International Journal of Microwave and Wireless Technologies, 2009, 1(6), 475–482. © Cambridge University Press and the European Microwave Association, 2010
doi:10.1017/S1759078709990572

Study of electromagnetic field stress impact on SiGe heterojunction bipolar transistor performance

ALI ALAEDDINE[1,2], MONCEF KADI[1], KAOUTHER DAOUD[2], HICHAME MAANANE[3] AND PHILIPPE EUDELINE[3]

This paper deals with the various aspects of electromagnetic field impact modeling on the SiGe heterojunction bipolar transistor (HBT) device for microwave applications. This study differs from conventional HBT device reliability research associated with other stresses. The originality of this study comes from the generation of a localized electromagnetic field using the near-field bench. A coupling phenomenon between the electromagnetic field and the micro-strip lines connecting the transistor are evaluated by electromagnetic and electrical simulations. After stress, the input and the transmission scattering parameters are affected. This is primarily due to the deviation of the input impedance and the reduction of the transconductance, respectively. The stress effects have been related to a base current degradation. This degradation is due to a hot carrier introducing generation/recombination trap centers at the Si/SiO_2 interface of the emitter–base spacer oxide, which leads to an excess recombination base current.

Keywords: HBT, Reliability, EMC, Modeling, DPI, Hot carrier

Received 30 June 2009; Revised 8 September 2009; first published online 7 January 2010

I. INTRODUCTION

A heterojunction bipolar transistor (HBT) has become a major player in wireless communication, low-noise amplifiers, mixers, and frequency synthesizer applications. HBTs extend the advantages of silicon bipolar transistors to significantly higher frequencies. They have become a natural choice for very high-frequency applications requiring high transconductance and low noise factor [1]. Emerging HBT technologies allow the integration of a large quantity of high-performance Radio Frequency (RF) circuits and high-speed digital circuits on a single chip. The most mature technology is the bipolar technology where the SiGe allows speeding up the device performance up to the millimeter wave range [2]. The SiGe technology exhibited very attractive high- and low-frequency noise performances due to the improvement given by the heterojunction [3]. Since electronic systems are integrating more and more functionalities in a confined volume, some devices can be the source of numerous electromagnetic disturbances which make other components in the vicinity more and more susceptible. In parallel, the immunity of these components has decreased at the same pace due to a steady reduction in the power supply voltage and consequently, the noise margin [4]. These applications exhibit very strict requirements in terms of reliability; before being involved at the industrial level, there is a need to evaluate the reliability of these devices and to identify the degradation mechanisms in order to be able to propose technological solutions. Many papers have been published on the SiGe HBT's reliability for radiation, thermal, and electrical stresses [2, 5, 6] but, to our knowledge, no reported work has been carried out on electromagnetic-radiated stress effects. The paper will be organized as follows. Section 2 will briefly present the new stress methodology generated by the near-field bench and the simplified equivalent electrical model of the printed circuit board (PCB). Section 3 introduces the electromagnetic coupling phenomenon and the complete electrical model of the board associated with the probe used for stress generation. Induced effects in the RF characteristics are presented in Section 4 with the similarity observed between the direct power injection (DPI) and the near-field stress effects. In Section 5, DC characteristics pre- and post-stress are discussed comparatively with the other known stresses.

[1]IRSEEM/ESIGELEC, Technopôle du Madrillet, Avenue Galillée, 76800 Saint Etienne du Rouvray, France.
[2]GPM/UMR 6634 CNRS, Avenue de l'Université, 76800 Saint Etienne du Rouvray, France.
[3]THALES AIR SYSTEMS, ZI du Mont Jarret, 76520 Ymare, France.
Corresponding author:
A. Alaeddine
Email: ali.alaeddine@esigelec.fr

II. DEVICES DESCRIPTION

A) Near-field injection system

An example of near-field disturbance setup is shown in Fig. 1. It includes the automatic near-field mapping system developed by the Research Institute for Electronic Embedded Systems (IRSEEM) [7] and equipment used for generation and measurement of the electromagnetic disturbance such as an RF signal generator, a power amplifier, a directional coupler, a power meter, an external power supply, and

https://doi.org/10.1017/S1759078709990572 Published online by Cambridge University Press

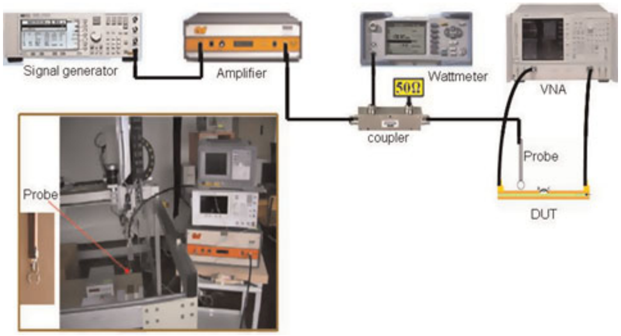


Fig. 1. Near-field stress system.

a vector network analyzer (VNA) to evaluate the component behavior during stress. This method is based on the use of a miniature near-field probe localized above the device under test (DUT) at a given height "*H*" to produce a strong localized electromagnetic field [8]. This probe is fed by the RF generator and the power amplifier through the directional coupler. In this, the loop "magnetic probe" is chosen among other types of probe, such as the monopole and the dipole. This probe, which is made using a coaxial cable, consists of a small loop with a diameter of about 10 mm and it is made up of an inner conductor for producing a magnetic field [7]. The probe produces principally the H_x magnetic field component when its surface is located in the *yz* plane.

