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New Insights Into Noise Characteristics of Hot Carrier Induced Defects in Polysilicon Emitter Bipolar Junction Transistors and SiGe HBTs

KUNFENG ZHU[1,2], PEIJIAN ZHANG[3], ZICHENG XU[4], TAO WANG[1], XIAOHUI YI[3], MIN HONG[3], YONGHUI YANG[1], GUANGSHENG ZHANG[1], JIAN LIU[1], JIANAN WEI[3], YANG PU[3], DONG HUANG[1], TING LUO[3], XIAN CHEN[3], XINYUE TANG[3], KAIZHOU TAN[3], AND WENSUO CHEN[2] (Member, IEEE)

1 Semiconductor Manufacturing Process Development Department, Sichuan Institute of Solid-state Circuits, Chongqing 400060, China
2 State Key Laboratory of Power Transmission Equipment and System Security and New Technology, Chongqing University, Chongqing 400044, China
3 Science and Technology on Analog Integrated Circuit Laboratory, Chongqing 400060, China
4 Glasgow College, University of Electronic Science and Technology of China, Chengdu 610054, China

CORRESPONDING AUTHORS: P. ZHANG AND W. CHEN (e-mail: pjzhang@whu.edu.cn; wensuochen@cqu.edu.cn)

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ABSTRACT Low frequency (LF) noise is a powerful and non-destructive technique for evaluating the oxide-semiconductor interface and an effective evaluating tool in characterizing electronic device's structure and reliability. In this study, we present a systematic analysis of the striking abnormal 1/f noise behavior of the hot carrier induced defects in highspeed polysilicon emitter bipolar transistors (PE-BJTs) and SiGe HBTs. Here, the comparative results before and after hot carrier degradation reveal that low frequency noise spectra are not correlated with the density and distribution of the interfacial defects, which related to Si dangling bonds reside at the SiO_2/Si interface in PE-BJTs and SiGe HBTs.

INDEX TERMS Hot carrier, interface defect, current gain, 1/f noise.

I. INTRODUCTION

Hot carrier degradation (HCD) is a major reliability issue of electronic components such as high speed polysilicon emitter bipolar junction transistors (PE-BJTs) and SiGe HBTs [1], [2], [3]. From a physical viewpoint of HCD, the reaction-diffusion theory has been a well-accepted framework for comprehensive understanding of the phenomena for a long period of time. Despite considerable progress in understanding and interpreting the electrical performance degradation behaviors has been achieved during the several past decades, but the exact underlying physics and atomic-level microscopic dynamics for the interface lattice defect formation are still missing [4]. It has been generally accepted that HCD involves two main mechanisms of bond breaking through incident carriers, either being very energetic or very numerous but less energetic [5], [6]. Moreover, hot carriers greatly change the density and distribution of the trapped oxide charges and the trapped interface charges, which locally perturb the device electrostatics and degrade the carrier mobility. As a consequence, both the increase of trap concentration at or near the Si/SiO_2 interface and the carrier mobility degradation can change the low frequency (LF) noise spectral densities [7], making LF noise analysis becomes a useful and non-destructive diagnostic tool in electronics reliability studies.

In ultra-scaled MOSFETs, the stress voltage V_{DD} is below 1 V. The channel electron seems unlikely to gain enough energy to become hot enough with energy above 1.5 eV. The electron cannot afford enough energy to dissociate the Si–H bonds at the interface underneath the gate dielectric. Therefore, the model of bond dissociation by the high energy carrier paradigm must be extended for reason that it fails to interpret the HCD effects even if the stress voltage V_{DD} is below 1 V. The degradation mechanisms should move from the classical accelerating field-driven lucky electron model to the model of carrier energy-driven HC degradation via multiple vibrational excitations of the bond.

