On the Effects of Hot Carriers on the RF Characteristics of Si/SiGe Heterojunction Bipolar Transistors

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***Abstract*—This contribution for the first time experimentally investigates the hot carrier effects on the RF characteristics (up to 30 GHz) of Si/SiGe heterojunction bipolar transistors (HBT's). Reverse base-emitter voltage stresses were applied at room temperature on BiCMOS compatible, sub-micron transistors. The main observed degradation is a decrease of S_{21}. It was found that this degradation is minimized (maximized) when biasing at constant collector (base) current. These results may be valuable indications also for degradations induced by ionizing radiations.**

***Index Terms*—BiCMOS SiGe HBT, HBT reliability, hot carrier, ionizing radiations.**

I. Introduction

HOT CARRIERS (HC) are a relevant reliability concern for advanced bipolar transistors, because of the employed high dopant concentrations [1]. This holds also for Si/SiGe HBT's, which are today moving toward analog applications up to 40 GHz [2]. All the works dealing with HC and/or ionizing radiations (IR) effects report on the dc characteristics and/or on the low frequency noise (LFN) behavior [1], [3]–[7]. Data on the RF characteristics are lacking, even if they are an important issue when RF applications are addressed. The high operation frequencies offered by the Si/SiGe HBT suggest this device for space microwave applications, where the concern of the IR has to be faced. It is known that both HC and IR induce very similar dc and LFN degradation modes [3], [4]. Data obtained from HC stresses can therefore give valuable indications about IR effects on the RF characteristics. The present paper experimentally investigates for the first time the HC effects on the RF characteristics of Si/SiGe HBT's. The experimental data are then compared with and supported by numerical simulations. We believe that the present paper is a timely and innovative contribution to the Si/SiGe HBT's reliability with interesting implications in the microwave applications field.

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II. Experiments

The HBT's are embedded with a BiCMOS process. The SiGe base layer is ultra high vacuum chemical vapor deposition (UHV-CVD) epitaxially grown and it features a triangular Ge profile. The one finger emitter features 0.8 μm width and 25 μm length. The devices exhibit a dc current gain in the range of 100 and typical intrinsic cut-off (f_T) and maximum oscillation ($f_{\max}$) frequencies of about 35 GHz and 50 GHz, respectively.

The devices were measured up to 40 GHz for different bias points. The base current ranged between 5 μA and 30 μA and the collector-emitter voltage was fixed at 1 V. The collector current density was around 10 kA/cm^2, which is a typical value for low noise applications. The stress procedure was carried out applying a reverse base-emitter voltage (V_{EB}) of 4 V up to 10 min. Under these stress bias conditions, the hot carriers damaging the base-emitter junction are holes [6]. All measurements and stress procedures were carried out at wafer level on a set of five devices.

III. Results and Discussion

The main behavior related to the stress is a decrease of the dc current gain associated to the rise up of a nonideal base current component featuring an ideality factor ranging from two to three while the collector current remains unchanged as reported in Fig. 1. The degradation speed (only few stress minutes were sufficient to turn it on) is attributed to the quite high V_{EB} value of 4 V applied during the stress. It is known indeed that the reverse base-emitter voltage stress effects are strongly accelerated by V_{EB} [8] (maximum applied $V_{EB} = 3.5$ V in [8]). Generally speaking, the accelerated stresses allow obtaining data in a short time with the drawback that new degradation mechanisms may occur. Nevertheless, the changes in Fig. 1 are the typical HC/IR induced degradation modes [1], [3]–[7]. The applied stress conditions are thus meaningful to the aim of our investigation.

Fig. 2 shows the effect of the stress on the forward transmission scattering parameter (S_{21}). The magnitude of S_{21} decreases when the measurements are carried out at the same base current as before the stress. On the other hand, no meaningful variations are observed when the measurements are performed at the same collector current. The insert in Fig. 2 shows the evolution of the extrinsic transition frequency f_T during the stress measured at constant I_B and at constant I_C. f_T does not change when i is measured at constant I_C, because of its dependence on the emitter charging time, which is inversely proportional to I_C [9],

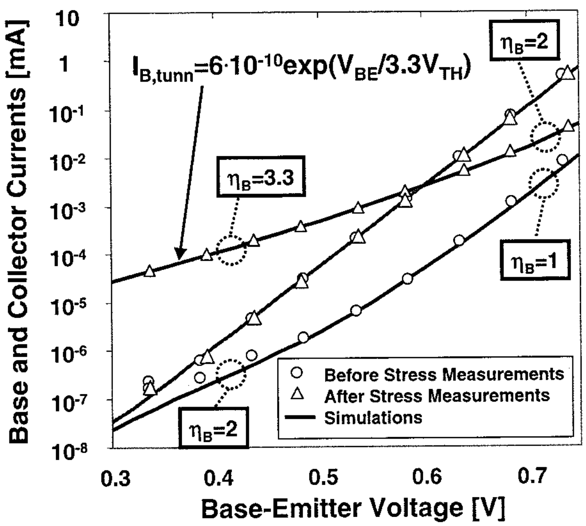

Fig. 1. Gummel plots before and after stress (simulations [—] and measurements $[O, \Delta]$).