B) PCB modeling

The SiGe HBT device under discussion here is designed in an SOT-343 footprint with a flat lead style "M04" package, and mounted like a common emitter amplifier on a PCB. The multi-finger transistors used in this study exhibit a DC current gain up to 300 and the BV_{CEo} is 2.3 V. The typical transition frequency (f_T) and maximum oscillation frequency (f_{MAX}) are about 60 GHz. An electrical simulation model for the PCB is developed using the Advanced Design System (ADS) software [9]. The PCB is realized in micro-strip technology, a line connecting the base and the collector of this transistor with a characteristic impedance $Z_C = 50°$, a length $L = 3$ cm, a width $w = 3$ mm and a thickness $t = 35$ μm. The aim of this modeling is to validate the electrical parameters constituting the HBT model and relate the variations of the electrical parameters to the source disturbance. By assembling the Gummel–Poon (G–P) model of the HBT with the package model and the models of all components and taking into account their high-frequency behaviors, a complete electrical model of the test board can be established [10]. The G–P model which is based on the integral charge control model includes some advantages describing device behaviors [11].

The global model of the PCB is depicted in Fig. 2. To validate this model, a comparison between measured and simulated *S*-parameters is required. Figure 3(a) (reflection *S* parameters) and Fig. 3(b) (transmission *S* parameters) show the comparison between scattering parameters measured

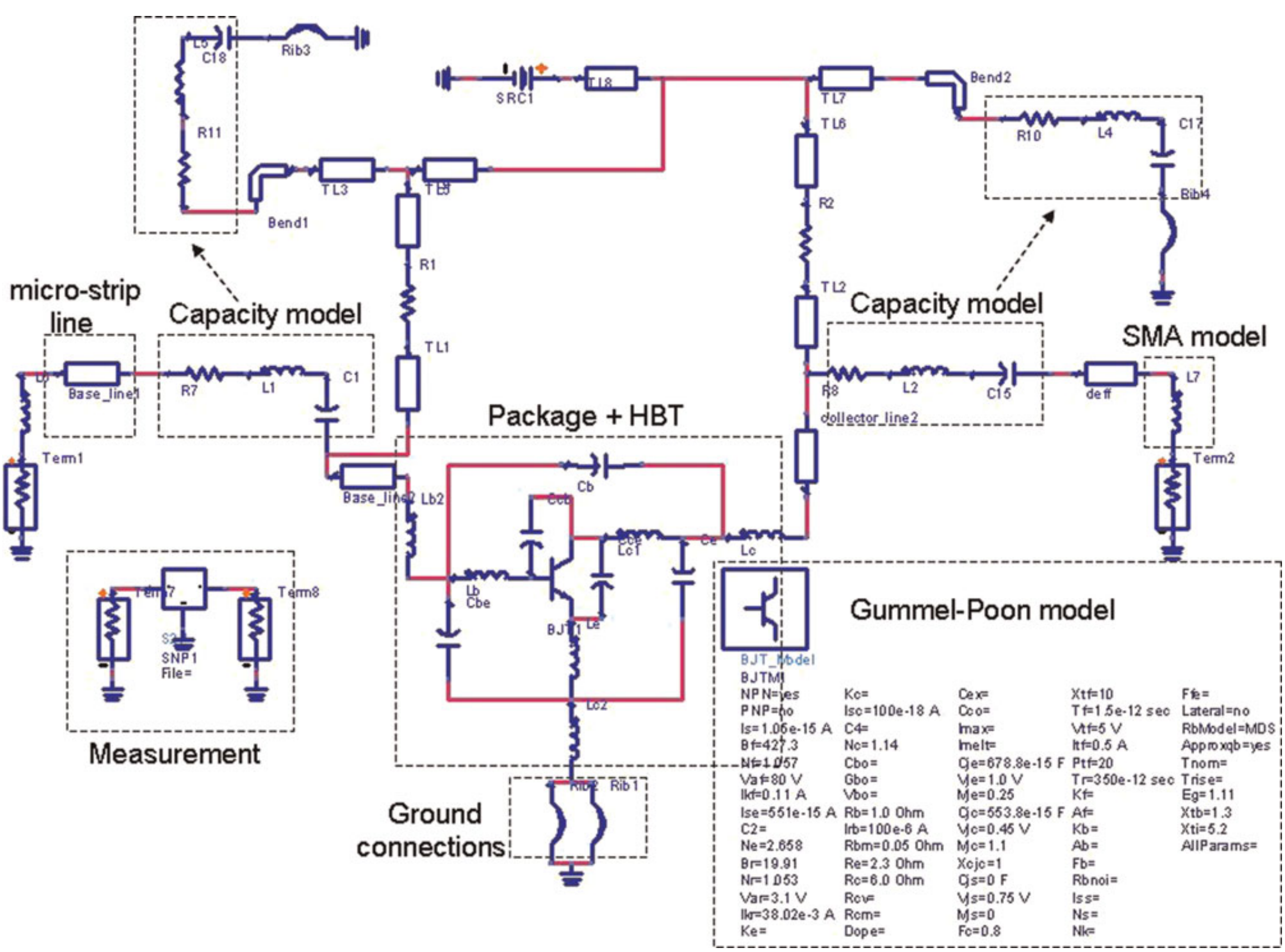


Fig. 2. Complete electrical model of the PCB (with the electrical G–P model).

