Device Design of SiGe HBTs with Low Distortion Characteristics using Harmonic Balance Device Simulator

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***Abstract*—Distortion simulation of a SiGe HBT based on physical model and applying harmonic balance method has been demonstrated. It was obtained that for short carrier lifetime the 3rd intermodulation distortion (IMD) current was reduced and the intercept point of 3rd IMD was improved in 6dBm with our example.**

Keywords-component; IIP3; distortion; harmonic balance; device simulation; SiGe; HBT; intermodulation

I. INTRODUCTION

Inter-modulation distortion (IMD) is one of the most important characteristics in the analog RF device and circuit. It has been studied using equivalent circuit model [1]. A harmonic balance (HB) device simulator which solves drift-diffusion transport equations in the frequency domain by harmonic balance technique can predict the distortion characteristics only from the physical and structural parameters. Distortion simulation of SiGe HBTs based on physical model using this tool has not been performed yet and strongly demanded.

The purpose of this work is to demonstrate the device design of SiGe HBTs with low distortion characteristics using a two-dimensional harmonic balance device simulator [2][3][4][5][6][7]. Intercept point of 3rd / 2nd inter-modulation distortion (IIP3/IIP2) were directly simulated based on physical model for SiGe HBTs. The carrier lifetime in base-emitter junction layer were found to have a close relation to distortion characteristics. It has been obtained 6dBm improvement of IIP3 with our example as the carrier lifetime decrease from 1e-7 sec to 1e-8 sec.

II. SINULATION METHOD

A SiGe HBT used in the simulation has a base layer consisting of a SiGe base-emitter p-n junction layer, a p-type SiGe base layer and un-doped SiGe spacer layer as shown in Fig.1. Ge mol fraction changes gradually throughout these layers. Simulations were performed with two-dimensional strucurure.

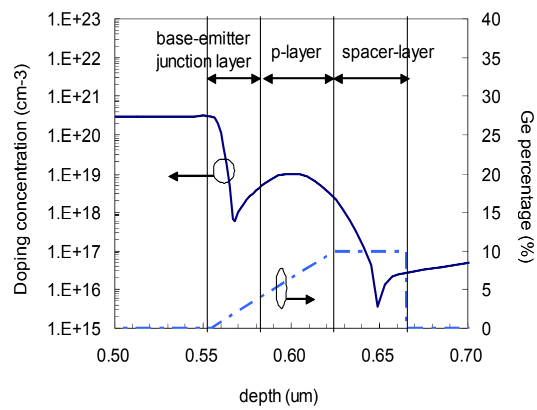

Fig.1 The Ge and doping profile of the SiGe HBT.

Gain, cut off frequency (fT), base capacitance (Cbb), base-collector capacitance (Cbc) and base-emitter capacitance (Cbe) for the graded SiGe HBT were simulated using high frequency small-signal AC simulation as it described in the paper [8] and [9].

Distortion characteristic was simulated using harmonic balance device simulator in which the normal set of semiconductor variables such as electron density, hole density and potential is expanded in a quasi-Fourier series at each spatial node and iteratively solved.

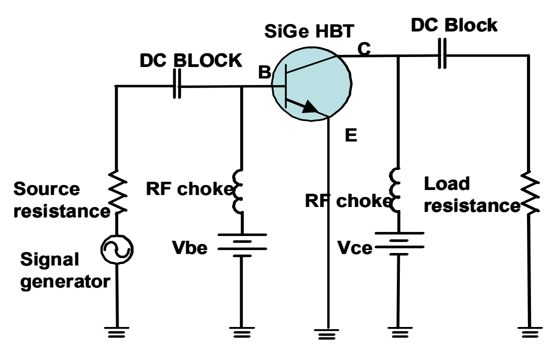

Fig.2 Circuit configuration of the mixed-mode harmonic balance device and circuit simulation of the SiGe HBT.

The boundary condition was given in accordance with the circuit circumstance because the matching condition of the input and output affects distortion characteristics. So, the mixed-mode harmonic balance device and circuit simulation was performed exactly as shown in Fig.2. In order to simulate intermodulation distortion, the two tones which have close-by frequency were input to the base. The spectrums of the output current were solved from the semiconductor variables such as electron density, hole density and potential which were expanded in a quasi-Fourier series. The power of IMD and fundamental wave was simulated as a dissipated power of the load resistance in circuit configuration as shown in Fig.2. In this paper, the input two tones have a frequency of 2.4 GHz and 2.41 GHz and a power of -40dBm. The load resistance was set to 50 ohm. Input Intercept Point of 3rd intermodulation distortion (IIP3) and Input Intercept Point of 2nd intermodulation distortion (IIP2) were calculated from the power of the fundamental wave, 3rd Intermodulation Distortion (IMD3) and 2nd Intermodulation Distortion (IMD2) respectively.

