POWER PERFORMANCE CHARACTERISTICS OF SIGE POWER HBTS AT EXTREME TEMPERATURES

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ABSTRACT

This paper presents the RF (6 GHz) power performance characteristics of SiGe power HBTs at cryogenic (77K) and high operation temperature (chuck temperature 120°C, junction temperature up to 160°C). It shows that, without specific device optimizations for cryogenic operation, the power SiGe HBTs exhibit excellent large-signal characteristics at 77K. Comparing with room-temperature operation, similar power gain, output power and PAE were obtained when the devices were operated at the cryogenic temperature. The SiGe power HBTs also operate well at high junction temperature with reasonable power gain and output power degradations. The modeling of the SiGe power HBTs under high operation temperature indicates significant increase of base resistance (R_B) and emitter resistance (R_E) that account for the degradation of power performance of these devices.

INTRODUCTION

Due to continuous downscaling and device structure optimizations, the operation frequency of SiGe heterojunction bipolar transistors (HBTs) has been dramatically increased [1]. Owning to their excellent RF performance and compatibility with low-cost CMOS technology, significant attention has been drawn on SiGe HBTs for their potential applications in extreme environments. Because of their unique bandgap-engineered features, SiGe HBTs are inherently suitable for cryogenic temperature (77K or 4.2K) operation, which offers an important niche market such as space communication system, low temperature sensor and superconductor instruments [2][3]. The dc, small-signal and noise performance of low-power, high-speed SiGe HBTs have been thoroughly investigated as of today [3]-[5]. However, to the authors' knowledge, the RF *power* performance of large-area SiGe power HBTs under cryogenic temperature has never been reported. On the other hand, high-temperature operation of electronic devices also plays an important role in a variety of applications [6]. Previous studies on low-power, high-speed SiGe HBTs showed the degraded performance characteristics under high-temperature operations [7]. Power SiGe HBTs with multiple emitter fingers often exhibit high junction temperatures due to their high power consumption. However, very limited studies on the high-temperature operation of SiGe power HBTs exist in the literature as of today. Under 75°C operation in a previous study [8], the change of major device parameters (like emitter and base resistances) was hardly observed. Furthermore, the detailed power-gain degradation behavior at high operation temperatures was never investigated before. In this paper, we report the dc, small-signal and especially the large-signal load-pull measurement results of SiGe power HBTs at extreme temperatures. The device degradation mechanisms under high operation temperature were elucidated by carefully modeling the devices.

DEVICE CHARACTERISTICS

The power SiGe HBTs investigated in this study were manufactured in a commercial SiGe BiCMOS platform. The power HBT consists of 40 emitter fingers, with a dimension of 0.9x10.16μm^2 for each finger. The devices were characterized under cryogenic temperature (77K) using liquid nitrogen cooling and at elevated temperature (120°C) on a hot stage. The measured device junction temperature at a stage-temperature of 120°C is about 160°C due to device self-heating. For comparison, the power performance of the devices at room temperature (300K) is also characterized.

Figure 1 shows the forward Gummel characteristics of the power SiGe HBT measured at the three temperatures. It is clearly shown that the base-emitter turn-on voltage increases with the cooling temperature because of the reduced intrinsic carrier concentration [3]. The transconductance g_m (the slope of the I_C curve) also increases with the cooling temperature because of the receded thermal energy kT with temperature. Figure 2 shows the current gain β as a function of collector current at different temperatures. The peak value of β increases from 107 at 160°C to 150 at 300K and to 800 at 77K, because of Ge-induced bandgap narrowing at the emitter-base edge of the quasi-natural base region along with the cooling of temperature [4].

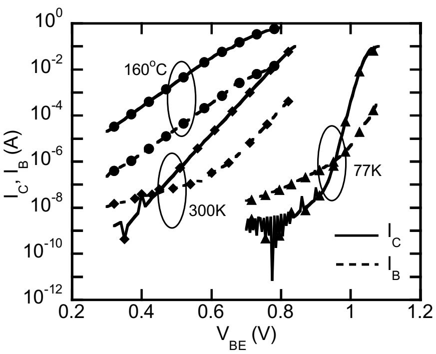

Figure 1. Measured forward-mode Gummel plots of the SiGe power HBT at room temperature, 77K and 160°C.

