FLIP-CHIP X-BAND OPERATION OF THERMALLY-SHUNTED MICROWAVE HBT's WITH SUB-MICRON EMITTERS

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ABSTRACT

Design and fabrication methods were developed for GaAs-based flip-chip HBTs with emitter sizes down to 1 μm or less. We have fabricated and tested identical size devices in both the conventional and the flip-chip configuration on the same wafer to make a direct comparison of their dc, microwave, and thermal properties. It was shown that flip-chip mounted microwave HBTs can produce the same or better electrical performance than their conventional upright counterparts while offering a 37% improvement in thermal resistance.

INTRODUCTION

The recently developed *thermal shunt* technique[1] combines the top side heat extraction with wide area heat spreading, and thereby provides a substantial reduction in thermal resistance. This approach was proven to prevent thermal runaway conditions often encountered with high power devices, and provided a very high power density operation (10 mW/μm^2 at 10 GHz)[1]. While thermal shunt structures can eliminate local temperature variations between the emitter fingers, the overall device thermal resistance continues to depend on the effectiveness of heat spreading structures. Because GaAs is a poor thermal conductor, a large heat spreading area may be required to substantially reduce the thermal resistance.

In a flip-chip configuration, HBT is mounted adjacent to a good heat sink with the emitters making direct electrical and thermal contact with the heat sink. The thermal resistance is reduced since the GaAs substrate is eliminated from the thermal path. No intentional heat spread areas are required on the GaAs substrate, therefore compact devices are possible. In previous attempts, flip-chip HBTs were produced with wide emitter fingers (3.5 μm to 6.4 μm) to enable the fabrication of heat extraction paths over the emitters[2,3]. Such large emitter devices are useful over a limited range of frequencies. *In this work, we have developed design and fabrication methods that enabled the fabrication of GaAs-based flip-chip HBTs with more conventional emitter sizes. We have tested identical size devices on the same wafer in both the conventional and the flip-chip configuration to make a direct comparison of their dc, microwave, and thermal properties.*

FABRICATION

The epitaxial layers of the HBT structures used in this investigation were grown by MOCVD on semi-insulating (SI) GaAs substrates. A thin (0.03 μm) layer of InGaAs was used as the top layer of the emitter to facilitate non-alloyed emitter metallization. The base layer was 0.1 μm thick and doped with carbon at 4E19 cm^{-3} concentration. The collector layer was 1.0 μm thick. Various device designs were simultaneously fabricated on the same wafer using an all-optical lithography process. The emitter finger length was 20 μm, whereas finger widths ranged from 0.7 μm to 1.5 μm. The number of emitter fingers in a unit-cell was varied from 4 to 16. TiPtAu metallization was used for the emitter and the base, and AuGeNi alloy was used for the collector.

Figure 1 shows a cross-sectional drawing of the flip-chip HBT unit-cell. Although this figure illustrates the thermal design for a single emitter finger cell for simplicity, all unit-cells fabricated in this work had multiple emitter fingers. A 12 μm thick thermal

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shunt was used to connect all emitter fingers electrically and thermally. The fabrication of thermal shunt was similar to that described earlier[4]. An additional 22 μm of plated gold post (thermal post) was added to the device, as shown in Figure 1. The excess heat removal from the device follows a path through the emitter contact into the thermal shunt bridge. Because of high thermal conductivity of Au in the thermal shunt, the heat is readily spread into the thermal posts, as shown.