III. SIMULATION RESULTS

Firstly, Ge percentage dependency of these RF characteristics for this HBT is shown in Fig.3. The collector current (Ic) was set to 0.16 uA/um which gives around a half of

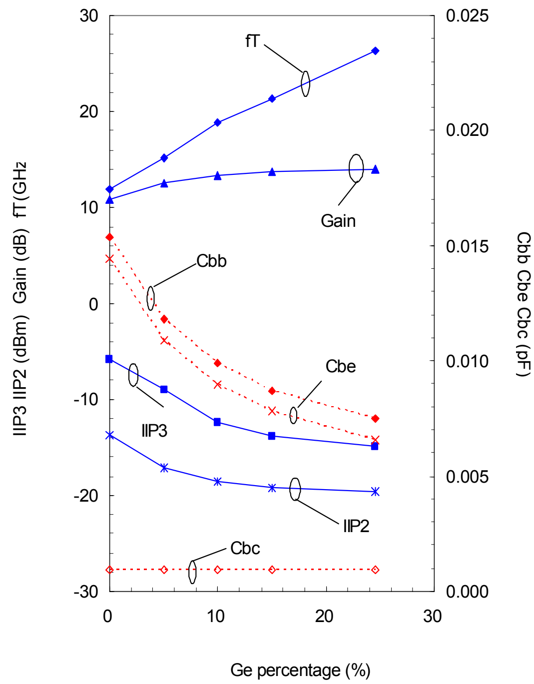

Fig.3 Ge percentage dependency of RF characteristics for the SiGe HBT with graded Ge Profile.

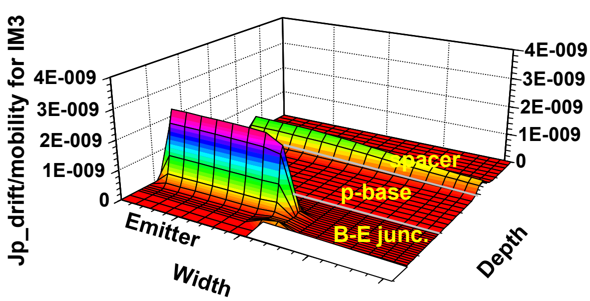

Fig.4 (a) Profile of the drift current density over mobility for hole of 3rd intermodulation (Carrier lifetime=1e-7sec).

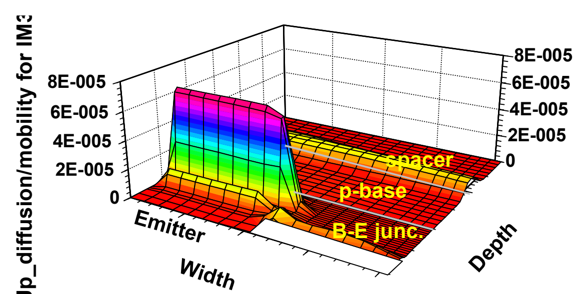

Fig.4 (c) Profile of the diffusion current density over mobility for hole of 3rd intermodulation (Carrier lifetime=1e-7sec).

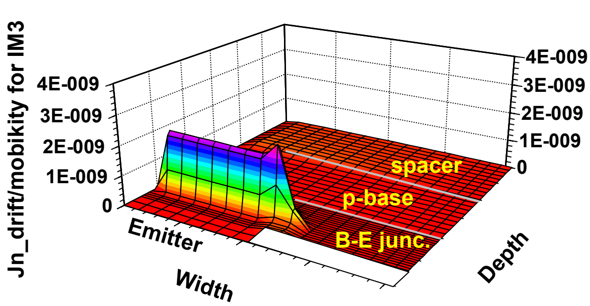

Fig.4 (b) Profile of the drift current density over mobility for electron of 3rd intermodulation (Carrier lifetime=1e-7sec).

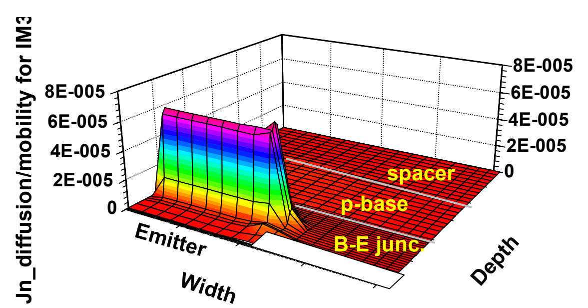

Fig.4 (d) Profile of the diffusion current density over mobility for electron of 3rd intermodulation (Carrier lifetime=1e-7sec).

