A 4 GHz HIGH POWER TRANSISTOR - DESIGN AND RELIABILITY

P. Wang, J. Chen, P. Froess & S. Kakihana
Hewlett-Packard Company
Palo Alto, California

Abstract

An experimental high power, high gain 4 GHz transistor is described. The design aspects of high breakdown voltage, ballasting resistors, metallization system and thermal design are reviewed. It is shown how these consideration have been optimized for device reliability and long MTF.

We have successfully built an experimental microwave transistor that at 4 GHz has achieved 1.3 watts of common base cw output power with 9 dB gain. This transistor operating common emitter class A has 11 dB gain and 500 mw of power at the 1 dB compression point. This basic transistor chip is designed to be the prototype cell for a high power device family. Five watts of output power with 7 dB gain is expected from a device consisting of a combination of these basic chips. Figure 1 shows the gain vs frequency at a constant output power of 1.3 watts in common base configuration. Figure 2 shows the gain vs output power in common emitter class A operation.

Unlike most microwave power transistors, our design utilizes the basic interdigital transistor structure. The emitters are 1.5 micrometers wide and are diffused with arsenic. Each emitter finger is individually ballasted with a Tantalum Nitride (Ta_2N) thin film resistor. The metallization system is Ta_2N-Mo-Au. Figure 3 shows the picture of an experimental high power transistor chip. A special non-chemical etching process was developed to maximize the cross sectional area of the conduction metal. A comprehensive thermal analysis and design ensured a thermal resistance of less than 25°C per watt for the silicon chip. The incorporation of these features will yield a device with a very long MTF.

Since almost all of the technical difficulties encountered with microwave power transistor are associated with avoiding failures and prolonging operating life, device reliability is the dominant factor in the entire design process. Therefore, several aspects of reliability design are discussed in detail.

High Breakdown Voltage

The maximum power of a microwave transistor is limited by the collector-base breakdown voltage and by the Kirk effect which sets the limit on current range. Thinner and heavily doped epi gives a wider current range, but thicker and lightly doped epi with large PN junction curvature [1] gives a higher breakdown voltage. Since a device may fail under high voltages due to an avalanche injection mechanism, it is essential to improve the device ruggedness by increasing the collector-base breakdown voltage. But this must be done without sacrificing current range. This end is accomplished by utilizing a deep diffused p+ guard ring and an overhanging metal field plate. More than 60 volts of collector-base voltage is achieved with a 3.5 micrometer thick, 2 ohm-cm resistivity epi with a wide current range.

Ta_2N Ballast Resistors

The current hogging effect is one of the most serious short term failure modes of high power transistors. This phenomenon is caused mainly by material defects and process variation. The non-uniformity causes localized high currents and their associated hot spots. The high localized temperature and the negative temperature coefficient of the emitter-base junction voltage leads to high injection in the area of elevated temperature. This in turn leads to even more local heat generation and eventually thermal runaway and secondary breakdown. This problem can be minimized by the inclusion of an integral ballasting resistor in series with each emitter finger. The negative feedback effect of the resistor's I-R drop can stop the current hogging, thermal runaway regeneration cycle.

In order to analyze this problem accurately, a Green's function has been derived from a complex three-dimensional thermal analysis. This coupled with a minority carrier injection mechanism model [2] leads to a computer derived, optimized resistor value of 20 ohms per finger. This resistor is fabricated by masking and etching a thin film of RF sputtered Ta_2N. The structure is illustrated in Figure 4. The film thickness and resistivity uniformity is within 5%. Ta_2N has a temperature coefficient of -50 ppm and it is extremely stable at high storage temperatures for long periods of time. Less than 1% change per 1000 hours at 200°C and less than 0.2% change per 20 years at 25°C have been demonstrated at Hewlett-Packard.

