Direct Measurement of the Maximum Operating Region in GaAs HBTs for RF Power Amplifiers

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ABSTRACT

Current and voltage waveforms of GaAs HBTs at 1GHz have been directly measured using a microwave waveform measurement system. The maximum operating region has been experimentally investigated by sweeping load lines. The limits of a small input power are found to come from the thermal runaway and avalanche breakdown of the device. With large input power, the HBT is found to operate beyond the DC limit of thermal runaway.

INTRODUCTION

GaAs HBTs are widely used in power amplifiers for mobile communication handsets. Since cellular phones are becoming smaller and priced lower, size-reduction is strongly required for the transistor of the power amplifiers. Achieving a high output power with a smaller chip size, HBTs are widely used in a very high current density state that results in a higher junction temperature. Furthermore, power amplifiers often suffer the high voltage of charging battery and standing waves [1]. Therefore, designers should consider the maximum operating region of the devices. Failure mechanisms and thermal instability in GaAs HBTs were studied under DC conditions [2,3]. Breakdown phenomena were measured even with a short pulse [3]. However, these thermal conditions are completely different from the real microwave operation of the device. Also, the electric fields in the device differ from those of the RF signal operation. At an RF frequency, no direct measurement of the microwave waveform near the operating limits has been reported. In this paper, the real current and voltage waveforms of HBTs at 1GHz have been directly measured. By sweeping load lines, the maximum operating region has been experimentally revealed. The limits resulting from thermal runaway and avalanche breakdown are also discussed.

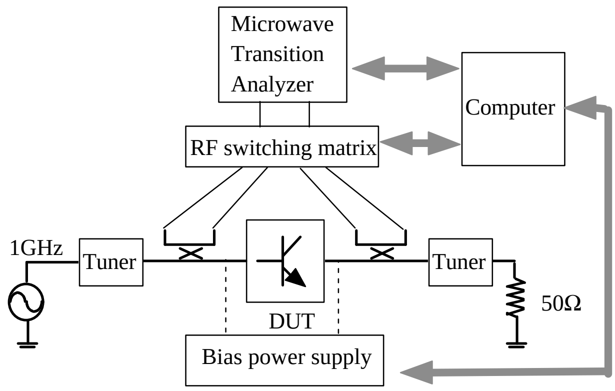

Fig.1 Microwave waveform measurement system

MEASUREMENT

Figure 1 shows a diagram of the waveform measurement system. The incident and reflected waves at the base and collector terminals are measured through the microwave transition analyzer up to 18GHz. The current and voltage waveforms at the

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transistor are calculated from the full-two-port calibration data [5]. The input and output matchings are adjusted with tuners to realize the proper load lines. The microwave waveforms at the base and collector pads of the device are calculated using the measured S-parameters of the test fixture.

An AlGaAs/GaAs high power HBT with emitter air-bridges is measured in the common-emitter configuration. The emitter size is 4x20um^2 x 100-fingers. The BVceo and BVcbo are 19.4V and 22V, respectively.

To find the maximum collector voltage (Vc) with each collector current (Ic), the following procedure is adopted. (1) The base and collector biases are supplied from the constant voltage sources. Vc is first set to 3V. Vb is selected to search proper operating area. (2) An incident wave of 1GHz with a fixed power of Pin is applied to the base. The collector current Ic0 is measured. (3) The Vc is increased by 0.2V. (4) If the HBT does not go into thermal runaway or burnout, Vb is adjusted to keep Ic as Ic0 measured in the procedure 2. (5) Procedures 3 and 4 are repeated until the HBT reaches its operating limits. These entire procedures are performed with several base voltages. The source and load impedances are fixed for simplicity.

RESULTS

With the small Pin of 19.6dBm, we performed the measurement procedure in Section 2. Two modes are observed. One is burnout of the HBT and the other is runaway of the collector current. Figure 2 shows the latter mode. At the Vc of 5, 7 and 9.5V, the load lines move in parallel with Vc, maintaining almost the same shape. The output power at each Vc results in almost the same value of 11dBm.

