SIMULATION OF SEMICONDUCTOR DEVICES AND PROCESSES Vol. 5
Edited by S. Selberherr, H. Stippel, E. Strasser – September 1993

Two-Dimensional Numerical Analysis on the Diffusion-Induced Degradation of AlGaAs/GaAs Heterojunction Bipolar Transistors

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Abstract

In this report, the effect of the beryllium *in situ* and *ex situ* outdiffusion into the emitter on the device characteristics is investigated by employing two-dimensional device simulators. It revealed that the current driving capability and RF performance are greatly affected by the beryllium diffusion due to thermal stress.

1. Introduction

Search for high speed electronic devices over the past few years has resulted in the demonstration of field-effect transistor (FETs) and heterojunction bipolar transistors (HBTs) with excellent microwave and millimeter-wave performance. As the circuit frequency limits of FETs are being approached, HBTs are gaining increasing attention in millimeter wave and high-speed digital applications because of their inherent high current handling capacity and high operation frequency. To achieve an outstanding power characteristics with high f_{MAX}, the base doping concentration of the typical AlGaAs/GaAs HBTs is made higher than 1×10^{19} cm^{-3} with extremely thin base thickness. To achieve this relatively high doping concentration for the base, Be are widely used as p-dopant for MBE and MOCVD growth, respectively [1]. However, the Be outdiffusion during epitaxial growth has been observed and was found to result in the redistribution of dopant profile at the heterointerface. In addition to the outdiffusion of Be during the growth, thermal stress at the high collector current densities can cause Be redistribution when the junction temperature is raised [2]. For the optimum design of the AlGaAs/GaAs HBTs in the microwave and millimeter-wave ranges, the influence of device characteristics on the Be redistribution due to thermal stress should be thoroughly investigated. In this study, we simulated device characteristics with redistributed Be diffusion profile in the base caused by the thermal stress.

2. Device Simulations

The structure of the simulated device consists of a 0.5-µm Si-doped GaAs subcollector, a 0.3-µm Si-doped collector with a doping concentration of 2×10^{17} cm^{-3}, 0.1-µm Be-doped GaAs base with a doping concentration of 1×10^{19} cm^{-3}, followed by a 0.2-µm Si-doped

AlGaAs emitter. On top of the emitter, a 0.2-μm GaAs layer with a doping concentration of 1 x 10^{19} cm^{-3} is assumed for ohmic contact. In addition, an undoped GaAs spacer of 300 Å is inserted between n-AlGaAs emitter and p-GaAs base.

In order to estimate device characteristics, a series of devices with simulated Be redistributed profile were employed. For instance, a sum of linear combinations of Gaussian profiles was employed to simulate diffused Be profile due to the thermal stress. The Be diffusion under the thermal stress shifts the junction into the AlGaAs region, which degrades the emitter injection efficiency of an HBT. The Be diffusion into the emitter region seems to form the potential barrier at the conduction band near the emitter-base junction. In this calculations, the assumed penetration depths of Be outdiffused into the emitter are 125, 250, 450, and 680 Å, respectively. The simulated device parameters of each structure are shown in Table 1.

Table 1. The parameters of the HBT simulated in this study influenced by Be diffusion at the emitter-base junction.

Devices	V_{BE} (V) (I_C=1μA)	V_{CEoff} (mV)	h_{fe} (I_C=0.1mA)	f_t (GHz) (I_C=0.1mA)	f_{max} (GHz) (I_C=0.1mA)
Structure #1	1.2	28	107	10	1
Structure #2	1.3	83	60	12	2
Structure #3	1.4	168	10	13	6
Structure #4	1.4	183	8	14	7

Two-dimensional device simulation revealed that one of the effects of Be outdiffusion into the emitter is the shift of the turn-on voltage at the emitter-base junction as shown in Table 1. The turn-on voltage changes from 1.2 to 1.4 V as the penetration depth varies from 125 to 680 Å due to the shift of the emitter-base junction into the AlGaAs region where the bandgap is the larger. Our calculation exhibits that a shift of turn-on voltage of 0.48 mV corresponds to approximately 1 Å of Be diffusion. In addition to the increase of the turn-on voltage of the emitter junction, the collector-emitter offset voltage in the common emitter output characteristics increases with the degree of Be outdiffusion. This seems to caused by the decrease of the reverse saturation current due to raised bandgap.

As shown in Fig. 1, the DC characteristics of AlGaAs/GaAs HBTs exhibits strong dependence on the redistributed Be diffusion profile. In other words, the deeper the Be dopant penetrates into the emitter, the lower common emitter current gain is obtained. This seems due to the decrease of the emitter injection efficiency. The calculated values of the common emitter current gain of the simulated devices varies by two orders of magnitude, as shown in Table 1. This implies the thickness of the spacer should be chosen such that the distance of Be outdiffusion is confined to the spacer.

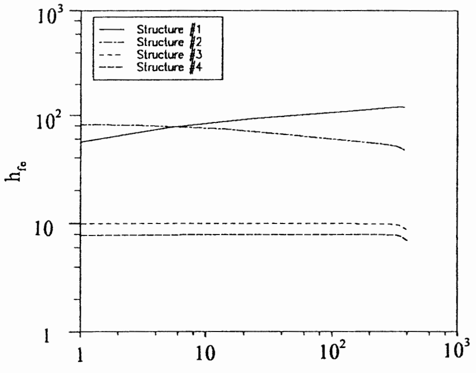

Fig. 1. A plot showing the dependence of the common emitter current gain on the redistributed Be diffusion profile under the thermal stress.

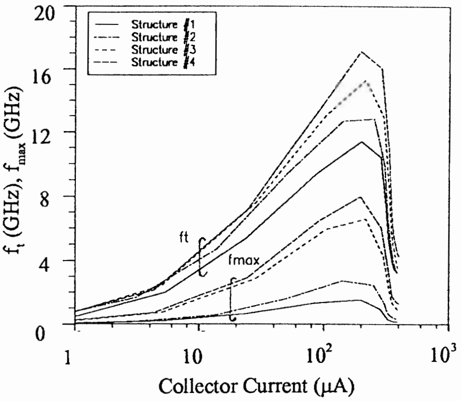

Fig. 2. A plot showing the dependence of cutoff frequency and maximum oscillation frequency on the Be diffusion.

Finally, the high-speed performance of the AlGaAs/GaAs HBTs is affected by the thermal stress. As shown in Fig. 2, the calculated cutoff frequencies changes from 10 to 14 GHz at the collector current of 0.1 mA as the penetration depth increases. Simultaneously, the maximum oscillation frequencies increase from 1 to 7 GHz with the penetration depth at the same collector current level. This seems to be due to the increase of the spike at the heterointerface, which results in the accelerated electrons launching into the base according to the calculation of the band diagram.

3. Conclusion

We report the study on the degradation of AlGaAs/GaAs HBT by thermal stress by employing two-dimensional simulators. Our simulation results revealed that the DC and RF characteristics are strongly affected by the *in situ* and *ex situ* thermal stress. The authors would like to express special thanks to Dr. Tim Crandle at Silvaco International for the encouragement and helpful discussions. This work was supported by ISRC-92-E-0023, Inha University, and ETRI.

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