The Effects of Feedback Capacitance on Thermally Shunted Heterojunction Bipolar Transistor's Linearity

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ABSTRACT

The effects of feedback capacitance on linearity of thermally shunted heterojunction bipolar transistors (HBTs) were experimentally determined through power load pull measurements. The results show state-of-the-art linearity performance of devices biased and matched for power operation at X-band. Gain is easily traded for increased linearity by increasing the feedback capacitance in the device design. The data shows that a self-aligned process is necessary to maximize power performance (gain and efficiency), but an advantage of a re-aligned process is the ability to trade gain for linearity by increasing the emitter-to-base metal separation. With this additional design flexibility in a fixed technology, circuit performance can be optimized through layout variations only. For example, one HBT technology would be suitable for a Transmit/Receive module and each block could be easily optimized for different performance specifications.

INTRODUCTION

Heterojunction bipolar transistors (HBTs) are well suited for microwave power applications due to their high power density, high frequency of oscillation at optical lithography dimensions, and relatively small size [1]. The addition of the thermal shunt was a novel approach to thermal management that enhanced the device's performance. The thermally shunted HBT has produced record power densities of 16mW/μm^2 [2] and state-of-the-art noise figures [3] in the same epitaxial structure. Monolithic mixed-mode circuits, such as high-power transmitters and low-noise receivers, benefit from these HBT characteristics. Their excellent linearity [4] is another advantage of these devices that is desirable for mixed-mode applications. Linearity relates to signal integrity in communication systems. For example, wireless communications require power amplifiers with high linearity to minimize interference with adjacent channels. In the case of military transmitters, linearity is essential to reduce signal distortion and side-lobes in phased-array radar. This study was designed to use large signal linearity testing to evaluate a device feature change, the feedback capacitance (C_{bc}), to enhance performance for different modes of operation.

EXPERIMENT SETUP

The data was measured using the Maury Microwave Load Pull system configured for on-wafer measurements. The figure of merit used is the carrier to third-order intermodulation ratio (C/I3) found from a two-tone test. We experimentally determined that a tone spacing of 100 kHz did not produce any frequency signals below the thermal response time of our devices. This problem can produce an AC temperature variation, which is harmful to device linearity [5]. The HBTs studied were AlGaAs/GaAs type operated at a collector voltage of 10 Volts and a current density of 33 kA/cm^2. The devices were biased in class A operation at the beginning of the power sweep and ended up in class AB at the saturated power condition. The intermodulation power tests were swept from an available power of 0 dBm to 20 dBm at 10 GHz. The devices were conjugately matched at a 13 dBm drive level for maximum power performance. No special match or bias conditions were used to enhance linearity. The data shown for each device type is the average of five individual devices.

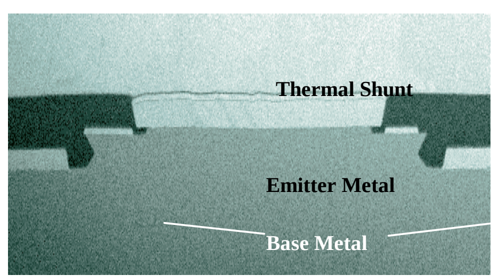


Figure 1. Focused ion beam cross section of a thermally shunted HBT. The spacing between the emitter metal and base metal is changed to vary the base-collector area.

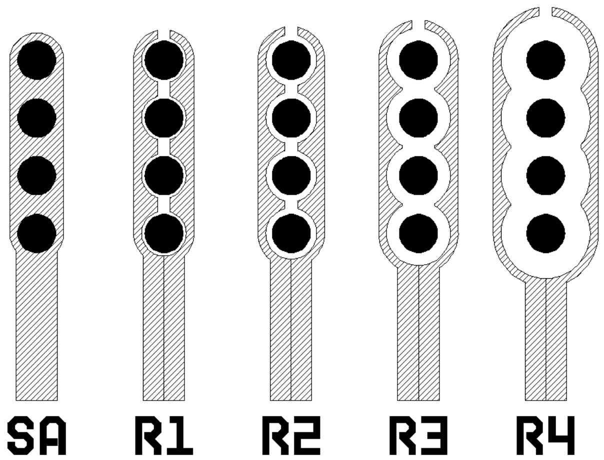


Figure 2. Layout of different base-metal schemes. SA: self-aligned, R1: re-aligned, 0.5µm separation, R2: re-aligned, 1µm separation, R3: re-aligned, 2µm separation, R4: re-aligned, 4µm separation.