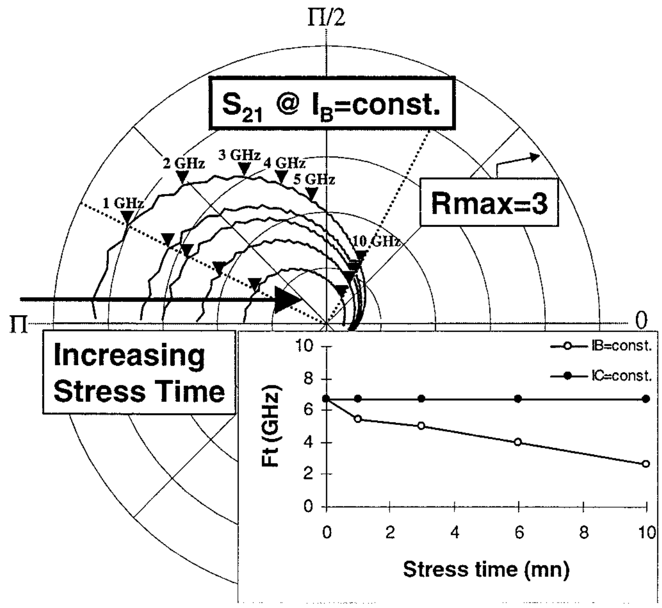

Fig. 2. Changes in the extrinsic scattering parameter S_{21} measured from 0.04 GHz to 30 GHz at I_B = const. during the stress. In the insert, the comparison between the extrinsic f_T evolution during the stress measured at constant I_B and at constant I_C.

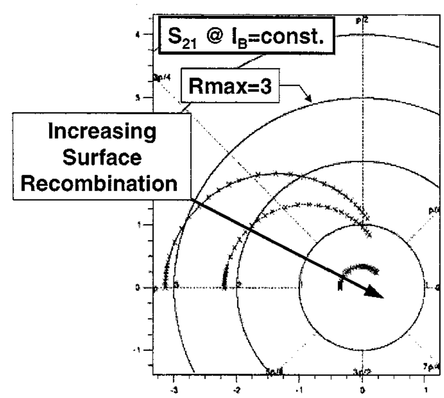

Fig. 3. Changes in the intrinsic transmission scattering parameter S_{21} simulated from 0.04 GHz to 40 GHz at I_B = const. and V_{CE} = 1 V before and after stress.

[10] As to the other S parameters, only minor changes were observed, regardless of maintaining constant the base or the collector current. The matching conditions are thus not strongly affected by the stress.

The Si/SiGe HBT's exhibit usually low noise figure and therefore they are interesting devices for low noise amplifiers (LNA's), which are critical components of a receiver front-end. In agreement with the Friis' formula [11], a reduction of the LNA gain can increase the LNA noise figure, because it reduces the noise isolation between the LNA input and the electronic circuitry (e.g. mixer) at the LNA output. The data on Fig. 2 suggest therefore that the LNA noise performance can be made more robust to the HC/IR effects by biasing the HBT at constant collector current.

To validate the experiments, some numerical simulations were carried out. The semiconductor device simulator Blaze™ by Silvaco was employed [12]. The first step was to reproduce the effects of the stress on the dc characteristics. Measured and simulated Gummel plots are compared in Fig. 1. A good agreement was obtained. In agreement with the literature, the degradation was simulated introducing Shockley–Hall–Read (SHR) surface recombination close to the emitter perimeter [5], [6], [13]. The SHR recombination features a recombination velocity of 9×10^3 cm/s on a lengh of 20 nm. This recombination mechanism allows to obtain an ideality factor (η_B) of the base current up to two [3] while in our case η_B is around three in the lowest bias range. Such a high value is usually the signature of band-gap traps assisted tunneling recombinations [1], [6]. This tunneling current component was modeled by using the expression reported in Fig. 1.

Once reproduced the dc degradation modes, the RF characteristics were simulated. They were carried out up to 40 GHz. Fig. 3 shows the changes in S_{21} simulated at a constant base current as a function of the surface recombination velocity. We can note that the simulations well reproduce the experimentally observed behavior (see Fig. 2). Still in agreement with the experimental experience, no changes in S_{21} were observed when the simulations were carried out keeping unchanged the collector current. Finally, the simulations confirmed also the minor changes observed in the other S parameters.

IV. Conclusions

In the present work, for the first time the HC effects on the RF characteristics of Si/SiGe HBT's have been experimentally addressed. The investigation revealed that the stresses mainly affect the S_{21} parameter while the other scattering parameters show only minor changes. In particular, it was found that the S_{21} reduction is maximize (minimized) when the base current (collector current) is kept constant. Numerical simulations confirmed all these experimental observations. Because of the similarity between HC and IR induced dc degradation modes, it can be assumed that similar behaviors can be expected also in the case of IR induced degradations. It is here worth pointing out that no changes in the S-parameters measured at constant IC were observed after proton irradiation [14].

The obtained results are of practical interest, because they suggest that the more constant the collector current is kept, the higher the microwave circuit (e.g., LNA) robustness to hot carriers is. These results can be therefore useful in the choice of bias network (passive or active) to be employed [15], [16]. Moreover, they indicate that useful information on the RF characteristics degradation can be obtained from dc measurements, avoiding, at least in a first attempt, the more time consuming and expensive RF characterizations. Finally, the results obtained in the present work generalize those already obtained in the past on AlGaAs/GaAs HBT's [17] and on AlGaAs/InGaAs pseudomorphic HEMT's [18].

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