https://doi.org/10.1017/S1759078709990572 Published online by Cambridge University Press

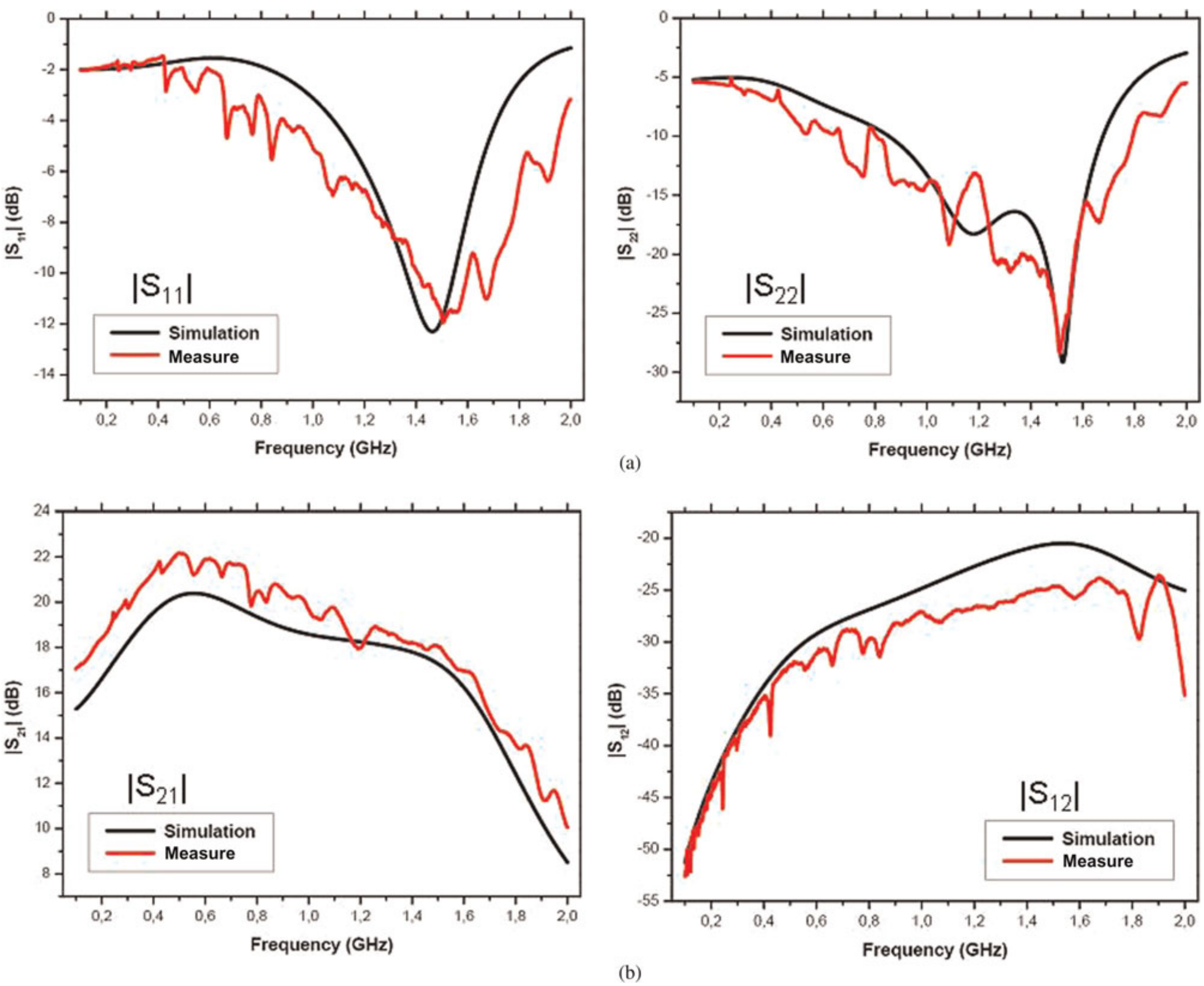


Fig. 3. (a) Comparison between the reflection *S* parameters measured and simulated, (b) comparison between the transmission *S* parameters measured and simulated ($V_{CE} = 2.3$ V, $I_C = 35$ mA, $I_B = 190$ μA).

and simulated. We have noticed a good accordance between experimental measurements and simulation results.

III. COMPLETE ELECTRICAL MODEL INCLUDING THE PROBE EFFECT

In order to examine the effects of the electromagnetic near-field stress on our component and select the most sensitive area of the PCB of Fig. 2, the magnetic probe is located at 1 mm above the package of HBT for the first time and it is fed by 40 dBm at 1 GHz. Noting that this level is used in order to accelerate our stress and taking into account the amount of power that can be reflected because the probe is not adapted, no measurement variation has been observed after a given stress duration. The same conditions are applied to the probe located above the micro-strip line connecting the collector or the emitter; no important degradation has been observed. Finally, the transistor was stressed on the micro-strip line connecting the base with the same conditions when the probe is located at 3 mm in front of the base input. We observed that the base is most sensitive to the disturbance, which is due to the electromagnetic coupling phenomenon between the induced field and the micro-strip line connecting the base of the HBT.