In contrast to the complicated cases of HCD in MOSFETs, HCD effects related reliability issues in BJTs are much more simplified. There are three major available hot carrier sources

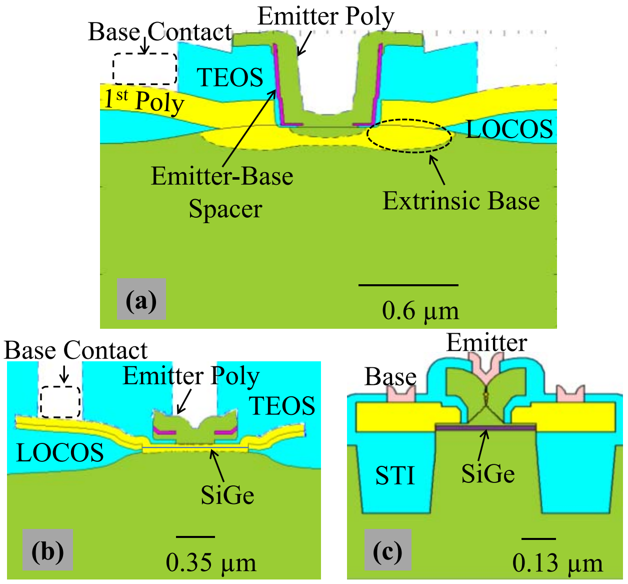

FIGURE 1. Representative cross-sections of the npn transistors. (a) 0.6-μm PE-BJT, (b) 0.35-μm and (c) 0.13-μm SiGe HBTs.

in PE-BJTs: reverse emitter-base (E/B) bias induced HCs [2], Auger electron produced HCs under high current stress [8] and the HCs come from mixed-mode (MM) stress [3]. HCDs under reverse E/B biased conditions have been traditionally studied since 1980s [2], [9], [10], where HCs are created by large electric fields across the E/B junction. In this study, we focus on the latter two HCD effects both in PE-BJTs and SiGe HBTs. Different from the case in MOSFETs, where HCDs produce a degradation of the drain current and transconductance, HC damage is mainly related to the creation of Si dangling bonds acting as trap sites at or near Si/SiO_2 interfaces, which lead to an increased Shockley–Read–Hall (SRH) recombination rate and hence an excess non-ideal base current component in BJTs. In addition to the hot carrier damage at Si/SiO_2 interface, the temperature dependent recovery of interface traps after HC stress has also been observed both in MOSFETs and SiGe HBTs [11], [12], demonstrating the opposite behavior of interfacial silicon dangling bonds which is passivated by molecular hydrogen. In this paper, the test result is deduced to be the net effect of the two factors. In contrast to the previous reports, a striking different 1/f noise behavior of the hot carrier induced defects in PE-BJTs and SiGe HBTs will be revealed in this study.

II. EXPERIMENTAL DETAILS

The devices under test (DUTs) used in this study including high speed PE-BJTs from a 0.6-μm node commercial complementary bipolar technology with a minimum BV_{CEO} of 12 V, and two types of SiGe HBTs from a 0.35-μm node with a minimum BV_{CEO} of 5 V and a 0.13-μm node with a minimum BV_{CEO} of 2.7 V SiGe BiCMOS technologies, respectively. Fig. 1 shows the corresponding cross-sections of these three types of devices. For the sake of simplicity but without loss of generality, PE-BJTs were biased under two stressing conditions to get the two kinds of hot carriers, i.e., Auger HCs and MM HCs, while SiGe HBTs were just under MM stress condition. As observed in Fig. 1(a), the symmetrical L-shaped spacer between the emitter and base shrinks the effective emitter width from 0.6-μm to 0.35-μm. In present case, both the PE-BJTs and the 0.35-μm SiGe HBTs hold the similar device structures with double polysilicon self-aligned architectures as illustrated in Fig. 1(a) and (b). Furthermore, deep trench isolation and local oxidation of silicon isolation have been used to reduce parasitics and leakages in these two DUTs. However, the 0.13-μm SiGe HBTs are deep trench isolation free only with carefully designed shallow trench isolation to increase the compatibility with the baseline CMOS technology platform.

To obtain complete degradation details of the DUTs after Auger HCs stress and MM HCs stress, we comparatively characterized the DC and LF noise performances of the three types of DUTs before and after HC stress. In the case of the high forward current stress, all the highspeed PE-BJTs were forward biased by using a homemade dual source meter with emitter, base and collector fixed at 0 V, 1 V and 2 V, respectively. For the MM stress, the DUTs were simultaneously subjected to large emitter current density and high collector-base (C/B) voltage, by fixing base, collector at constant voltages. The emitter and substrate terminals remain grounded using Keysight B1500A sampling mode, where V_{BC} is much higher than BV_{CEO} but smaller than BV_{CBO} to avoid the DUTs permanent damage. Although there is no unambiguous definition of the stress bias condition for MM stress, a relatively high emitter current is adopted by adjusting the V_{BE} together with a proper V_{BC} voltage to ensure obvious degradation occurs but without device destruction. V_{BE} is set at 0.8 V both for 0.6-μm PE-BJTs and 0.35-μm SiGe HBTs (with the emitter current densities are 7 mA/μm^2 and 5.4 mA/μm^2, respectively), whereas V_{BE} keeps a relatively small value from 0.7 V to 0.75 V for the 0.13-μm SiGe HBTs (with emitter current density about 8 mA/μm^2) because it can be damaged more easily compared to the other two counterparts. All transistors were packaged in 24 pin dual-in-line packages, both the DC and low frequency noise measurements have been performed on at least three samples. The 1/f noise was measured using the E4727A Advanced Low–Frequency Noise Analyzer together with B1500A from Keysight.