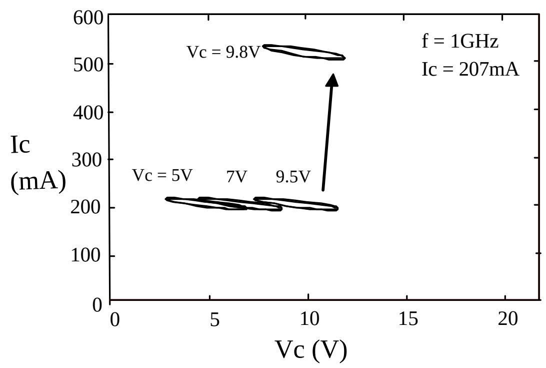

Fig.2 Measured load lines with Ic runaway

However, the load line jumps up at the Vc of 9.5V, where the average Ic increases from 207mA to 520mA. At this point, the base bias is no longer the voltage source but the current source, because Ib reaches the current limit of the base biasing power supply. With this state, the HBT survives and still outputs the RF power. But the device goes to burnout without the limit of the base current.

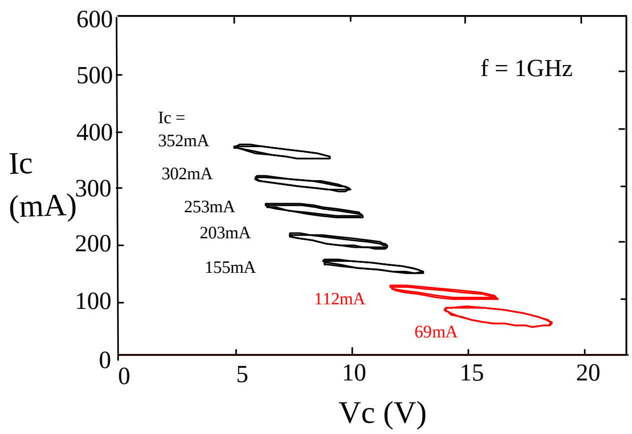

Fig.3 Maximum load lines with the Pin of 19.6dBm

Figure 3 shows all the load lines just before reaching its operating limits. With the low Ic of 69mA and 112mA, HBT rushes into burnout, while the others go to collector current runaway as demonstrated in Fig.2. Therefore, these lines represent the maximum operating region of the device with this specific input power, source and load impedances.

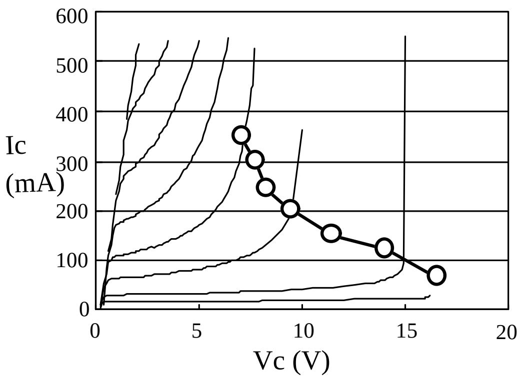

Fig.4 Measured DC Ic-Vc characteristics with constant Vb, where the circles denote the average Vc,Ic of the load lines shown in Fig.3.

If the amplitude of the load line is small, the operating limit should be related to the DC characteristics of the device. Figure 4 shows the DC Ic-Vc characteristics with a constant Vb. The circles in Fig.4 denote the average Vc and Ic of the maximum load lines in Fig.3. The circles over 100mA show good agreement with the points of thermal runaway in the DC Ic-Vc curve. Therefore, only the average Vc and Ic of the load lines affect the limits. However, the load line with the Ic of 69mA differs from the DC limit shown in Fig.4.