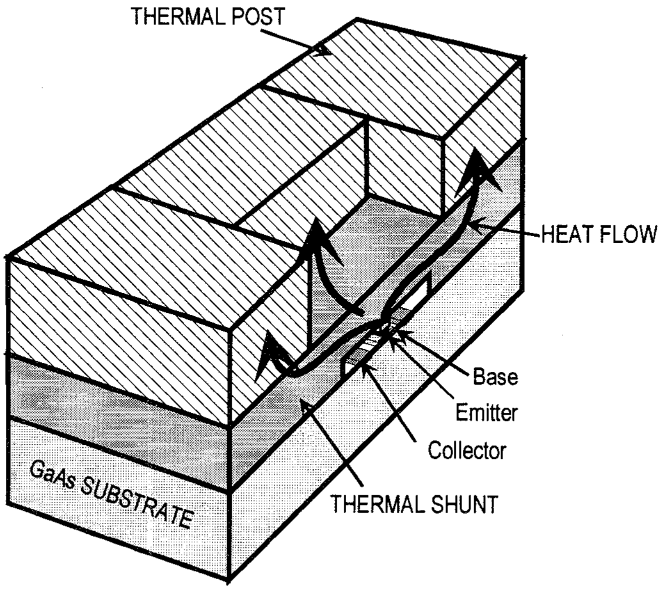

Figure 1: Cross-sectional drawing of flip-chip HBT.

We have fabricated conventional thermal shunt devices without thermal posts side-by-side with those having thermal posts. Figure 2 shows a scanning electron microscope (SEM) picture of a device with thermal posts. Contacts were made to the base and the collector terminals of these devices with via holes etched through 100 μm thick substrate. Emitter contacts of the conventional thermal shunt device were grounded using similar metallized via holes. Figure 3 shows a flip-chip HBT chip mounted in a test fixture. Each chip contained 2 identical devices; the first one was used for on-wafer (from the backside) small-signal microwave measurements, and the other one for power measurements in test fixtures. The conventional devices with identical cell designs were mounted upright in similar test fixtures for comparative microwave small-signal and power measurements. AuSn solder was used in mounting both device types on Au-plated copper test fixtures. In the case of flip-chip mounted devices, the height of the thermal post was found to be sufficient to separate the chip from the ground plane during the standard soldering process without any additional precautions.

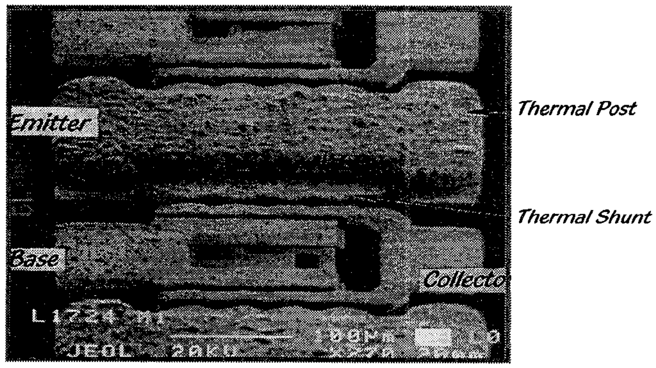

Figure 2: SEM Picture of HBT unit-cell with thermal posts.

RESULTS AND DISCUSSION

The thermal resistance of similar size soldered flip-chip and conventional thermal shunt devices were measured using the method described by Sugahara[5]. On the average, the flip-chip mounted devices showed a 37% improvement in thermal resistance compared to the conventional thermally shunted devices. Considering that the thermal shunt structure had already reduced the thermal resistance of the conventional device by about 50% (compared to devices without thermal shunts),[1] this additional improvement in thermal resistance is significant in absolute terms.

Figure 4 shows the measured maximum available-stable gain (MAG/MSG) characteristics for a 8-finger unit cell with 1.5 μm emitter finger width. A slight increase in gain was obtained at lower frequencies as the collector current increased from 40 to 80 mA. The gain characteristics of the flip-chip device at 80 mA is compared with the conventional device tested under the same bias conditions in figure 5. The extrapolated maximum oscillation frequency, f_{max}, values for both devices are very similar (i.e. 60 GHz for conventional and 67 GHz for flip-chip HBTs). We measured other size unit-cells at various bias conditions and found that the extrapolated f_{max} values remained within 12% between the conventional and the flip-chip devices.