A) High-frequency structure simulator (HFSS) coupling model

To study the coupling between the PCB and the external electromagnetic field, several numerical methods have been developed so as to predict the disturbance induced in the tracks. The structure comprising probe and simplified PCB model was modelled using the HFSS based on the finite element method (FEM) [12]. The simplified PCB structure considered is a micro-strip line with a characteristic impedance $Z_C = 50^\circ$, a length $L = 3$ cm, a width $w = 3$ mm, and a thickness $t = 35$ μm. This line is located at a height of 1.6 mm above the ground plane. An FR4 substrate is used with a relative permittivity $\varepsilon_r = 4.4$. The ADS model of the PCB helped us in identifying the impedance loads of the micro-strip line terminals. The probe simulated with HFSS is located above the micro-strip line and is fed by a variable power at the frequency of 1 GHz. The induced voltage at the base of the transistor,

https://doi.org/10.1017/S1759078709990572 Published online by Cambridge University Press

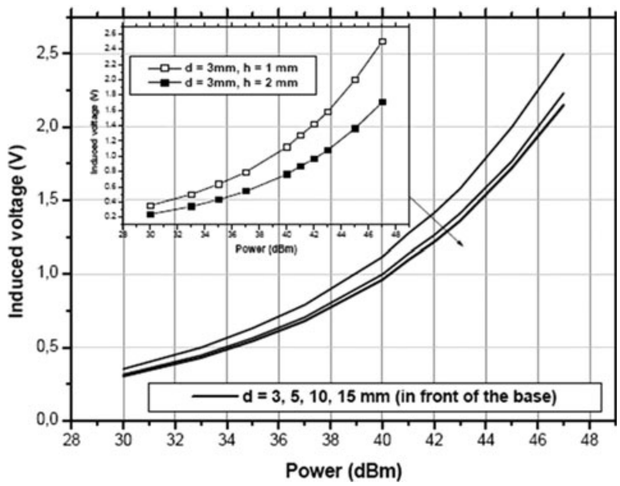


Fig. 4. Induced voltage of the microstrip line versus the power injected in the probe. Inset shows the induced voltage for two probe heights.

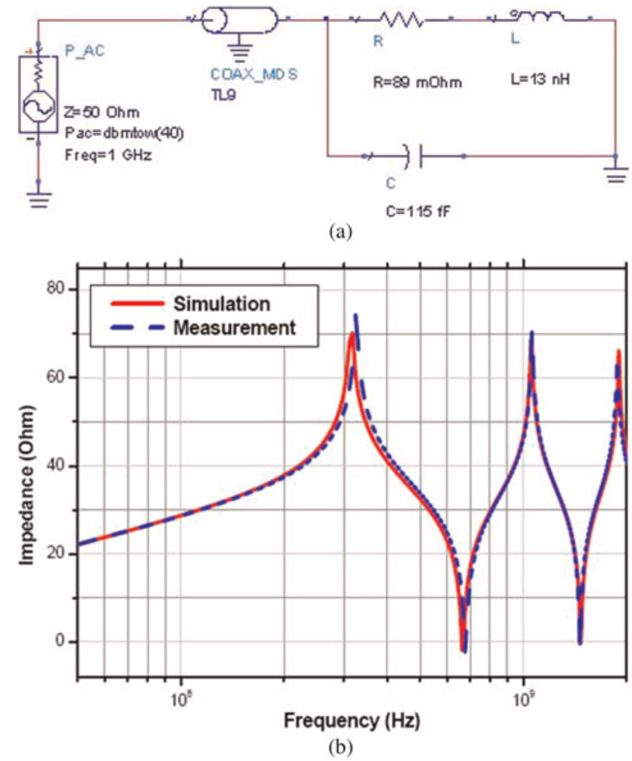


Fig. 5. (a) Equivalent model of the injection probe, (b) simulated (solid line) and measured (dashed line) impedance profiles of the injection probe.

according to the power injected in the probe, is shown in Fig. 4.

Moving the probe along the micro-strip line indicates that the induced voltage is important when the probe is located very close to the load ($d = 3$ mm). Voltage values shown in the inset of Fig. 4 are obtained by simulating two heights "h" of the probe above the micro-strip line.

B) Modeling of the injection probe

The electromagnetic coupling phenomenon established between the magnetic probe and the micro-strip line is modeled using the ADS software in order to develop an electrical aggression model comprising the PCB structure. Therefore, each part of the setup must be modeled separately as equivalent passive elements; these individual models must then be combined in order to obtain the whole equivalent model. Likewise, the model of the injection probe must be expressed as equivalent impedance in this study. The injection probe of the near-field setup is essentially a coaxial cable with a copper core, but its impedance is not 50 Ωin this case. The modeling relies on the knowledge of the impedance of the element, which is extracted from the S_{11} parameter obtained from a VNA. The model of the injection probe is inductive, with a low series resistance and a parasitic capacitor [13].

Figure 5(a) depicts a schematic of the equivalent electrical model of the probe as well as its actual values of the equivalent elements. Figure 5(b) plots a comparison between the simulated impedance profile and the measurement performed on the experimental setup, which shows a very good correlation.