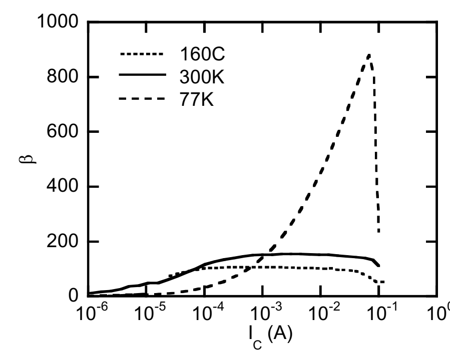

Figure 2. Measured current gain of power SiGe HBT as a function of collector current at room temperature, 77K and 160°C.

The small-signal performance of the SiGe HBT was characterized at the three temperatures using an Agilent 8346A PNA. The calibrations were carried out and verified at 300K, 77K and 160°C, respectively. Power gain (MAG/MSG) was calculated from the measured S-parameters. Figure 3 shows the MAG/MSG curves as a function of frequency under different temperatures at a current level of I_C=80mA. It is observed from Fig. 3 that the maximum stable power gain (MSG) is increased at 77K. However, the maximum available power gain (MAG) doesn't show any substantial increase at 77K. The values of f_{max} only show a slight improvement at 77K. These small-signal power gain characteristics are different from that of the low-power, high-speed SiGe HBTs [2] [3]. It is noted that these power devices investigated here were not particularly optimized for cryogenic operation. The base doping concentration was not made well above the Mott transition to effectively suppress the carrier freeze-out. The increased base resistance (R_B) due to carrier freeze-out when temperature under 100K has a negative impact on the MAG part of the small-signal power gain curve [9]. Figure 3 also shows that both MSG and MAG degrade when the operation temperature was elevated. At 6GHz, the small-signal power gain of the SiGe HBT is reduced from 21dB at 300K to 10.5dB at 160°C. The f_{max} is also decreased from 26GHz at 300K to 12GHz at 160°C. However, such phenomenon was not revealed in the previous study, in which the operation temperature of 75°C was used [8].

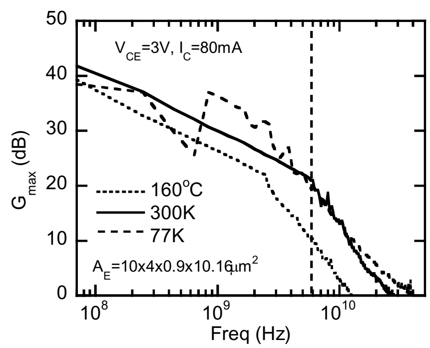

Figure 3. Measured small-signal power gain (MAG/MSG) at room temperature, 77K and 160°C under the same current density.

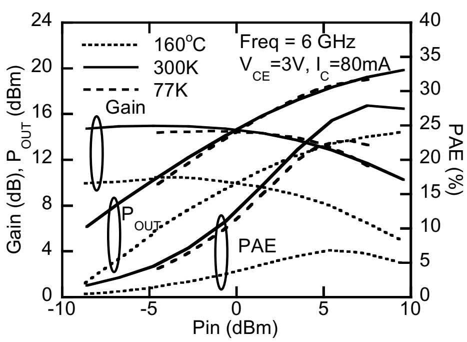

Figure 4. Measured power performance of the SiGe power HBT biased under class-A operation at 6GHz, under room temperature, 77K and 160°C.

The large-signal performance of the SiGe power HBT was characterized at 6 GHz using a Focus Microwaves CCMT1816 load source pull system. The system was calibrated and verified at 300K, 160°C and 77K, respectively. At each temperature, the device was initially biased under class-A with same V_{CE} of 3V and I_C of 80mA. The source and load impedances were tuned for the maximum P_{out}. Figure 4 shows the measured P_{out}, power gain, power-added efficiency (PAE) as a function of input power (P_{in}) under different operation temperatures. It can be observed from Fig. 4 that there are barely differences between 300K and 77K on the power gain and P_{out}, with saturated P_{out} of 20 dBm and a linear gain of 15 dB. The only degradation is the peak PAE. At 300K, the HBT has a peak PAE of 27.5% and it is reduced to 23% at 77K. The major reason is the increased collector current at lower temperature.