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the maximum cut off frequency and minimum noise figure of this device. It was observed that for lower Ge concentration the IIP3 and IIP2 were improved and the fT and gain were reduced because the Cbe was increased. This Cbe is a diffusion capacitance when the base emitter junction was forward-biased. It is found that the higher germanium content of a graded SiGe HBT improves fT but deteriorates the distortion characteristics.

Profile of the diffusion and the drift current density over mobility of 3rd IMD for the graded SiGe HBT with 10% Ge and a lifetime of 1e-7 sec is shown in Fig 4. This current density over mobility of IMD was calculated from the IMD carrier densities and the IMD potentials. It was observed a peak of IMD current for both electron and hole at the SiGe base emitter p-n junction layer. It is much higher than the peak of IMD hole current at the base collector p-n junction in the SiGe spacer layer. Moreover, the diffusion current density was 4 orders of magnitude larger than the drift current density. It suggests that the base emitter p-n junction has some relation to the distortion property and the reducing of the IMD diffusion current in the SiGe base-emitter p-n junction layer is effective to improve the distortion characteristics.

Carrier lifetime dependency of RF characteristics for the graded SiGe HBT with 10% Ge is shown in Fig.5. It was observed that for short lifetime the base emitter capacitance (Cbe) was decreased and the IIP3 was improved without reducing the fT. Especially for a carrier lifetime of 1e-8 sec,

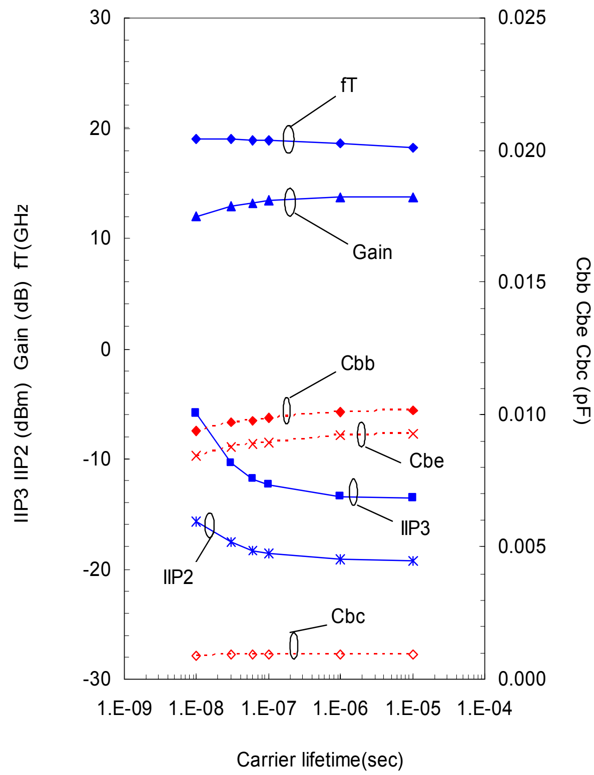

Fig.5 Carrier lifetime dependency of RF characteristics for the graded SiGe HBT with 10% Ge.

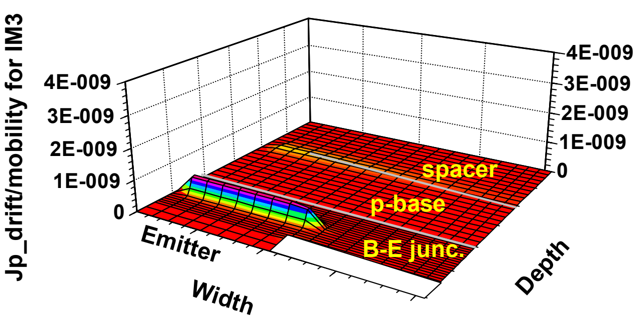

Fig.6 (a) Profile of the drift current density over mobility for hole of 3rd intermodulation (Carrier lifetime=1e-8sec).