C) Modeling of the micro-strip line

In order to describe the electromagnetic coupling phenomenon between the probe and the micro-strip line, a mutual inductance "M" must be integrated between both elements. However, the modeling does not follow the proposed model of the micro-strip line in the ADS software because it must contain an inductive element. By using the HFSS simulator, the electric and magnetic fields of the loop fed by 40 dBm reach their maximum 6500 V/m and 58 A/m, respectively, in the range 3×3 mm^2 that is given by the simulated near-field map on the plan perpendicular to the surface of the loop. Then, the coupling is mostly on the portion of the micro-strip line. Figure 6(a) displays the schematic of the equivalent electrical model of the micro-strip line. A very good correlation is shown in Fig. 6(b) which plots a comparison between the simulated impedance profile and the ADS proposed model of the line.

D) Simulation of the complete electrical model

By combining all the models computed previously, a complete electrical ADS model of the stress setup comprising PCB can be established. In addition to that, inductive coupling between line and probe is required using a mutual inductance "M". In order to validate the complete electrical model of the stress setup, comparisons are given between the induced voltage obtained by the electromagnetic simulator HFSS and the induced voltage obtained by using the electrical ADS model. The variation of the base voltage according to the power injected in the probe models is plotted in Fig. 7. This correlation clearly demonstrates the relationship between both models. It can be noted that the values of the induced voltage in front of the base reach 1 V at 40 dBm of power injected in the probe.

IV. EXPERIMENTS AND MEASUREMENTS

The stress procedure consists of a near-field disturbance as previously shown in Fig. 1. In this study, a near-field aggression is generated through a magnetic probe with a diameter

https://doi.org/10.1017/S1759078709990572 Published online by Cambridge University Press

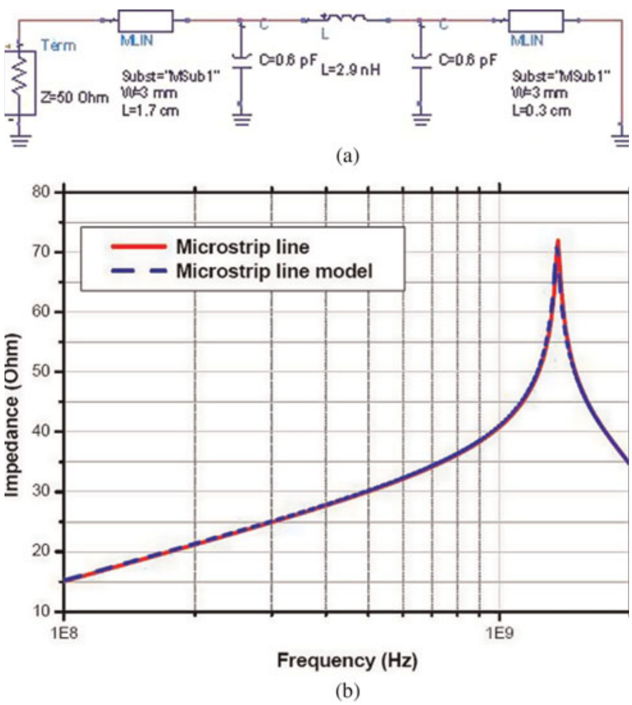


Fig. 6. (a) Equivalent model of the micro-strip line, (b) simulated equivalent model (dashed line) and proposed ADS model (solid line) impedance profiles of the micro-strip line.

of 10 mm located at 1 mm above the DUT. This probe was fed by an RF generator (0 dBm) at 1 GHz and a 40 dB power amplifier through a directional coupler which allows the measurement of incident powers. The probe is located at 3 mm in front of the base input since it is most sensitive to the disturbance. This is due to the electromagnetic coupling phenomenon between the induced field and the micro-strip line connecting the base of the HBT, at least in our configuration.

A) *S*-parameters characterizations

To analyze the effects of the electromagnetic near-field stress on our component, the HBT is characterized with the help of an HP8720ES network analyzer (VNA). Figure 8 plots the

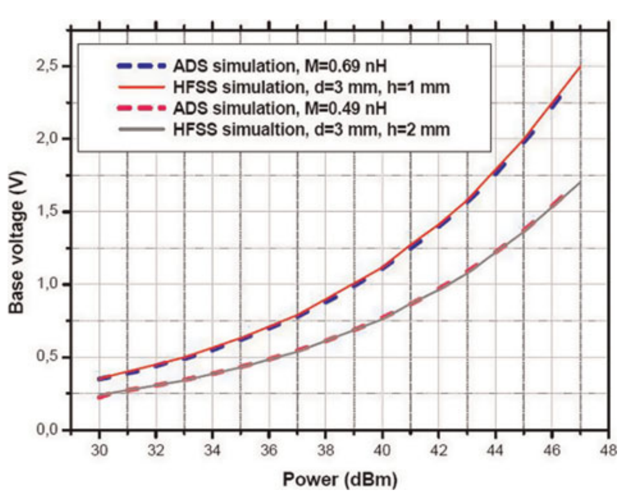


Fig. 7. Induced voltage from the ADS simulation (dashed line) and from the HFSS simulation (solid line) versus the power injected in the probe models.

