Use the electromagnetic field stress to study the reliability of the SiGe HBT

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Abstract: In this paper, we investigate a new reliability damage mechanism in SiGe Heterojunction Bipolar transistor (HBTs). This study differs from conventional HBT/SiGe device reliability associated with other stress. Since it results from an Electromagnetic field aggression which consists of a new stress methodology. The near-field bench is used to disturb with electromagnetic field the Device Under test (DUT) on a localized area, contrary to the disturbance created in the TEM cell. We find that only the base is most sensitive to the disturbance caused, when compared to those on the package, collector and emitter. This is primarily due to the electromagnetic coupling phenomenon between the induced electromagnetic field and the microstrip line connecting the base of the transistor. Degradations in the base current and the current gain are identified. It is induced by a large $I_B$ leakage current due to hot carrier which introduces generation/recombination center traps and leads to excess non-ideal base current.

Key-Words: HBT, Reliability, EMC, Hot carrier, Simulation.

1 Introduction

With recent technology advancement, SiGe heterojunction bipolar transistor (HBT’s) have become viable candidates for most microwave applications [1]. Several companies have put first generation SiGe, HBT’s into production with values $f_T$ and $f_{max}$ around 50GHz, second generation technologies are already at an advanced stage of development with values $f_T$ and $f_{max}$ around 100GHz [2], while the state of the art is 500GHz. The shrinking sizes and the high doping levels which consists a heavily doped emitter and extrinsic base in SiGe, HBT’s result in a much higher electric field at p-n junctions. They have indirectly posed a threat to device reliability causing the hot-carrier (HC) damage [3]. A vast range of RF and mixed-signal circuits are possible with this technology which has demonstrated very attractive capabilities in term of mobile phones, WLNA, satellite communications and Radar applications. However, electronic systems are integrating more and more functionalities in a confined volume; consequently some components can be the source of numerous electromagnetic disturbances which make the components in the vicinity more and more susceptible [4]. Many papers have been published on the SiGe, HBT’s reliability for radiation, thermal and electrical stress but none of them of our knowledge were carried out on electromagnetic stress. This paper introduces in section 2 the stress methodology of the near-field bench and the distribution of the magnetic field generated by the magnetic probe used in our experiment. Then section 3 presents the operating conditions of the DUT and the electromagnetic coupling phenomena which show the most sensitive area of the DUT. The stress induced effects on the DC characteristics are presented and discussed comparatively with the other stress in the section 4. Finally the stress effects on the capacitance measurement are discussed in section 5. Conclusion will be outlined in the last section of this paper.

2 Method descriptions

The near-field disturbance method is based on the use of a miniature near field probe placed above the device under test (DUT) at a given height “H” to detect or produce a strong localized electromagnetic field (see Fig.1). In this work, we choose the loop “magnetic probe” among other types of probes, such as the monopole and the dipole. The monopole
consists of a 50 ohm open-end coaxial cable oriented to the Z direction which produces an electric field \( E_z \) and the dipole consists of a balanced wire dipole which produces an electric field \( E_x \), \( E_y \)[5]. The stress induced effects on the HBT is much stronger using the “magnetic probe”, comparatively with other probes and applying the same stress time. This probe consists of a small loop and it is made up of the inner conductor to produce a magnetic field \( H_y \).

A near-field aggression is generated through a magnetic probe located at 1mm above the DUT such as the loop diameter should not exceed ten millimetres. This probe was fed by a RF generator (0dBm) at 1GHz and a 40 dB power amplifier through a directional coupler which allows the measurement of incident and reflected powers through a power meter. Cartography of the electromagnetic field induced by the loop is used during this study to locate the areas of high field levels by means of commercial software HFSS based on the finite element method (FEM). On the Fig.2 we illustrate a near field map of the magnetic field simulated. The magnitude of magnetic fields of the loop fed by 40 dBm at 1 GHz reach its maximum 58 A/m in the range 3×3 mm\(^2\), that is given on the plan perpendicular to the surface of the loop at 1 mm below it. The configuration (P= 40 dBm, f= 1GHz and H=1mm) is used in our experimental setup, for the first time, in order to accelerate our stress and taking into account the amount of power that can be reflected because the probe is not adapted. Accelerated Life Testing (ALT) is commonly practiced in product life testing and analysis, in order to improve the product performance and reliability. Under ALT, units are tested at higher-than-operating levels of stress (e.g., temperature, vibration, voltage, humidity, etc.) to induce early failures. These Failures data are then extrapolated to obtain estimates for product characteristics, such as MTTF (Mean Time To Fail) and reliability or robustness.