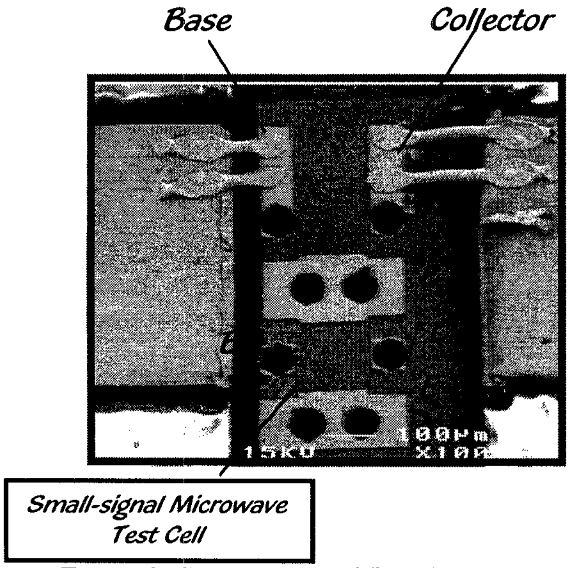

Figure 3: SEM picture of flip-chip HBT chip mounted in microwave test fixture.

The large-signal characterization was carried out at 10 GHz in an automatic load-pull system with V_{ce} = 9 V and V_{be} = 1.33 V applied to all devices. The collector current was allowed to increase with the RF input power from the quiescent value in a Class AB mode of operation. Figure 6 shows the results obtained with 4-, 8-, and 12-finger unit-cells. In each case the power-added efficiency reached about 50% value at output power levels proportional to the device size. A similar behavior was obtained with unit-cells containing 0.7 μm emitter finger widths, as shown in Figure 7.

A comparison of power results for the conventional and the flip-chip mounted devices are shown in Figures 8 and 9 for 8-finger and 12-finger cells, respectively (each emitter was 1.5 μm x 20 μm). Both the power and the efficiency curves tracked each other closely, as shown. Although the saturated power and the maximum efficiency values were about the same between the same size devices, the linear power gain value was about 1 dB higher for the conventional devices. This difference is probably due to slightly lower collector current values obtained with the flip-chip devices under the same bias conditions due to their lower thermal resistances and hence slightly higher V_{be} turn-on values.

In summary, we have demonstrated by direct comparison that flip-chip mounted microwave power HBTs can produce the same or better electrical performance than their conventional upright counterparts under identical test conditions while exhibiting 37% reduced thermal resistances. We have also demonstrated that the flip-chip fabrication technique can be applied to various size devices including devices with sub-micron emitter fingers.

Acknowledgments

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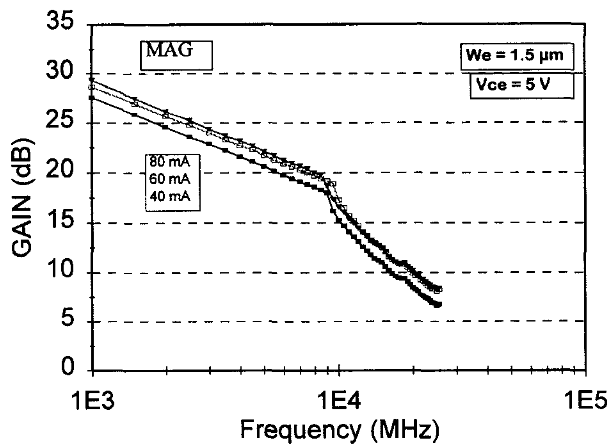

Figure 4: Small-signal microwave gain characteristics of a 8-finger flip-chip unit-cell.

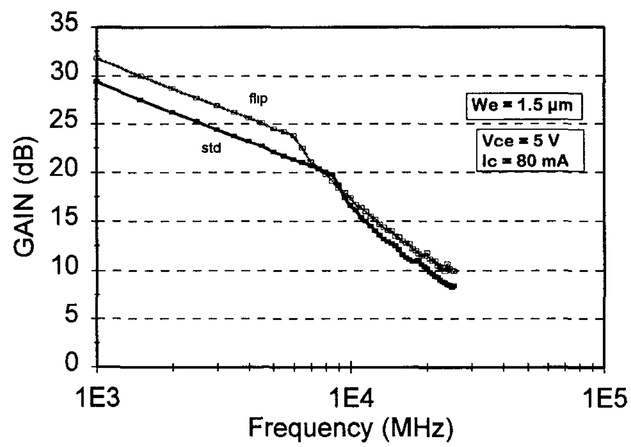

Figure 5: Comparison of small-signal microwave gain characteristics of 8-finger unit-cells.