Figure 4 shows the clear degradation of power performance characteristic with a junction temperature of 160°C. The linear gain is dropped from 15dB at 300K to 10dB at 160°C. The peak PAE at 160°C is only 6.8% which is much smaller than that at 300K. Despite the degradation of the power performance, the device still can deliver about 15dBm (32mW) saturation P_{out} at 6 GHz. In order to understand the underlying mechanisms for the observed degradation of power performance characteristics of the device under high-temperature operation, the SiGe power HBT under 300K and 160°C operations was carefully modeled. It shows that the R_B increases from 9.6Ω at 300K to 28.6Ω at 160°C, while the emitter resistance (R_E) increases from 0.1Ω at 300K to 0.5Ω at 160°C. Namely, the increase of R_B at high-temperature operation is the major reason for the degradation of G_{max} and f_{max} at high frequency range and the degradation of MSG is due to the increase of R_E. It is important to note that the degradation of both R_B and R_E cannot be revealed when the operation temperature is not sufficiently high [8].

CONCLUSION

The dc, small- and large-signal performance of power SiGe HBT was characterized at room temperature, 77K and 160°C. Although the power device is not particularly optimized for cryogenic operation, the load-pull measurement results indicate excellent power gain, P_{out} and only very minor degradation on PAE from the power SiGe HBT operated at 77K comparing with the performance at 300K. The degradation of power performance of SiGe power HBTs at high temperature is found to be due to the significant increase of emitter and base resistance.

ACKNOWLEDGMENT

This work was supported by NSF under grant ECS 0323717.

REFERENCES

[1] J.-S. Rieh, D. Greenberg, A. Stricker and G. Freeman, *Proceedings of the IEEE*, vol. 93, no 9, pp. 1522-1538, 2005.

[2] J. D. Cressler, *Proceedings of the IEEE*, vol. 93, no. 9, pp. 1559-1582, 2005.

[3] J. D. Cressler, J. H. Comfort, E. F. Crabbe, G. L. Patton, J. M. C. Stork, J. Y.-C. Sun and B. S. Meyerson, *IEEE Transactions on Electron Devices*, vol. 40, no. 3, pp. 525-541, 1993.

[4] B. Banerjee, S. Venkataraman, Y. Lu, Q. Liang, C.-H. Lee, S. Nuttinck, H. Dekhyuon, Y.-J. E. Chen, J. D. Cressler, J. Laskar, G. Freeman and D. C. Ahlgren, *IEEE Transactions on Electron Devices*, vol. 52, no. 4, pp. 585-593, 2005.

[5] S. Pruvost, S. Delcourt, I. Telliez, M. Laurens, N.-E. Bourzgui, F. Danneville, A. Monroy and G. Dambrine, *IEEE Electron Device Letters*, vol. 26, no. 2. pp. 105-108, 2005.

[6] P. L. Dreike, D. M. Fleetwood, D. B. King, D. C. Sprauer and T. D. Zipperian, *IEEE Transactions on Components, Packaging, and Manufacturing Technology A*, vol. 17, no. 4, pp. 594–609, 1994.

[7] T. Chen, W.-M. L. Kuo, E. Zhao, Q. Liang, Z. Jin, J. D. Cressler and A. J. Joseph, *IEEE Transactions on Electron Devices*, vol. 51, no. 11, pp. 1825 – 1832, 2004.

[8] K.-M. Chen, A.-S. Peng, G.-W. Huang, H.-Y. Chen. S.-Y. Huang, C.-Y. Chang, H.-C. Tseng, T.-L. Hsu and V. Liang, *IEEE Transactions on Electron Devices*, vol. 52, no. 7, pp. 1452-1458, 2005.

[9] Z. Ma and N. Jiang, *IEEE Transactions on Electron Devices*, Vol. 52, No. 2, pp. 248-255, 2005.