Degradation of an X-K_u Band GaAs/AlGaAs Power HBT MMIC Under RF Stress

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***Abstract*—This paper summarizes the observed degradation in the performance of a high-efficiency X-K_u band 1-W HBT power MMIC operating under ~2 dB compression for an extended period. The main finding of this study is that no *new* degradation mechanisms appeared, even under severe RF stress; the device degraded in the same manner as with dc stress only. The only significant change in device characteristics was increased base leakage current that resulted in a monotonic reduction in current gain after an initial period of stability. Output power of the MMIC remained essentially unchanged even after current gain had dropped to 60% of its initial value. RF properties of the device, both small and large signal, showed little change even after severe deterioration of dc characteristics. The results of this study suggest that HBT reliability can be effectively evaluated for most applications by applying only dc stress to the device.**

I. Introduction

The reliability of *power* GaAs/AlGaAs HBT's is of great interest because these devices are being targeted for several future commercial and military products. HBT based power amplifiers have demonstrated outstanding power added efficiencies up to 18 GHz [1]–[3] in both wideband and narrowband circuits and over a wide range of operating voltages. These features, coupled with the need for only one power supply to bias the device, make HBT's very attractive for all applications where prime power must be carefully rationed, e.g. airborne radars and battery-operated systems.

While several researchers have reported on the observed changes in HBT parameters under dc stress [4], [5], there has been little published data on HBT behavior under RF stress. In this letter, we present preliminary results on the degradation of 1-W X-K_u band HBT MMIC power amplifiers operated CW under 2-dB compression. The HBT's are biased at $V_{ce} = 7$ V and $J_c \sim 50-55$ kA/cm^2 for this test. This MMIC is the same as that reported previously [6], [7] except that ballast resistors were added to the devices used here without re-optimizing the circuit performance for the new device. The function of the ballast resistors is to increase the dc power that can be dissipated in the device before encountering current collapse. Once the device is in current collapse, one emitter finger tends to draw a significant portion of the total current, which can lead to failure through excessive local heating.

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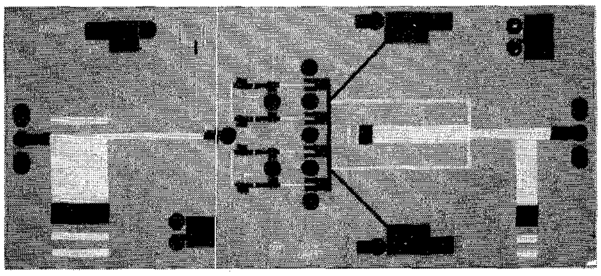

Fig. 1. A photograph of the 1-W HBT MMIC used in this study.

II. MMIC Description

A photograph of the 1.45 mm × 3.48 mm MMIC used in this study is shown in Fig. 1. This single-stage amplifier is designed to provide ~1 W over 9–15 GHz from four common-emitter 0.25-W unit cells connected in parallel. Each unit cell comprises four 2 μm × 20 μm emitters in a 2 × 2 arrangement. A 5-Ω thin film ballast resistor is in series with each emitter finger to extend the threshold of current collapse [8] to >1.2 W for the output device.

HBT MMIC's are fabricated on 3-in. wafers with MOCVD-grown epitaxial layers consisting of a 7000-Å-thick 3–8 × 10^{16} cm^{-3} collector, a 1000-Å-thick 4 × 10^{19} cm^{-3} carbon-doped base, and an n^+ GaAs emitter cap layer. The base and emitter contacts are self-aligned and fabricated as described previously [1]. Wet etching is used to etch down to the base epi-layer, which reduces the effective emitter dimension to ~1.5 μm × 20 μm due to undercutting. MMIC's also employ MIM capacitors, transmission lines, thin film resistors, air-bridge interconnects, and through-substrate via holes. Chip thickness is 100 μm.

III. Test Results

The MMIC under test was soldered to a CM-15 carrier with 50-Ω input/output microstrip transmission lines and the MMIC carrier was bolted to a metal block equipped with a cartridge heater, a thermocouple, dc bias terminals, and 50-Ω coaxial connectors. The fixture has ~0.5-dB insertion loss at each RF port.