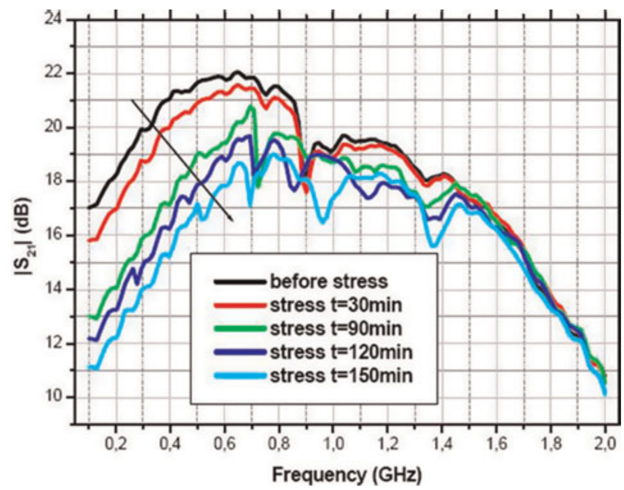


Fig. 8. Measured S_{21} parameter before and during the electromagnetic stress.

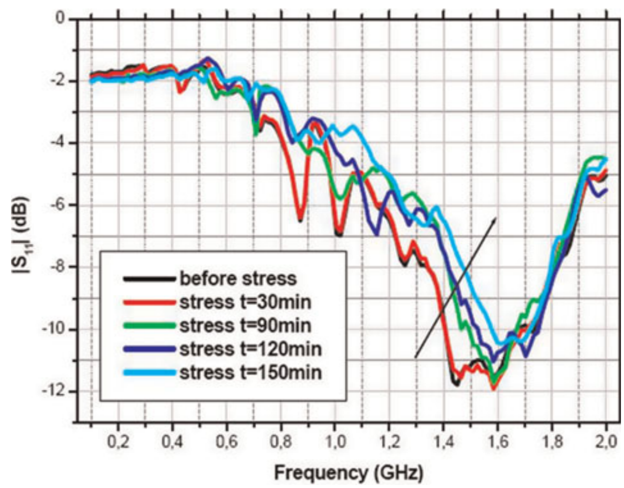


Fig. 9. Measured S_{11} parameter before and during the electromagnetic stress.

stress effects on the forward transmission scattering parameter (S_{21}). The magnitude of the S_{21} parameter, which represents the power gain of an RF input signal, exhibits a deviation after stress by more than 5 dB. This is because of an increased reduction in the transconductance which is consistent with the degradation of the DC current gain [14]. The changes in S_{21} parameter are caused by the increase in the non-ideal base current component [15, 16].

On the other hand, the *S*-parameter measurements revealed that the stress affects the input scattering parameter (S_{11}), while the other scattering parameters show only minor changes. The effects of the electromagnetic field stress on the S_{11} parameter are shown in Fig. 9. This deviation indicates that the input impedance has been changed after the electromagnetic field stress. This shift could result from the increase of the dynamic base resistance. This is due to the base current increase and the reduction of the base current slope versus the base–emitter voltage [14], which is consistent with the variation of S_{11}.

B) DPI approach

The objective of this study is to prove the similarity between DPI and near-field stress effects. A simulation is performed

https://doi.org/10.1017/S1759078709990572 Published online by Cambridge University Press

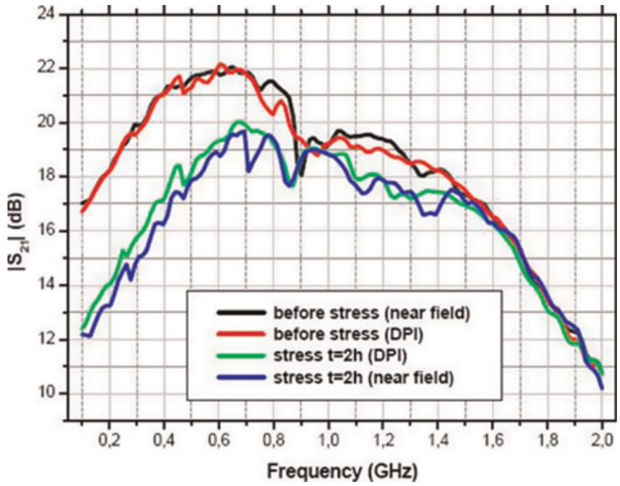


Fig. 10. Measured S_{21} parameter before and after both DPI and near-field stress.

using the ADS model of the PCB to obtain the equivalent power between the DPI and the near-field stress. The equivalent power received by the HBT during near-field stress, which is 18 dBm at 1 GHz, was directly injected in port 1 connected to the base of the transistor. A continuous-wave (CW) disturbance is injected in the components through a 1 nF injection capacitor using the coupler and the injection setup, the amplifier and the RF generator. The influence of both disturbance types on the transmission parameter (S_{21}) for the same stress duration is shown in Fig. 10. The DPI and the near-field stress effects are similar after the same stress time. This comparison clearly demonstrates the relationship between both types of stress. It indicates that the probe/micro-strip line coupling phenomenon is the responsible for the near-field stress effects.

C) Static measurements

Apart from the high-frequency characteristics, the DC characteristics were also affected by the electromagnetic stress. To examine the stress-induced effects, the HBTs are characterized by the Gummel plots; the forward current gain beta and the

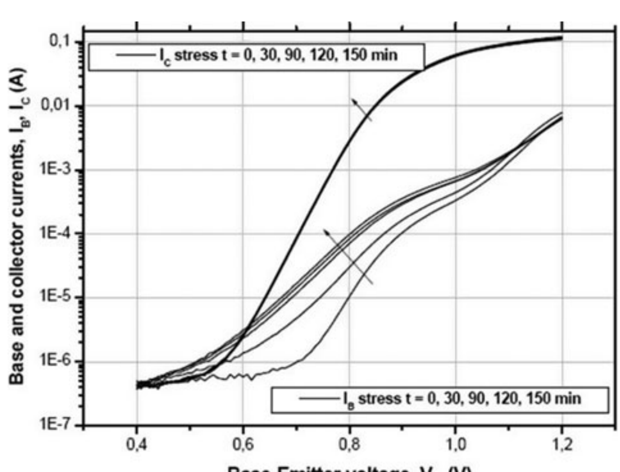


Fig. 11. Forward Gummel plots before and after stress.