### 3 Stress effects study

#### 3.1. RF characteristics

For this experiment, a HBT SiGe designed in SOT-343 footprint is mounted like a common emitter amplifier on a Printed circuit Board (PCB). Firstly, the magnetic probe is fed by 40dBm at 1GHz and is located 1mm above the package. We have not observed degradation after 8 hours of stress. The same conditions are applied for the probe located above the microstrip line connecting the collector or the emitter; any important degradation can be seen. We find that only the base is the most sensitive location for the disturbance.
The S-parameters performed with the vector network analyzer (VNA) are shown in Fig.3, as a function of frequency up to 2 GHz before and after electromagnetic stress. The amplitude of the transmission parameter $S_{21}$ between 100MHz and 2 GHz is degraded by more than 6dB. Hence this suggests significant degradation in forward power gain. The same results are obtained in both powered and non powered components during the stress. We found a decrease in the module of $S_{21}$ which is affected by a degradation mechanism. The change in $S_{21}$ is caused by the increase of the base current when the collector current remains unchanged [10].

### 3.2. Coupling study

An electromagnetic coupling phenomenon is established between the magnetic probe and the microstrip line. The printed circuit board (PCB) which includes the model of HBT from package to die, is modelled using the Advanced Design System (ADS) software. The validation of this model is ensured through a comparison between measurement and simulation of S-parameters. This simulation helped us in identifying the impedance loads of the micro-strip line terminals. The probe simulated with HFSS is located above the microstrip line and is fed by a variable power at the frequency of 1 GHz.

![Fig.4 Induced voltage of microstrip line versus the power injected in the probe. Inset shows the induced voltage for two probe positions.](image)

The probe simulated in HFSS is positioned at 1 mm above the microstrip line and it is moved from the load. This probe is excited by a RF signal at 1 GHz and with a variable input power. The variation of the induced voltage of the line according to the power injected in the probe is represented in Fig.4. The displacement of the probe along the microstrip line indicates the maximum of the induced voltage when the probe is located very close to the load. Voltage values indicated in the inset of Fig.4 are obtained by simulating two probe positions above the line (h=1mm, 2mm). The structure considered to HFSS simulation is a microstrip line with a characteristic impedance $Z_C = 50 \, \Omega$, a length $L=3$ cm, a width $w=3$ mm and a thickness $t=35 \, \mu m$. This line is located at a height $h=1.6$ mm above the ground plane (see Fig.5).

![Fig.5 Structure simulation of the probe and the microstrip line with the HBT mounted on circuit board.](image)

### 4 DC characteristics and discussion

To examine the electromagnetic stress induced effects on our component, the HBT’s is characterized the Gummel plots, the forward current gain beta and the I-V curves. The tested multi-finger Si/SiGe HBT’s used in this study have a typical transition frequency 60GHz and exhibit a DC current gain up to 400, the $B V_{C E 0}$ is 2.3V. Agilent HP-4142 Precision Semiconductor Parameter Analyzer was used for DC characterization. Biasing mode and monitoring were conducted under computer control using commercial software IC-CAP from Agilent. This characterization includes Gummel plots, DC gain (beta) versus $I_c$ and collector I-V curves. The typical forward Gummel plot of HBT measured with different stressing times is shown in Fig.6. The kink in the base characteristics indicates the onset of quasi-saturation, and beyond this point ($V_{BE} = 1.1V$) the gain decreases. Quasi-saturation is therefore often seen in Gummel plots at high currents [6]. Also we can observe that the collector current remains unchanged during the stress when a large
degradation of the base current is occurring. We have compared the electromagnetic stress induced effects with the well-known stress $I_B$ degradation such as the thermal, irradiation, electrical-reverse and mixed mode. The commonly understood mechanism responsible for this shift in base current is the generation of a damage region at the sidewall-spacer oxide and silicon interface [1], [2]. This damage induces interface traps (Si/SiO2) in the E-B space oxide due to hot carrier (HC) injection [3], [7], [8].