The MMIC was biased in Class AB mode. DC bias was provided by two voltage power supplies connected to the collector and base terminals, respectively. The collector voltage was set at 7 V and the base voltage was adjusted to achieve a quiescent collector current of 62 mA, ~25% of the current at 1-W output power. The input power to the MMIC, a CW signal at 11 GHz, was generated by a signal generator and amplified by a TWT amplifier. It was adjusted to get ~30 dBm output power from the amplifier. The amplifier gain was compressed by ~2 dB under these conditions. The input power and the bias supply voltages were held constant during the test. All dc and RF parameters were monitored periodically without turning off the RF signal.

MMIC's from three different wafers processed in separate lots were tested in the manner described above with very similar results. For a typical MMIC, the initial test conditions are as follows:

$P_{\text{in}} = 23.6$ dBm
$P_o = 30.1$ dBm
$G_a = 6.5$ dB
Power Added Efficiency = 45%
$I_c = 246$ mA; $V_c = 7$ V
$I_b = 16.5$ mA; $V_b = 1.37$ V
DC $\beta = 14.9$
Ambient temperature = 40°C.

The power gain is lower than reported earlier [6], [7] because the MMIC was not optimized for devices with ballast resistors. The junction temperature is estimated to be 154°C by using the technique described by Dawson [9]. Under RF stress, the only significant change in device characteristics is a decrease in dc current gain (β). The output power and collector current remain relatively stable, as shown in Figs. 2 and 3, even for a 40% decrease in β. For typical MMIC's, the current gain remains stable for the first 100–300 hours and then declines monotonically. This behavior is similar to that observed with dc stress only [5]. In the case of the MMIC described in this letter, β was stable for the first ~150 hours. The output power dropped by ~0.2 dB and the collector current changed from 250 mA to 235 mA after 800 hours of stress. During this period, the base current increased from 16.5 to 26 mA. The output power, P_o, decreased monotonically after β started to drop. Although this test was terminated after 800 hours, it is expected that P_o would have continued to decline with further stress. The small signal gain of the amplifier shows only a slight change after β degradation. Fig. 4 shows the small signal gain before and after stress measured at the *same* collector current for the MMIC described here; in general, gain can increase or decrease after the test. Gummel plots of the HBT before and after RF stress show increased base leakage with very little change in the collector current characteristics (Fig. 5). This too, is similar to the change observed in carbon-doped-base HBT's under only dc stress. The power-added efficiency of the amplifier dropped only slightly during the RF stress test. In the case described above, the PAE decreased from 44% to 42% after 800 hours even though β had degraded by 40% during this period! The junction temperature is estimated to remain almost unchanged during the RF stress test since the only significant change is in the base current, which is a small fraction of the total device current. Our measurements indicate that the power dissipated in the HBT increased from 960 to 980 mW after 800 hours.

IV. Conclusion

This letter has summarized the observed degradation in the performance of a high efficiency X-K$_u$ band 1-W HBT power MMIC operating under ~2-dB compression for an extended period. The GaAs/AlGaAs HBT had a carbon-doped base layer and self-aligned base-emitter contacts. It was biased in Class AB mode with a voltage source at the base for this test.

The main finding of this study is that no new degradation mechanisms appeared even under severe RF stress; the device degraded in the same manner as with dc stress only. The only significant change in device characteristics was increased base

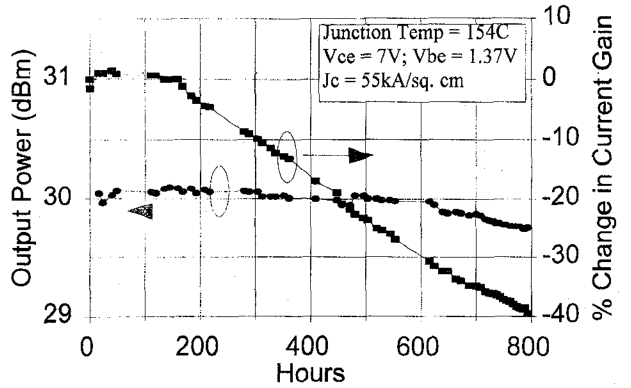

Fig. 2. The output power and dc current gain (β) of the amplifier as a function of time. Note that the power drops by <0.5 dB even after β has degraded by 40%.