III. RESULTS AND DISCUSSION

Fig. 2(a) and (b) illustrate the Auger HCs induced DC characteristic variations in Gummel-Poon (G-P) and current gain degradation curves in PE-BJTs. S_{IB} curves shown in Fig. 2(c) indicate that the 1/f noise spectra remain nearly unchanged, which haves been previously reported [8]. Fig. 2(d), (e) and (f) exhibit the corresponding G-P curves, current gain curves and noise spectra of the PE-BJTs before and after MM stress. It is clearly exhibited that base current greatly increases in the low injection level while collector current keeps unchanged both after Auger and MM HCs stress. Interestingly, a striking abnormal noise spectra behavior is observed both in the

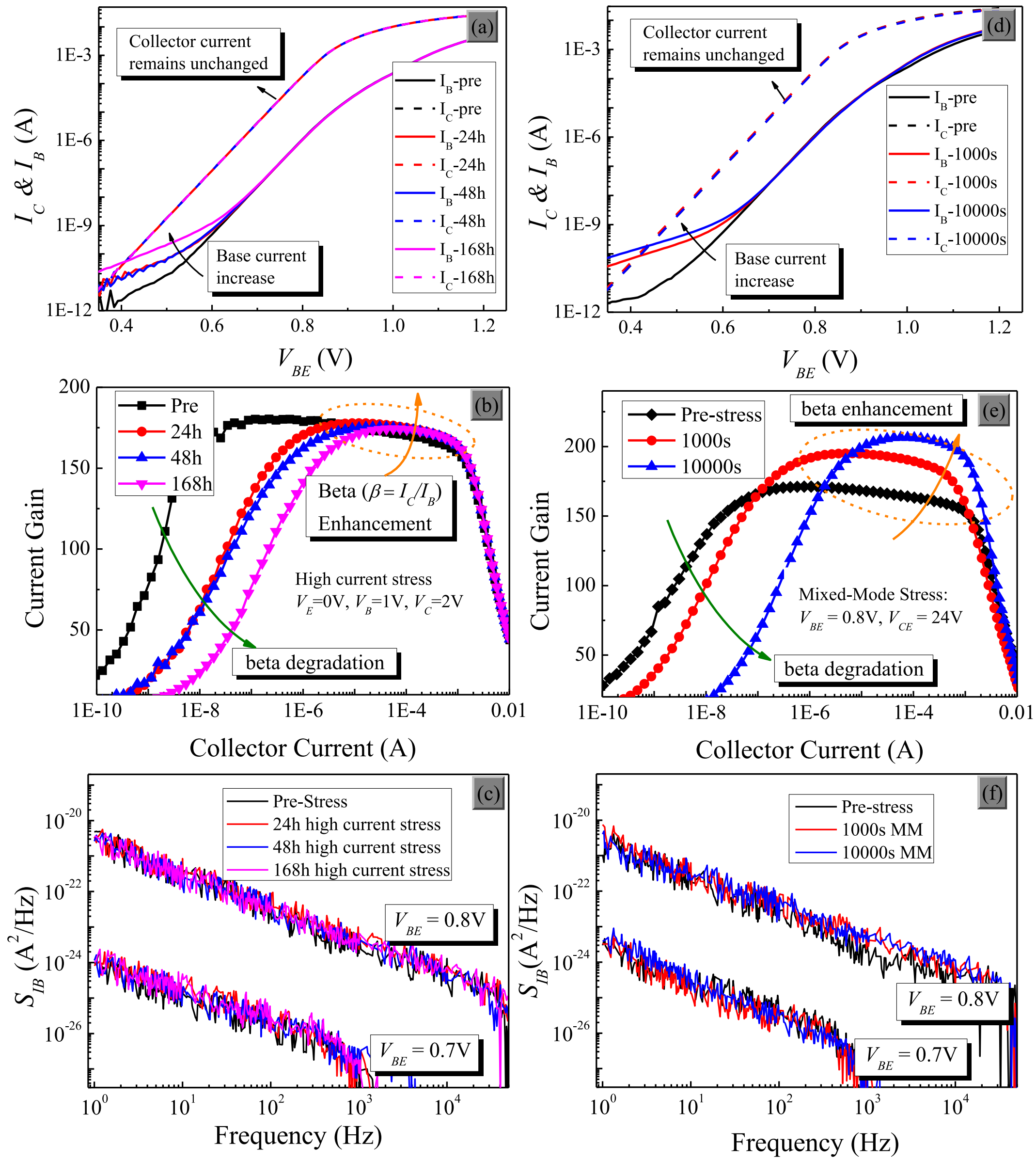

FIGURE 2. Comparative DC curves and low-frequency noise spectra in PE-BJTs with different HCs stressing. (a), (b) and (c) forward high current Auger hot carriers stressing, (d), (e) and (f) MM stressing.

Auger HC stressed and MM stressed PE-BJTs, i.e., there is unconspicuous variation of noise spectra versus HCs can be observed despite obvious DC performance degradations occur as indicated in Fig. 2(a), (b), (d) and (e).

Current gain degradation in the low injection level can be ascribed to Si:H bond-breaking followed by nonideal base current increase via trap-assisted SRH recombination at SiO_2/Si interface, where the interface traps originate from the energetic hot carriers induced silicon dangling bonds. On the other hand, current gain enhancement in the middle to high injection level is attributed to two reasons. First, the reduction of the minority carrier injection into the polysilicon emitter and base. Second, the carrier mobility degradation due to hot carrier released atomic hydrogens passivation of dangling bonds along the grain boundaries in polysilicon emitter [8], [13]. In addition, current gain enhancement, and more importantly, is to the best of our knowledge the first time to be reported under MM stress condition. With regard to the hot carrier damage behaviors, it has been claimed that MM hot carriers are more likely to stop near the polysilicon-silicon interfaces of the emitter and base, but Auger hot-carrier generation can happen deep within the polysilicon emitter and base [13]. Our results suggest otherwise, i.e., it is speculated that MM hot carriers and Auger hot carriers show similar bond dissociation and defect generation behaviors at the SiO_2/Si interfaces and PE grain boundaries.

To further demonstrate this abnormal noise spectra behavior especially in MM stressed DUTs. Two types of SiGe HBTs with different node technologies, as stated in Section II, were employed for verification. Illustrated in