I–V curves, using an Agilent HP-4142 Semiconductor Parameter Analyzer. The typical forward Gummel plots of HBT measured for different stressing times are shown in Fig. 11. We can observe that the collector current remains unchanged during the stress while a large degradation of the base current is occurring. The degradation mode is similar to previous literature report such as thermal, irradiation, and electrical stress.

The commonly associated mechanism responsible for this shift in base current is the generation of a damage region at the sidewall-spacer oxide and silicon interfaces. This damage induces interface traps (Si/SiO2) in the E–B spacer oxide due to a hot carrier injection [2, 5, 17]. These stresses induce generation/recombination trap centers and lead to an increase in the recombination component of the base current which produces the current gain degradation [5, 18].

V. CONCLUSION

In this paper, a new reliability study in SiGe HBT resulting from electromagnetic field aggression was investigated. A complete electrical model of an electromagnetic near-field setup was presented. Each part of this model (injection probe and PCB) was characterized and modeled, thanks to the ADS software. The modeling relies on the frequency behavior of an element and on the knowledge of its input impedance. Comparisons were made between the induced voltage obtained by the electromagnetic simulator HFSS and the induced voltage obtained by using the electrical ADS model in order to validate the complete electrical model. Then, taking into account the probe/micro-strip line coupling phenomenon with the important value of the induced voltage in front of the base, the stress impact was understood. It has been found that the amplitudes of the transmission parameter (S_{21}) and the input parameter (S_{11}) are degraded after stress. Hence this indicates significant degradation in forward power gain and changes in the input impedance, respectively. The stress effects have been related to a base current degradation. This degradation appears due to a hot carrier introducing generation/recombination trap centers at the Si/SiO_2 interface. The comparison between the DPI and the near-field stress effects indicates that the probe/micro-strip line coupling phenomenon is responsible for the near-field stress effects.

REFERENCES

[1] Frégonèse, S.; Avenier, G.; Maneux, C.; Chantre, A.; Zimmer, T.: A compact model for SiGe HBT on thin-film SOI. IEEE Trans. Electron Devices, **53** (2006), 296–303.

[2] Huang, S.-Y. et al.: Electrical stress effect on RF power characteristics of SiGe hetero-junction bipolar transistors. Microelectron. Reliab., **48** (2008), 193–199.

[3] Régis, M. et al.: Noise behaviour in SiGe devices. Solid-State Electron., **45** (2001), 1891–1897.

[4] Chahine, I.; Kadi, M.; Gaboriaud, E.; Louis, A.; Mazari, B.: Characterization and modeling of the susceptibility of integrated circuits to conducted electromagnetic disturbances up to 1 GHz. IEEE Trans. EMC, **50** (2008), 285–293.

[5] Cressler, J.D.: Silicon Heterostructure Handbook: Materials, Fabrication, Devices, Circuits and Applications of SiGe and Si

https://doi.org/10.1017/S1759078709990572 Published online by Cambridge University Press

Strained-Layer Epitaxy, CRC Press–Taylor and Francis Group, USA, 2006, chap 4.11, 525–538.

[6] Zhang, S.; Niu, G.; Cressler, J.D.; Osten, H.-J.; Knoll, D.: The effects of proton irradiation on SiGe: C HBTs. IEEE Trans. Nucl. Sci., **48** (2001), 2233–2237.

[7] Bouchelouk, L.; Riah, Z.; Baudry, D.; Kadi, M.; Louis, A.; Mazari, B.: Characterization of electromagnetic fields close to microwave devices using electric dipole probes. Int. J. RF Microw. Comput.-Aided Eng., **18** (2008), 146–156.

[8] Baudry, D. et al.: Applications of the near-field techniques in EMC investigations. IEEE Trans. EMC, **49** (2007), 485–493.

[9] ADS Users Manual, Agilent, (2006).

[10] Antonini, G.; Ciccomancini Scogna, A.; Orlandi, A.: De-embedding procedure based on computed/measured data set for pcb structures characterization. IEEE Trans. Adv. Packag., **27** (2004), 597–602.

[11] Fiori, F.; Pozzolo, V.: Modified Gummel–Poon model for susceptibility prediction. IEEE Trans. Electromagn. Compat., **42** (2000), 206–213.

[12] HFSS v10.0 Users Manual, Ansoft, 2006.

[13] Alaeldine, A. et al.: A direct power injection model for immunity prediction in integrated circuits. IEEE Trans. EMC, **50** (2008), 52–62.

[14] Huang, S.Y. et al.: Hot-carrier induced degradations on RF power characteristics of SiGe heterojunction bipolar transistors. IEEE Trans. Device Mater. Reliab., **5** (2005), 183–189.