![Fig.6 Typical Gummel plot under Electromagnetic stress with different stressing times.](image)

Theses stresses induce Generation/recombination trap centers and lead to an increase in the recombination component of the non-ideal base currents [1]. For the tested HBT’s the base-emitter ideality factor increased after stress, this is consistent with increased leakage in the base emitter junction and with the observed increase in the base current.

![Fig.7 stress effects on the Current gain versus collector current](image)

The “failure criterion” for all reliability evaluations was -10% degradation in beta from the initial value at the start of each stress test [9]. Fig.7 reports the current gain as a function of bias current of showing the effects with different stressing times. Each report ascribes the shift in current gain principally to a base current shift, the current gain decreases with an increase of the base current after stress. For clarity reasons, we have plotted the current gain to indicate this important variation which may indicate that the SiGe layer is not stable [7] and/or the Shockley-Hall-Read (SHR) surface recombination is increased located around the emitter perimeter [10] at least with respect to these conditions of stress. We conclude this section by showing the output characteristics of collector current versus the collector voltage with the base current as parameter. We can see the effects with different stressing times at $I_B=190\mu A$. The current collector decreases after stress with the same base current, as shown in Fig.8. We ascribe this result to the shift of the current gain after structure degradation.

![Fig.8 stress effects on the output characteristics (collector current versus $V_{CE}$ with $I_B=190\mu A$).](image)

5 Capacitance measurements

The junction capacitances have to be studied, because it affects not only the high frequency behavior of the device, but also the static behavior via the direct and inverse Early effect [11]. The capacitance splitting implies the need of two different capacitances corresponding for junction and diffusion capacitances. The capacitance associated with the charge variation in the depletion layer is called the junction capacitance, while the capacitance associated with the excess carriers is called the diffusion capacitance. In practice, the depletion approximation equation is accurate under reverse and low forward bias conditions for all
junctions but rapidly loses validity under moderate to strong forward bias [12].

Figure 9 plots the Base-Emitter capacitance before and after electromagnetic field stress when the Collector is left open during this measurement. Noting that this illustration includes, in practice, some parasitic components like package or pad capacitances since all the transistors investigated in this paper were measured in the package. In addition, these results show a kink in the Base-Emitter capacitance which indicates the transition from vertical to horizontal operation. This kink appears when the B-E voltage is equal to the effective vertical punch voltage which is emitter doping dependant [13]. The plot shows that there is a considerable increase in the B-E capacitance characteristics after electromagnetic stress. This could be attributed to an increased of the carrier concentration in the B-E junction after stress [14], which is in agreement with the increase of the nonideal base current in forward Gummel plots after stress.

6 Conclusion

In this study, we have presented a new reliability damage mechanism in SiGe HBTS from the application of Electromagnetic field which consists of a new stress methodology and differs with other stress. We find that the base is the most sensitive to the disturbance caused. Electromagnetic coupling phenomenon is studied to obtain the real induced voltage at the input of the DUT and to understand the stress type. By using the S-parameters measurements, we find that the forward transmission scattering parameter \(S_{21}\) is affected by this stress. Important stress effects have been discussed when we have identified a base current degradation. This degradation appears due to hot carrier introducing generation/recombination center traps which lead to excess non-ideal base current and hence current gain degradation. We found a large increase of carriers in the Base-Emitter junction which modifies B-E capacitance causing it to increase. Our results imply that this electromagnetic stress suggests that further attention from a HBT SiGe reliability point of view.

References