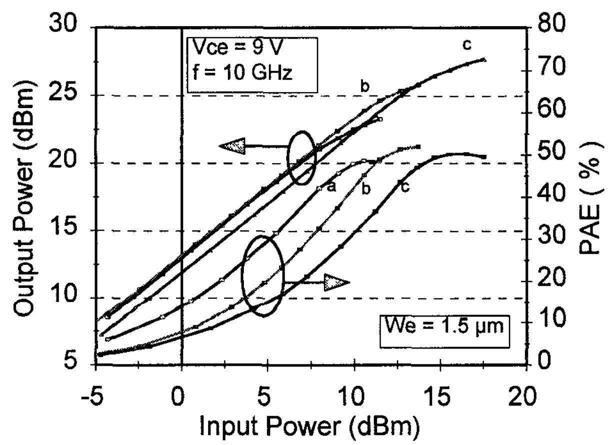

Figure 6: Comparison of microwave power characteristics of a) 4-finger, b) 8-finger, c) 12-finger flip-chip HBT unit-cells.

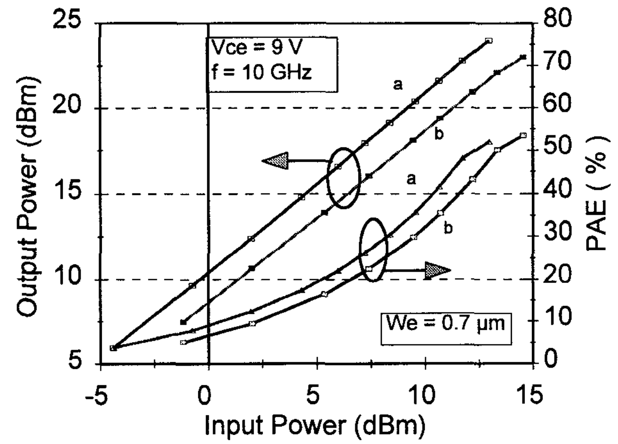

Figure 7: Comparison of microwave power characteristics a) 8-finger, b) 12-finger flip-chip HBT unit-cells.

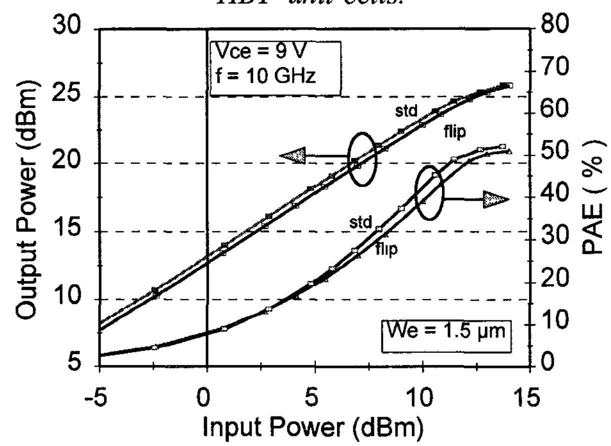

Figure 8: Microwave power characteristics of 8-finger conventional and flip-chip unit-cells.

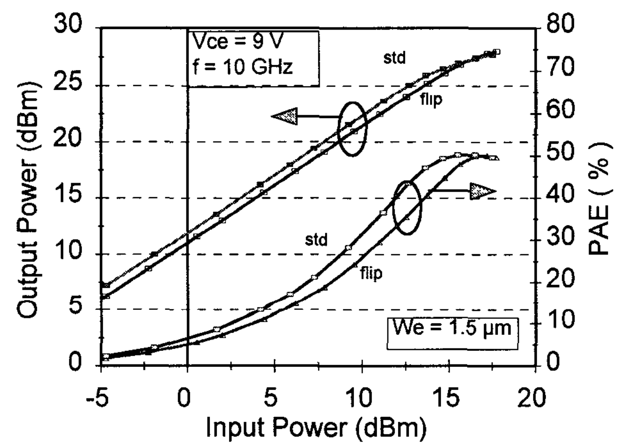

Figure 9: Microwave power characteristics of 12-finger conventional and flip-chip unit-cells.