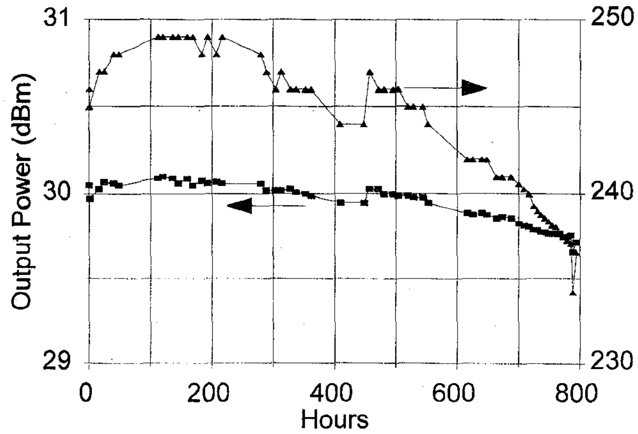

Fig. 3. Collector current drops by <10% during the period in which β has dropped by 40%.

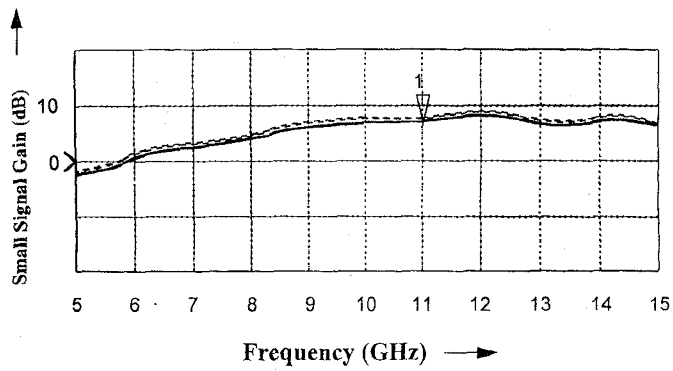

Fig. 4. The small signal gain before and after stress measured at the same collector current. In general, gain can increase or decrease after the test. ——— Before stress. - - - - After stress.

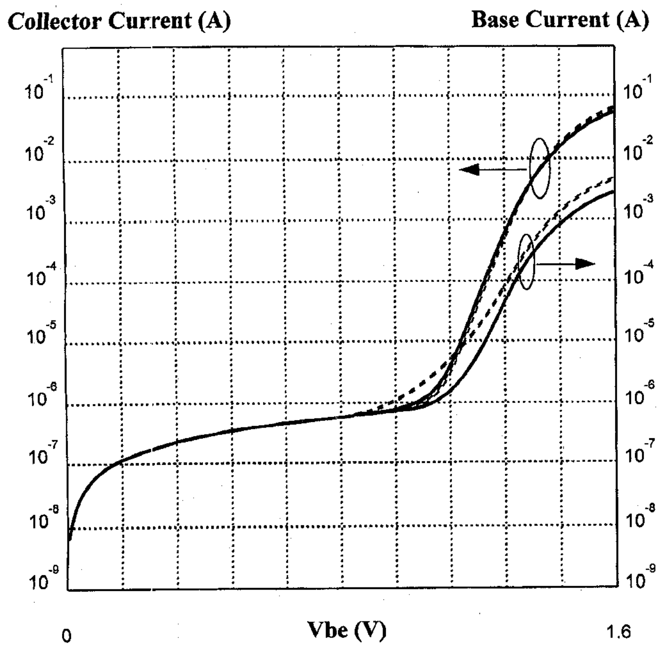

Fig. 5. Gummel plots of the HBT before and after RF stress show increased base leakage with very little change in the collector current characteristics. —— Before stress. - - - - After stress.

leakage current, which resulted in a monotonic reduction in current gain after an initial period of stability. RF properties of the device, both small and large signal, showed little change even after severe deterioration of dc characteristics. HBT's are distinct from the PHEMT's and MESFET's in this regard; these devices can exhibit additional failure modes under large signal RF operation [10].

The results of this study suggest that HBT reliability can be effectively evaluated for most applications by applying only dc stress to the device. Techniques developed to improve current gain stability will have the most significant impact in extending the reliability of HBT amplifiers. Since little change was observed in device RF parameters, microwave power amplifiers will fail in practice when the base power supply is unable to supply the increased base current as a consequence of reduced β. This assumes that the amplifier is biased with a voltage source at the base terminal. For these applications, the failure criterion should be an absolute minimum value of β rather than a percent decrease in β, which is more relevant for analog and digital applications.

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