The devices tested were configured with four, 6 µm diameter emitter elements along one base finger. A cross-section micrograph of our devices, prepared using a Focused Ion Beam system is shown in Figure 1. With emitter undercut, this device's active area is approximately 100 µm^2. We tested four variations of this device, labeled R1, R2, R3, and R4 in Figure 2. The layout difference between these four devices is the spacing between the emitter metal and the base metal. These spacings are 0.5 µm, 1 µm, 2 µm, and 4 µm, respectively. The self-aligned (SA) device is shown here to illustrate that this process minimizes the emitter to base spacing. Figure 3 is a schematic of the large signal HBT model used in [6]. Increasing the emitter-to-base metal separation increases the base-collector width which corresponds to an increase in the extrinsic base-collector capacitance, C_{bc1}, and the extrinsic base resistance, r_{b1}.

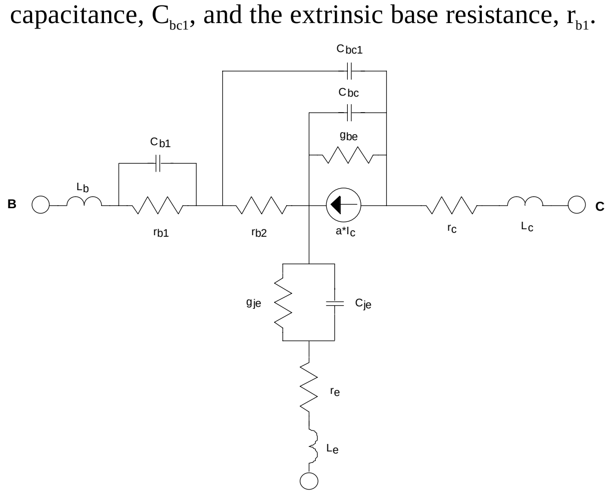
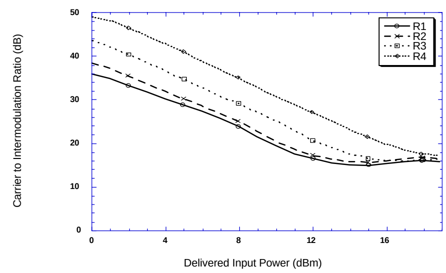


Figure 3. Large signal HBT model



MEASURED RESULTS

The measured C/I3 and power gain (G_n) are shown in Figu

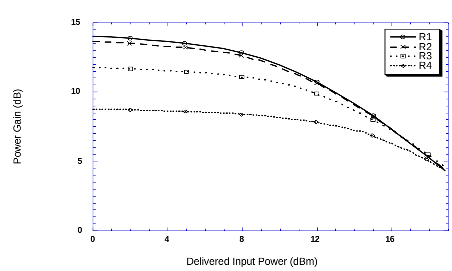
Figure 4. C/I3 for different base finger widths.

state

band. These results clearly demonstrate a large increase in linearity is possible by trading off gain. This is only possible before the device reaches saturation, which is a highly nonlinear region of operation. However, the decrease in gain also decreases the power-added efficiency. The relationship between G_p, C_{bc}, and r_b is shown in equation (1) where F_T is the current cutoff frequency,

$$G_p = \frac{F_T}{8\pi (r_b + r_e) C_{bc} f^2} \qquad (1)$$

r_e is the emitter resistance, r_b is the total base resistance, and C_{bc} is the total base-collector capacitance. This equation assumes no emitter lead inductance and a conduction angle of 180°[7]. For these four device types, F_T should be the same since it is a function of the base transit time, which depends on the base thickness and doping. Figure 6 is a plot of the small signal parameter $|h_{21}|^2$ which is used to extrapolate the device F_T. From this plot, the F_T of these devices is approximately 37 GHz.



