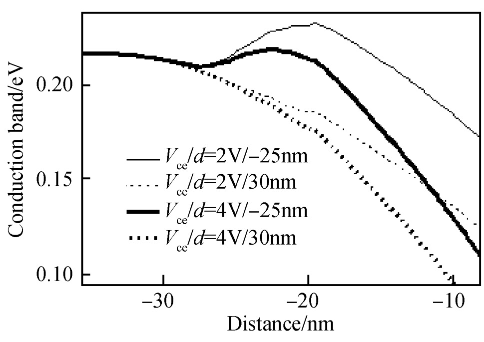

Fig.6 Comparison of conduction band bottom for HBTs with $d = -25$nm and $d = 30$nm at $V_{ce} = 2$V and $V_{ce} = 4$V

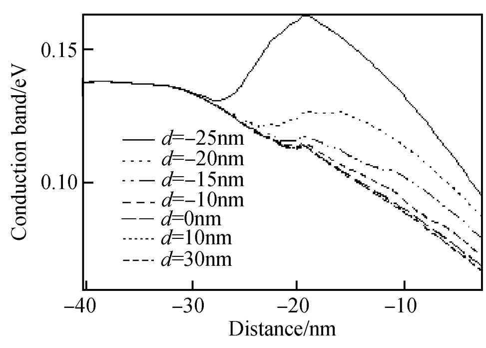

Fig.8 Conduction bands of HBTs with various d values at peak f_T at $V_{ce} = 2$V

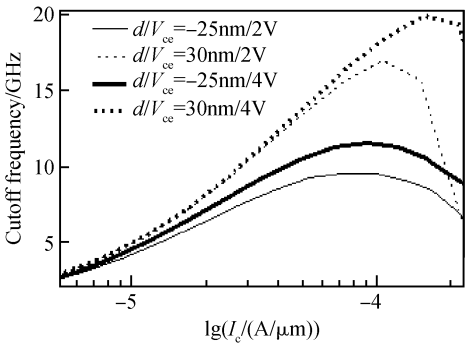

Fig. 9 Comparison of f_T-I_c characteristics for HBTs with $d = -25$nm and $d = 30$nm at $V_{ce} = 2$V and $V_{ce} = 4$V

duction band barrier greatly degrades the frequency characteristic. As d changes from -20 to 0nm, although there are no conduction band barriers, the cutoff frequencies differ by about 20% with varying d values. Especially for $d = -15$nm and $d = -10$nm, the current gains differ little at medium I_c (referring to Fig. 3) but the peak cutoff frequencies have a certain difference because at high I_c the conduction bands of the two are different from each other. Thus, the heterojunction could influence the conduction band in the vicinity of the BC junction significantly and eventually cause a frequency characteristic degradation before the HBE effect takes place. As d changes from 0 to 30nm, the peak cutoff frequencies hardly change because their conduction bands remain nearly unchanged with d, as shown in Fig. 8.

Figure 9 shows the comparison of f_T-I_c characteristics at $V_{ce} = 2$V and $V_{ce} = 4$V. The cutoff frequency at $V_{ce} = 4$V is larger than that at $V_{ce} = 2$V. This is because the higher V_{ce} causes a wider BC depletion region, and thus a more effective confinement of the neutral base within the heterojunction, helping alleviate the heterojunction barrier effect.

4 Experiment results and analysis

According to above simulation, we have fabricated SiGe HBTs, #1 and #2, which are the same except for the thickness of the i-SiGe layer to investigate the impact of collector heterojunction position on device performance. To avoid the SiGe relaxation problem caused by the thermal budget during processing, the entire SiGe thickness is kept no more than 60nm. The epitaxy parameters for the SiGe base are shown in Table 1, and the thicker i-SiGe layer stands

Table 1 SiGe epitaxy parameters of devices #1 and #2

Label	Buffer Si	i-SiGe	p^+ SiGe	EB i-SiGe	Cap Si
#1	10nm	20nm	20nm, $1\times10^{19}cm^{-3}$	10nm	20nm
#2	10nm	30nm	20nm, $1\times10^{19}cm^{-3}$	10nm	20nm