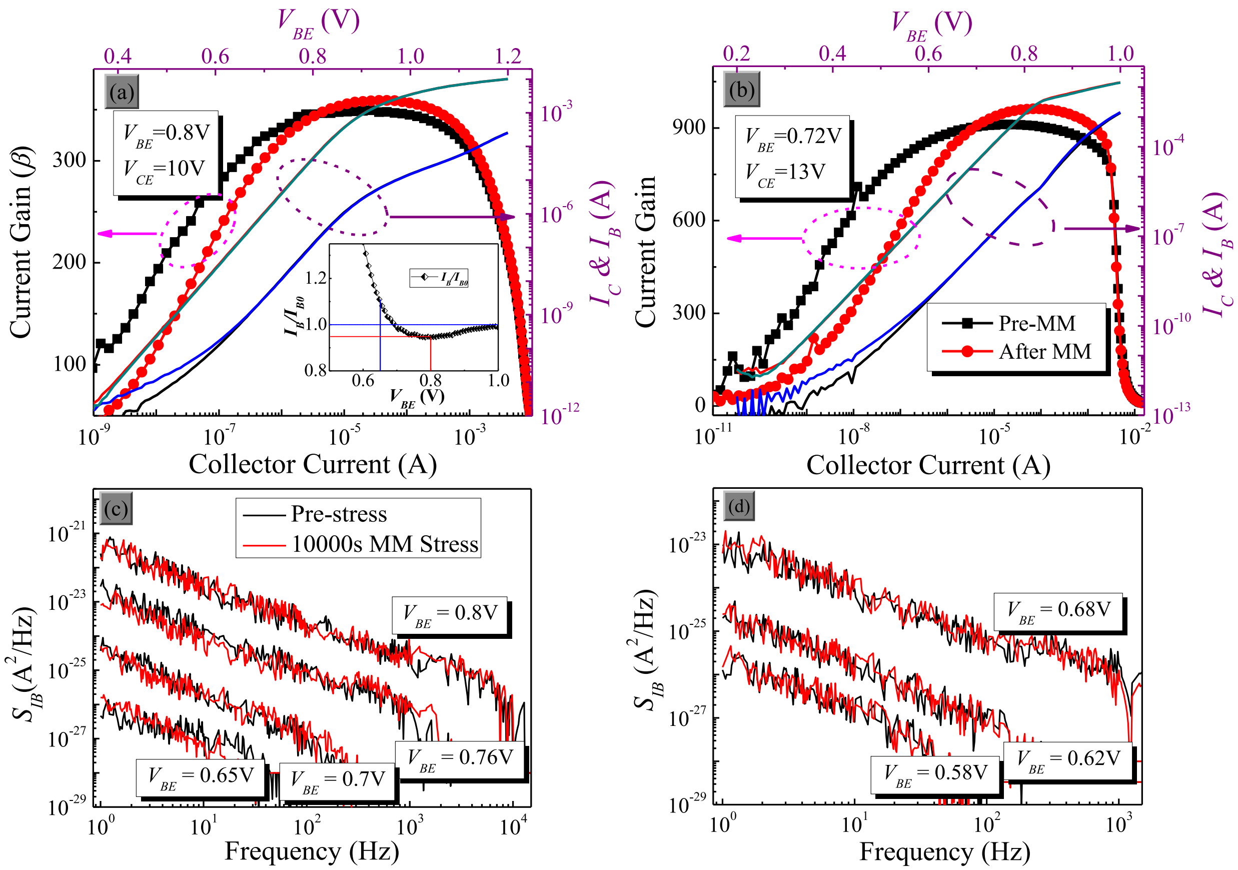

FIGURE 3. Comparative DC characteristics and low-frequency noise spectra in different SiGe HBTs before and after MM stress. (a) and (c) 0.35-μm 5V SiGe HBTs, (b) and (d) 0.13-μm 2.7V SiGe HBTs. Inset: Normalized base current I_B/I_{B0} after 10000 s MM stress.

Fig. 3 are the noise spectra S_{IB} and DC performance variations of the two different SiGe HBTs before and after MM stress. As an example, in the inset in Fig. 3(a), normalized base current I_B/I_{B0}, is plotted versus V_{BE} for the 0.35-μm SiGe HBT. It can be seen that the minimum base current is about 95% of the fresh device at $V_{BE} = 0.8$ V, while it exceeds 10% over the original value at $V_{BE} = 0.65$ V after 10000 seconds MM stress. In contrast to the degradation behavior reported in the literature based on the lucky electron model, where the base current noise spectrum deviates from the original ideal 1/f frequency dependence and the noise spectral density goes much higher than its initial value after MM stress [14]. There is an obvious difference apparent, clearly indicative that both the two SiGe HBTs exhibit a similar DC and LF noise characteristics after MM stress induced degradation as their PE-BJT counterparts, i.e., the noise spectra S_{IB} of the DUTs are negligibly affected during the MM stressing procedure as indicated in Fig. 3(c) and (d).

High frequency circuit operation needs devices to work closer to their physical limits in order to compensate for the loss of output power. Power applications require a collector-base voltage range as large as possible, leading to operating point biases beyond BV_{CEO} and close to the edges of the transistor operating regime. Process scaling brings the benefits of increased speed and performance, however, it also becomes a major reliability concern. As a result, a scaled SiGe HBT with reduced breakdown voltage is more susceptible to hot carrier effects. It is necessary to carefully evaluate the hot carrier reliability and to understand the underlying degradation mechanism before the device being used in a circuit.

Lots of theoretical works have been pursued in the past decades to provide a fundamental understanding of Si-H dissociation mechanisms for the goal of an accurate microscopic description of HCs induced damage at the device level. The most important and widely accepted one is the energy driven paradigm based on the acceleration integral, which is calculated from the energy distribution function of the carriers, has been developed to include both single and multiple carrier processes of the bond dissociation in MOSFETs [6]. Recently, Kamrani et al. extended the distribution function to account for both hot electrons and hot holes and solve the coupled system of Boltzmann transport equations to obtain the required energy distribution function of the carriers to reconsider the MM degradations in SiGe HBTs [15].