Since our emitter design (r_e) and F_T are not changing, the decrease in gain is due to the increasing r_b and C_{bc}.

Equation (1) shows the effects of the large-signal gain on the parasitic elements. These effects can also be seen in the small signal response of these devices. The maxim

Figure 5. Power gain for different base finger widths.

but scaled by the parasitics. Equation (2) is a simplified

$$F_{max} = \sqrt{\frac{F_T}{8\pi r_b C_{bc}}} \qquad (2)$$

expression for the relationship between F_T and F_{max}. Again, as the base finger widens, r_b and C_{bc} will increase and F_{max} should decrease. Figure 7 is a plot of the maximum available gain (MAG). F_{max} is determined by extrapolating MAG to 0 dB. At the 10 GHz point, this plot shows that the R1 device has the highest gain and R4 has the lowest. The F_{max} for device R1, R2, R3, and R4 are 55 GHz, 50 GHz, 38 GHz, and 26 GHz, respectively. These small signal results show again that increases in C_{bc} and r_b reduce the device's gain.

We attribute the trade-off between gain and linearity to be caused by C_{bc}. C_{bc} scales with the change in the base collector area to a first order approximation. On the other hand, r_b scales as the natural log of the emitter-to-base metal separation due to the base metalization scheme used. There have been many studies on the linearity of HBTs in [6][8][9][10] and they agree that C_{bc}, not r_b, creates non-linear currents in an HBT. The studies do not agree on what effect C_{bc} has on the overall linearity of the device.

To isolate either C_{bc} or r_b as the parasitic responsible for the linearity/gain trade-off, we tested three additional devices. These devices were tested with the same bias, match, and power conditions as the previous devices. The first device was a 354 (3 micron emitter dot diameter, 5 dots per finger, 4 fingers) that has an active

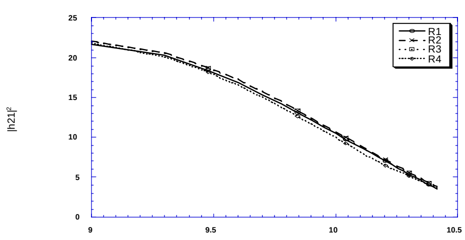


Figure 6. F_T curves for different base finger widths

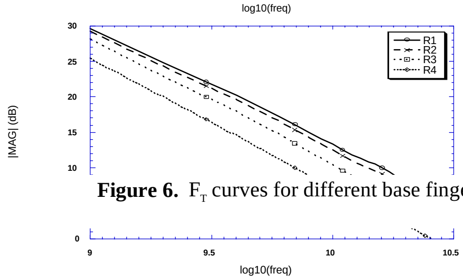


Figure 7. F_{max} curves for different base finger widths

area of 141 μm^2 and a base collector area of 1000 μm^2. The second device was a 462 (4 micron emitter dot diameter, 6 dots per finger, 2 fingers) that has an active area of 150 μm^2 and a base collector area of 760 μm^2. The third device was a 622 (6 micron emitter dot diameter, 2 dots per finger, 2 fingers) that has an active area of 113 μm^2 and a base collector area of 460 μm^2. Based on the previous results, we expected the 354 to have the best linearity and worse gain and the 622 to have the worst linearity and best gain based solely on the base collector area.