Figure 5 shows the average Ib of all the measured waveforms. The average Ib of the 69mA load line decreases with Vc, while that of the other load lines increases. The decrease in the Ib indicates avalanche breakdown, because avalanche multiplication near the BVceo results in the hole injection into the base region, increasing the forward bias (hole feedback effect). Thus the limit of the 69mA load line is determined by the BVceo. Namely, if the peak voltage of the load line touches BVceo, the device will go to burnout. Two categories, breakdown and thermal runaway, seem to determine the operating region of the GaAs HBT.

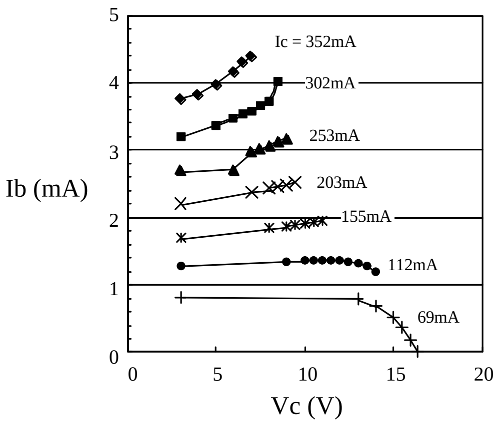

Fig.5 Measured average Ib of the load lines versus Vc with the Pin of 19.6dBm

In order to confirm this idea, the same measurement with a larger input power Pin of 28.4dBm was performed. The source and load impedances were kept same as those of the previous measurement. The gray and black lines in Fig. 6 represent the measured maximum load lines with the Pin of 28.4dBm and 19.6dBm. The solid lines denote the average Vc, Ic of the load lines. The average Vc of the large Pin over the Ic of 100mA increases from 2V to 3.5V compared with small Pin. This means the HBT driven with large signal can survive beyond the DC thermal limits. However, the average Vc of the 77mA load line decreases 1V. Since the voltage amplitude of the load line increases with a larger Pin, the average Vc becomes lower to keep the peak voltage in touch with BVceo. This result proves that breakdown voltage determines the limit at low collector current.

However, it is difficult to explain the increase in the average Vc by the ordinary thermal theory. Because the thermal time constant is too long compared with the period of the 1GHz signal, only the average Vc and Ic are considered to affect the thermal property. Therefore, the average Vc should be independent of input power levels. This is inconsistent with the measured results. The inconsistency can be due to the fact that the base current increase caused by thermal runaway is balanced with the hole injection near the breakdown, because the average Ib with a large Pin slightly decreases at high Vc.

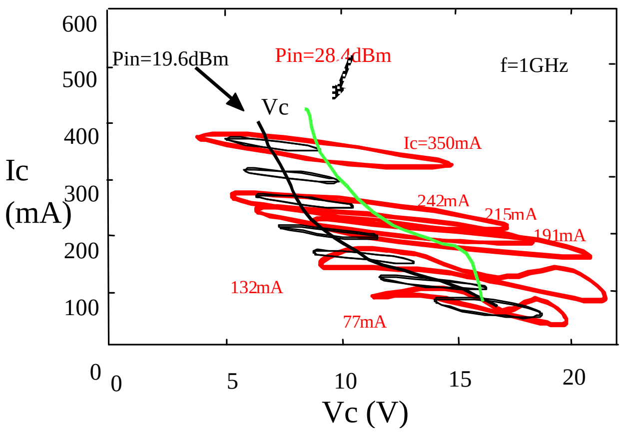

Fig. 6 Measured maximum load lines with the Pin of 19.6dBm (black) and 28.4dBm (gray). Solid lines show the average Vc,Ic of each load line.

CONCLUSIONS

The load and source waveforms of the GaAs HBT at 1GHz have been directly measured using a microwave waveform measurement system. The maximum operating region has been experimentally examined by sweeping load lines. Under a small input power operation, the avalanche breakdown and thermal runaway limit the operating region of the HBT. In a small collector current region, breakdown dominates the Vc limit, while thermal runaway restricts the limit in a large collector current region. With a large input power, the HBT is found to operate beyond the DC limit of thermal runaway.

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