Based on this theoretical framework, the basic degradation process for the MM stress can be drawn as follows in our case. Electrons traverse the base and become sufficiently energetic hot electrons due to the huge electric field at the C/B junction, these hot electrons initiate impact ionizations resulting in a great amount of energetic hot electron-hole pairs. The secondary holes and electrons drift toward the base and collector respectively, owing to the polarity of the field. Some

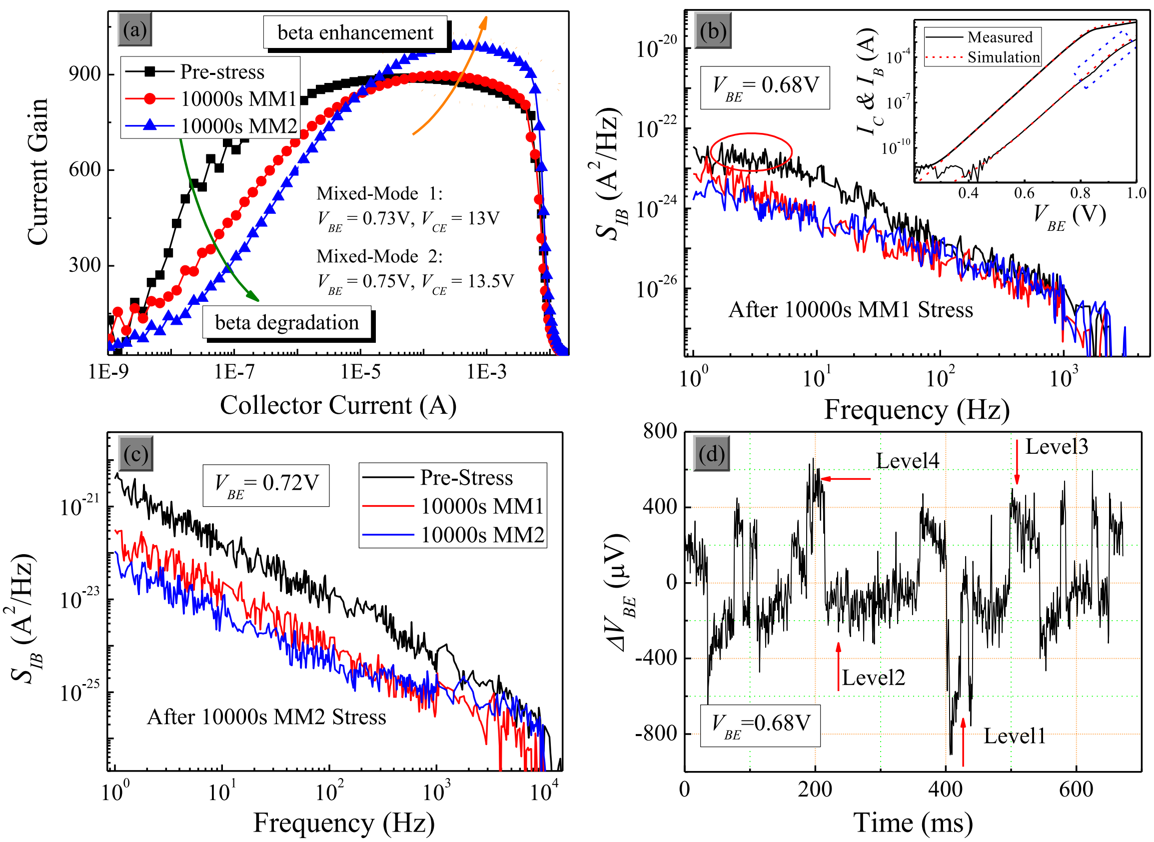

FIGURE 4. Comparative DC characteristics and low-frequency noise spectra in the SiGe HBTs with pre-existing oxide vacancy defects before and after MM stress. (a) Current gain degradation after two modes of MM stress. (b) Base current noise spectra S_{IB} after MM1. (c) Base current noise spectra S_{IB} after MM2. (d) RTN of the fresh device. Inset: Fitting Gummel-Poon curve using IC-CAP with HiCUM.