Figure 8 shows the linearity results and Figure 9 has the gain results. The (C/I3) of these devices does not shift nicely like the previous results. This was expected because the devices compared have different emitter designs and active area. The base resistance of these devices will change by the internal base resistance, r_{b2}, since they are self-aligned devices, which minimizes r_{b1}. A first order approximation for r_{b2} scales inversely with the periphery of the emitter dots. These devices have peripheries of 60π, 48π, and 24π for the 354, 462, and 622 devices. So the 354 device should have the lowest base resistance and the 622 should have the highest. In this series of devices, the best linearity came with the highest C_{bc} and the lowest r_b. The same trend was observed with the R1-R4 devices

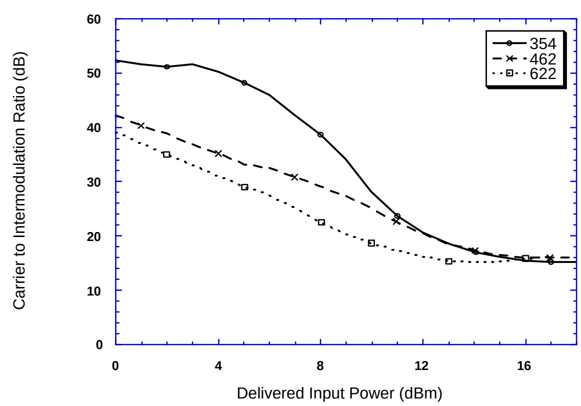


Figure 8. C/I3 curves for 354, 462, and 622 devices

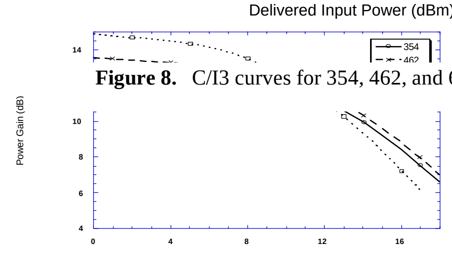


Figure 9. Power gain curves for 354, 462, and 622 devices

with respect to C_{bc} but the opposite trend occurred with respect to r_b. From this data, and other data not shown, we are confident that the feedback capacitance is the mechanism for trading gain for linearity. We have plans to test a special device structure that will only scale C_{bc} to further study its effect on device linearity.

DISCUSSION

It is surprising that a larger nonlinear component in a device with exponential I-V characteristics improves linearity. This issue has been studied extensively in [6] [8][9] and [10] with the conclusion that nonlinear current components have a 180° phase difference which cancels out the overall nonlinear current. Therefore, a large C_{bc} creates a larger nonlinear current that better cancels out the other nonlinear currents.

This performance trade-off leads a discussion of self-aligned versus re-aligned HBT technologies. We have developed a self-aligned HBT process that gives us excellent device performance. Our process is an emitter first process[11]. The self-aligned base contacts are achieved by depositing base metal over all the base and emitter areas. This allows the base contacts to be as close to the emitter as possible. Since the extrinsic feedback capacitance and base resistance are minimized, the gain and the maximum frequency of oscillation are maximized. The key to this process is a retrograde emitter metalization step, which requires critical alignment to make a working device. Figure 1 shows the retrograde emitter structure and a base metal layer on top of the emitter dot, which is a product of the self-aligned process. By making devices with a re-aligned process, an additional design control is introduced. This process is still an emitter first process, but now the base metal is placed down at some distance from the emitter elements. With a critical alignment, it is possible to approach a self-aligned emitter-to-base metal separation. By simply increasing the emitter-to-base separation, the HBT can be built to meet a variety of gain and linearity specifications in the same epitaxial structure.

SUMMARY

Our experimental results clearly demonstrate that gain can be traded off for linearity by simply increasing the emitter-to-base metal separation. We are confident that the trade-off mechanism is the feedback capacitance and we have shown data to support this claim. We have future device structures in mind that will further help us isolate the feedback capacitance and base resistance and their effects on device linearity. Added to the fact that this device process has already achieved world record power densities and state-of-the-art noise figures, the thermally shunted HBT is quickly becoming an attractive solution for monolithic mixed-mode circuit applications. A self-aligned process is optimized for power and noise while a re-aligned process allows a simple base contact design change to produce better linearity which allows both high-power and high-linearity devices to be fabricated at the same time.

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