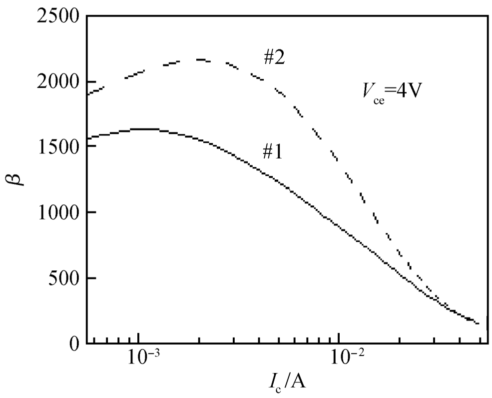

Fig. 10 β-I_c characteristics of #1 and #2

for the larger d value discussed previously. Each device has ten 10μm×0.7μm emitter fingers and the total emitter area is 70μm^2.

Figure 10 shows the β-I_c characteristics measured from the two devices. When i-SiGe becomes thicker, the current gain increases. At the same time, the onset of gain degradation for #2 is later than #1. Comparing Fig. 3 and Fig. 10 demonstrates that they have the same traits for the DC current gain and the onset of gain degradation.

Figure 11 compares the f_T-I_c characteristics of #1 and #2. The increase of i-SiGe thickness causes the increase of cutoff frequency at the same I_c. This is coincident with the simulation too.

Based on the simulation above, if the heterojunction is far enough from the neutral base, the changes in DC current gain and cutoff frequency are not sensitive to the variation of value d. As there is an apparent DC current gain difference of about 30% between SiGe HBTs #1 and #2 whose i-SiGe thicknesses differs 10nm, it can be concluded that the #2 might not reach the best f_T-I_c characteristic. Therefore, an i-SiGe layer thicker than 30nm will be necessary to obtain better frequency performance and the SiGe HBTs fabricating process with a lower thermal budget will

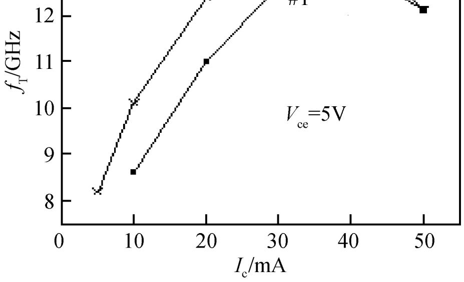

Fig. 11 f_T-I_c characteristics of #1 and #2 be better to get the further heterojunction by less boron outdiffusion and thicker i-SiGe layer with a non-relaxed SiGe base.

5 Conclusion

This paper has discussed the influence of heterojunction location relative to a BC junction on device behavior for SiGe HBTs. The corresponding device simulation results and measurement data reveal that both DC and HF device performance are strongly impacted by the degree of confinement of the neutral base in the SiGe layer, even in the absence of a conduction band barrier. As an extreme case, when the heterojunction falls inside the neutral base, a conduction band barrier will occur and thus both DC and HF device performance will be badly degraded, causing heterojunction barrier effects (HBE). When pushing the heterojunction toward the collector up to the position causing the band barrier to disappear, the HBE will be eliminated, with current gain and cutoff frequency obviously increased. After the disappearance of the band barrier, if the SiGe enclosure of the neutral base further increases, the BC accelerating field will be enhanced, and hence the current gain and cutoff frequency will continue to improve until the heterojunction is far enough from the neutral base. At this region, the alteration of heterojunction position could introduce a significant change of the peak cutoff frequency for HBTs with a graded BC junction, for example 20% in this paper. After that, the device performance starts to saturate. This is the optimal heterojunction position for a SiGe HBT design considering DC gain and especially HF performance.

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异质结位置对缓变集电结 SiGe HBT 性能的影响

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摘要：研究了 npn 型 SiGe HBT 集电结附近的异质结位置对器件性能的影响.采用 Taurus-Medici 2D 器件模拟软件，在渐变集电结 SiGe HBT 的杂质分布不变的情况下，模拟了各种异质结位置时的器件直流增益特性和频率特性.同时比较了处于不同集电结偏压下的直流增益和截止频率.分析发现即使没有出现导带势垒，器件的直流和高频特性仍受 SiGe 层中性基区边界位置的影响.模拟结果对 SiGe HBT 的设计和分析都具有实际意义.

关键词：SiGe HBT；集电结；HBE；相对位置；器件性能

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