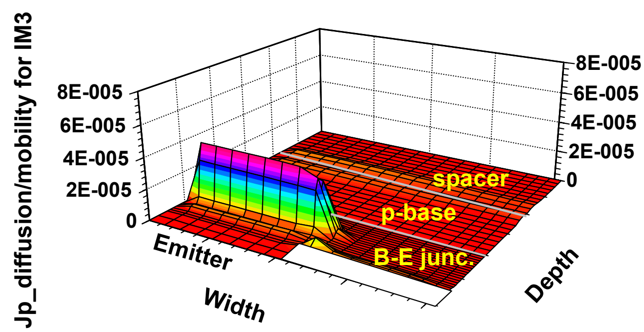

Fig.6 (c) Profile of the diffusion current density over mobility for hole of 3rd intermodulation (Carrier lifetime=1e-8sec).

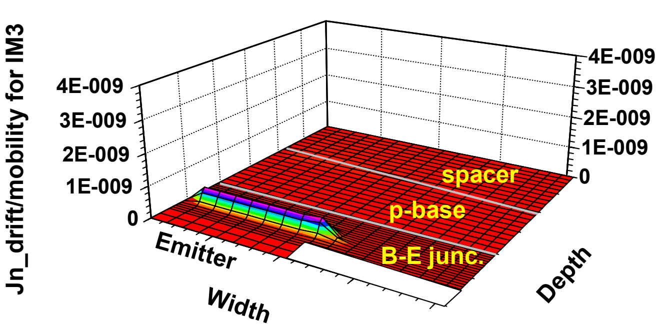

Fig.6 (b) Profile of the drift current density over mobility for electron of 3rd intermodulation (Carrier lifetime=1e-8sec).

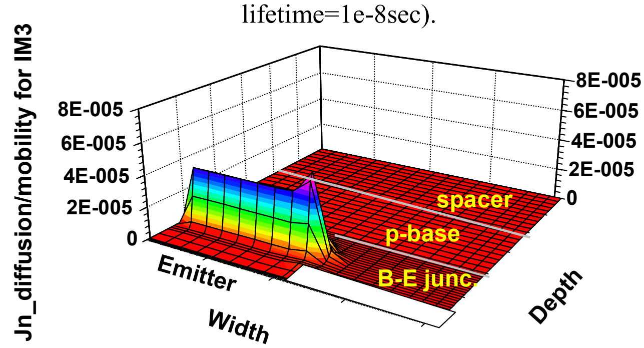

Fig.6 (d) Profile of the diffusion current density over mobility for electron of 3rd intermodulation (Carrier lifetime=1e-8sec).

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IIP3 was dramatically improved. It is well known that the Cbe is a diffusion capacitance and it decreases by reducing the accumulation of the minority carrier in the region of base emitter junction. So, it is expected that the shortening lifetime of minority carrier is effective for changing the condition of the carrier diffusion.

Profile of the diffusion and drift current density over mobility of 3rd IMD for the HBT with a lifetime of 1e-8 sec is shown in Fig 6. It was found that IMD current for hole and electron in the base-emitter p-n junction layer was decreased as the carrier lifetime decreased from 1e-7 sec to 1e-8 sec. It is observed that both of diffusion and drift current were reduced. The diffusion current was larger than drift current and the dominant.

The lifetime from 1e-7 sec to 1e-8 sec is in a realizable range and it is described in the paper referred [10] that increasing the oxygen concentration in the SiGe should reduce the carrier lifetime in SiGe. We also studied that in SiGeC HBTs, the cabon in SiGe reduced the carrier lifetime of the base region and increased the base current [11]. Although carbon is generally introduced to SiGe in order to relax the lattice strain and realize higher doping of germanium, improvement of the distortion characteristics should be also expected from our result.

In all simulations described previously, the minority carrier lifetime was distributed uniformly in the semiconductor region. We also confirmed that this improvement of IIP3 was obtained by reducing the lifetime only in the base-emitter p-n junction layer. It suggests that the diffusion capacitance and recombination at the base emitter p-n junction is a major contributor to the distortion characteristics.

IV. Conclusion

Using harmonic balance device simulator, distortion characteristic of SiGe HBTs was simulated for the first time.

We had a physical insights from the bird's-eye views which separated the the IMD current into the drift distortion current and the diffusion distortion current. From these insights, we considered that the recombination and the carrier diffusion in the base emitter p-n region have close relation to the distortion characteristics and then designed a SiGe HBT with low distortion characteristics using this tool. It has been clarified that shorter carrier lifetime in a base-emitter p-n junction layer reduced the 3rd IMD diffusion current. It has been obtained 6dBm improvement of IIP3 with our example as the carrier lifetime decrease from 1e-7 sec to 1e-8 sec.

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