of the energetic holes can be further accelerated and traverse the base into the emitter and can potentially participate in further impact-ionization events till scattering events cause the carrier to lose all of its kinetic energy. Some of these hot carriers strike the E/B spacer oxide interface and the ultra-thin interfacial oxide between emitter and base leading to the Si–H bond breakage, as a consequence of base current increase in the low injection level. The net SRH transition rate via interface traps, of density N_{it} and energy E_T, present within the bandgap can be described as [16]

$$U = \frac{\sigma_n \sigma_p v_{th} N_{it} \left(pn - n_i^2\right)}{\sigma_n \left[n + n_i \exp\left(\frac{E_t - E_i}{kT}\right)\right] + \sigma_p \left[p + n_i \exp\left(\frac{E_i - E_t}{kT}\right)\right]}$$

where k is the Boltzmann constant, T is the absolute temperature, v_{th} is the thermal velocity, E_t and E_i are the trap energy and intrinsic Fermi energy, σ_n and σ_p are the electron and hole capture cross sections, respectively. The transition rate U reaches a maximum value when $E_t = E_i$, indicating that only those traps near the mid-gap are effective generation and recombination centers. Based on the degradation behaviors of the DC curves of the DUTs both in Fig. 2 and Fig. 3, these hot carriers induced interfacial defects are exactly the effective generation and recombination centers in present cases.

On the other hand, a fraction of the hot carriers can release atomic hydrogen from the hydrogen traps, e.g., metal/poly-Si interface, and these atomic hydrogens diffuse to the poly/crystalline-Si interfaces and polysilicon boundaries then deactivate the silicon dangling bonds. As a consequence, base current decrease in the middle to high injection level. The interface states are well identified and associated with the so-called Pb centers by electron spin resonance studies [17], [18], [19]. These HCD induced SRH centers located very close to the intrinsic Fermi level, while the portion of the SiO_2 defect energy distribution that is most easily accessible to LF noise is the region within a few kT of the Fermi level. Traps contribute to the fluctuations by a weighing Fermi factor, which peaks sharply at the interfacial Fermi level. It has been proved that the possibility that the interfacial traps acted more to modify the carrier mobility rather than to change the carrier concentration and not all traps at the interface participate equally in producing the current fluctuations [20], i.e., the interfacial defects responsible for low-frequency noise are not usually distributed evenly in space or energy. As a consequence, no correlation of low frequency with the density and distribution of the Si dangling bonds related interface defects is observed in PE-BJTs and SiGe HBTs in present case.

It should be pointed out that quite different results are obtained after MM stress for some special DUTs, indicating that the link between the defects and degradation mode is not yet fully understood. Fig. 4 shows the MM stress induced changes in S_{IB} of the special HBTs, where the special DUT is defined as the one its fresh base current cannot be well fitted by the compact model [21], i.e., the pre-existing oxide defects induced some second-order effects resulting the base current deviates from the ideal formula especially in the low injection level as indicted in the inset in Fig. 4(b). One can observe that both the spectrum after MM1 and MM2 stress exhibit a noise component decrease. Meanwhile, it is clear that the pre-stress LF spectra is not an ideal 1/f style but with the presence of Lorenzian component, which is associated with generation-recombination centers in the oxide. The Lorenzian component has been verified as random telegraph signal (RTN) as indicated in Fig. 4(d) [22], [23], which involves capturing and emitting electrons by the oxide *E'* centers in oxide from the channel in MOSFETs. These oxide defects can be either from manufacturing process in the fresh device or from electric stress induced degradation process [22]. It can be deduced that the fresh S_{IB} deviation from 1/f dependence originating from these pre- existing process oxide defects. Moreover, these oxide traps can be annealed or passivated by the HCD released atomic hydrogens, as a consequence, the RTN disappeared after MM stress resulting in the magnitude of spectra S_{IB} decrease and become more 1/f noise like as indicated in Fig. 4(b) and (c).

IV. CONCLUSION

In conclusion, 1/f noise characteristics have been comparatively examined before and after Auger HCs and MM HCs stressing both in highspeed PE-BJTs and SiGe HBTs. It reveals that both Auger HCs and MM HCs induce great DC performance degradation but have no impacts on the 1/f noise variability. The DC performance degradation is interpreted in the terms of the Si–H bond breakage and Si dangling bonds passivation at the SiO_2/Si interfaces and along the polysilicon boundaries. More importantly, HCs damage in PE-BJTs and SiGe HBTs not only greatly changes the carrier number fluctuation but also involves carrier mobility variation. It seems that Si dangling bond related interface defects show no correlation with low frequency noise in PE-BJTs and SiGe HBTs.

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