[15] Jenkins, K.A. et al.: Use of electron-beam irradiation to study performance degradation of bipolar transistors after reverse-bias stress. IEEE Tech. Dig. Int., **8** (1991), 873–876.

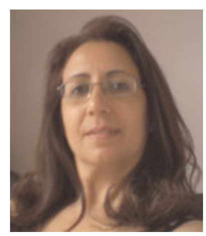
[16] Kuchenbecker, J. et al.: Evaluation of the hot carrier/ionizing radiation induced effects on the RF characteristics of low-complexity SiGe heterojunction bipolar transistors by numerical simulation. Microelectron. Reliab., **40** (2000), 1579–1584.

[17] Rennane, A.; Bary, L.; Roux, J.L.; Kuchenbecker, J.; Graffeuil, J.; Plana, R.: Reliability properties of SiGe HBTs. Appl. Surf. Sci., **224** (2004), 341–346.

[18] Alaeddine, A.; Kadi, M.; Daoud, K.; Beydoun, B.; Blavette, D.: Characterization and simulation of SiGe HBTs degradation induced by electromagnetic field stress, in *Proc. 16th IEEE, Int. Symp. on the Physical & Failure Analysis of Integrated Circuits*, China, 2009.

Ali Alaeddine was born in Zabboud (Lebanon), in April 10, 1984. He received master's degrees in electronics, electrotechnic, automatic from the Lebanese University, Beirut, in 2006, and research master's degrees in microtechnology, architecture, and systems from INSA of Rennes, France, in 2007. Since then, he has been working toward the Ph.D degree in collaboration with the Research Institute for Embedded Systems (IRSEEM), Ecole Supérieure d'Ingénieurs (ESIGELEC), Rouen, France, and Groupe de Physique des Matériaux (GPM/University of Rouen), Rouen, France, with the partnership of THALES AIR SYSTEMS company, Ymare, France, and within the frame work of the CARNOT ESP institute, France, dealing with reliability study of the silicon/germanium components under electromagnetic disturbance. His research interests include electromagnetic compatibility and microelectronics reliability.

Moncef Kadi was born in Constantine (Algeria), in March 17, 1974. He received the Electr. Eng. Dipl. from the University of Constantine, Constantine, in 1996, the master's research degree (D.E.A.) in optoelectronic, optics, and microwaves from the National Polytechnic Institute of Grenoble (INPG), Grenoble, France, in 2001, and the Ph.D. degree in RF and optics from the University Joseph Fourier, Grenoble, in 2004. In October 2004, he joined the Research Institute for embedded systems (IRSEEM), Ecole Supérieure d'Ingénieurs (ESIGELEC), Rouen, France, as a postdoctoral fellow, and is currently a lecturer/researcher. His current research interests include electromagnetic compatibility, antenna design, probe characterisation, and susceptibility of integrated circuits.



Kaouther Daoud was born in Tunis (Tunisia), in March 18, 1960. She was a graduate from IEF (Institut d'Electronique Fondamentale), Paris XI University. Her Ph.D. research activities in France Telecom Laboratories (CNET, 1984–1987) include optimizing a self-aligned technology of GaAs/GaAlAs heterojunction bipolar transistors for microwave applications. Since 1989, she is a lecturer and a professor at INSA (Institut National des Sciences Appliquées) and the University of Rouen. She is in charge of a microelectronic team in the GPM laboratory (Groupe de Physique des Matériaux UMR 6634 CNRS). She is mainly involved in fundamental and applied research with microelectronic critical processes related to device miniaturization and failure analysis: defects and diffusion of p- and n-type dopants in ultra-shallow junctions, segregation in semiconductor–oxide interfaces, activation anomalies, and failure analysis. She is also currently collaborating in academic and industrial partnerships in French and European programs.

Hichame Maanane was born in Vernon (France), in January 3, 1977. He received the doctorate degree from the University of Rouen in 2005. The thesis subject addressed during 3 years (2002–2005) dealt with RF transistors reliability issues for RADAR Applications. From 2005 to 2007, he was an associate professor at the University of Rouen. Since September 2007, he has been a research & development engineer in THALES AIR SYSTEMS (Surface RADAR Business Line, Rouen). He works on design for reliability applied to RF sub-assemblies for both civilian and military applications. He has authored and co-authored several papers on microelectronics reliability. He is also a paper reviewer in IEEE Transactions Device Materials and Reliability & IOP journals.

https://doi.org/10.1017/S1759078709990572 Published online by Cambridge University Press

Philippe Eudeline was born in Honfleur (France), in January 13, 1956. He graduated from the Engineering School ENSEA (Ecole Nationale Supérieure de l'Electronique et de ses Applications). He started his carrier with Thomson-CSF Microwave Links Division as a microwave engineer developing subassemblies such as solid state transmitters and local oscillators. Since 2000, he has been the technical director of a French–Dutch department within the THALES AIR SYSTEMS Company. He has been in charge of the research and development of advanced technologies for microwave equipments (antenna, receivers, transmitters, T/R modules, and synthesizers). He is also deeply involved in the Thales Corporate for Hardware technologies development. He is a writer and co-writer of more than 50 technical papers and owns several patents. He is also the associated professor in the French University of Rouen and ESIGELEC engineering school teaching microwave and radar techniques. He is a senior member of IEEE and currently the chairman of the French IEEE MTT Chapter.

https://doi.org/10.1017/S1759078709990572 Published online by Cambridge University Press