Thermal Design

For a microwave power transistor, as the aspect ratio is increased by using narrower emitter widths, the power density is increased. This leads to very high junction temperatures. High operating junction temperatures not only degrade device performance, but also create more potential for device failure due to the accelerated rate of metal migration. The Green's function formulation was used to calculate the junction temperature and the temperature distributions of devices built on various size chips and with various configurations of the active area. Figure 5 shows the effect of active area configuration, spacing and chip size on junction temperature rise for three different designs. The final design chosen was a 20 x 25 mil chip with four active areas separated by specific distances. The actual measured junction temperature agrees with the calculated value and has a thermal resistance of 23°C per watt.

Metallization

Electromigration is a long term reliability problem associated with microwave transistor metallization system. Black's exponential expression [3] shows that longer MTF can be achieved (a) by using heavier metals with a high activation energy, (b) by increasing the metallic cross sectional area, and (c) by lowering the film temperature. Designed for a long MTF, this device uses an RF sputtered Ta_2N-Mo-Au combination for metallization. Ta_2N is a refractory metal with a very high melting temperature suitable as a barrier between gold and silicon. Mo is used as a media to "glue" Ta_2N and gold together. Gold is a noble metal with heavy mass, high density and a high activation energy of 1.2 ev. It is the optimum material to use as the main conductor when metal migration is a problem. To maximize the cross sectional area of the metal conductors in this extremely small geometry, a special metal etching process was developed. It enables the metal to be etched without undercutting, thereby achieving a high ratio of thickness to width. To demonstrate this point, Figure 6 shows a scanning electron microscope picture of a metal finger with a width of 1 micron and a thickness of 0.8 microns. Fifure 7 shows the expected MTF vs film temperature of RF sputtered Mo-Au films and Al films. The Al data was obtained from Black's report. The Mo-Au data was obtained experimentally by E. Littau of Hewlett-Packard Laboratory.

MTF

This device has metal fingers 2.5 micrometers wide and 0.8 micrometers thick. The thermal resistance is 25°C per watt and it is designed to operate normally with a current density of 2 x 10^5 amperes/cm^2. If the device delivers 1.3 watts of RF power at a 30% collector efficiency, exprapolating from Figure 5, a MTF of 10^6 hours is expected at 25°C case temperature. At 100°C case temperature a MTF of 1.5 x 10^5 hours is expected.

Several hundred transistors utilizing the same process and metallizations are undergoing a step stress test at 150°C junction temperature and 1.75 x 10^5 amps/cm^2 current density. To date 400,000 device hours have been accumulated without a failure.

Conclusion

An experimental high power, high gain 4 GHz transistor has been built and demonstrated. Both the device design and the fabrication process have been optimized for reliability and long MTF.

Acknowledgment

The authors wish to thank W. Jackson and H. Abraham for their contribution in Ta_2N process and to D. Bigelow for his work in metal etching.

References

1. S.M. Sze and G. Gibbons, "Effect of junction curvature on breakdown voltage in semiconductors", Solid State Electron., vol. 9, Sept. 1966, pp. 831-845.
2. The details of the derivation and applications have been presented at IEDM, 1972, Session 4-3. Completed paper is to be published.
3. J.R. Black, "Electromigration - a brief survey and some recent results", IEEE Trans. on Electron Devices, April 1969, pp. 338-347.

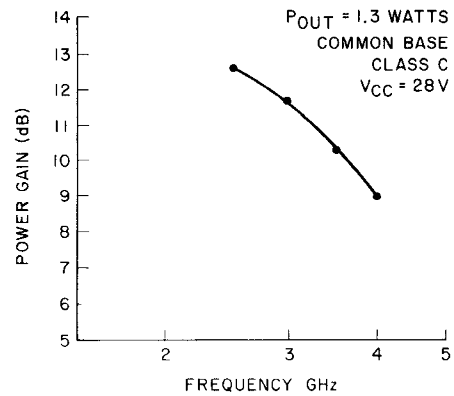

Fig. 1. POWER GAIN VS FREQUENCY IN COMMON BASE CLASS C OPERATION.

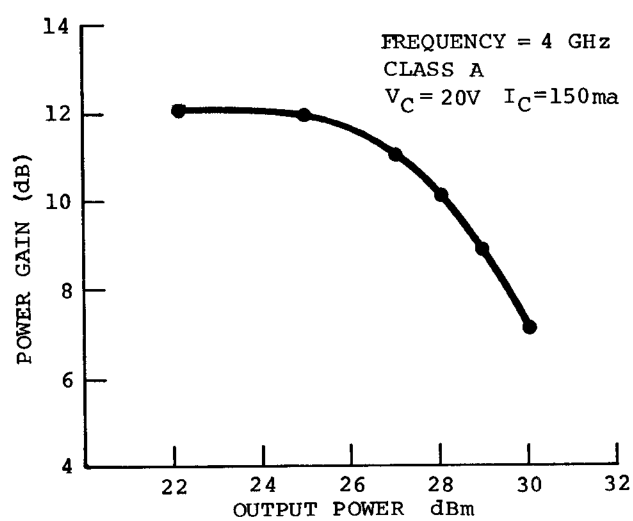

Fig. 2. GAIN VS OUTPUT POWER IN COMMON EMITTER CLASS A OPERATION.

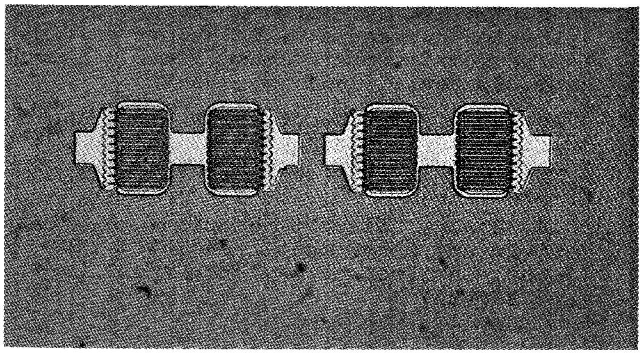

Fig. 3. AN EXPERIMENTAL HIGH POWER TRANSISTOR CHIP.

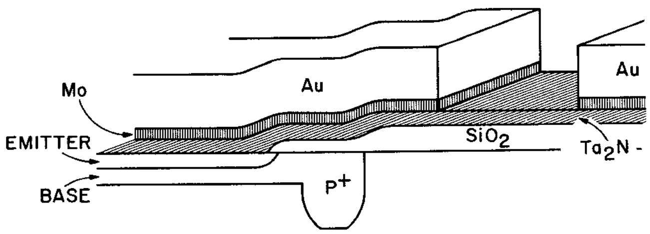

Fig. 4. Ta_2N EMITTER BALLASTING RESISTOR STRUCTURE.

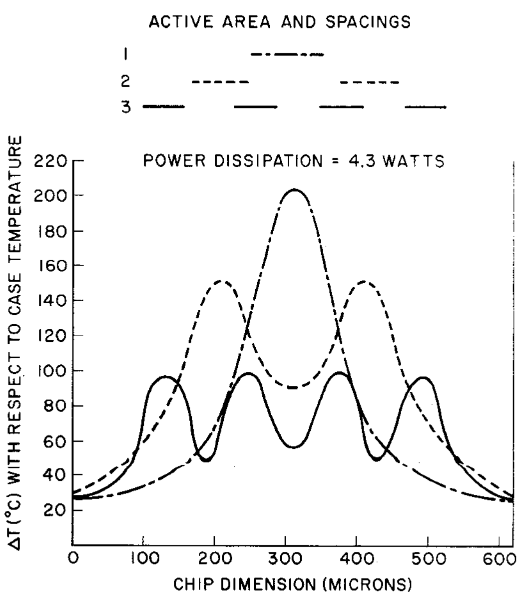

Fig. 5. THE EFFECT OF ACTIVE AREA CONFIGURATION AND SPACING ON JUNCTION TEMPERATURE RISE.

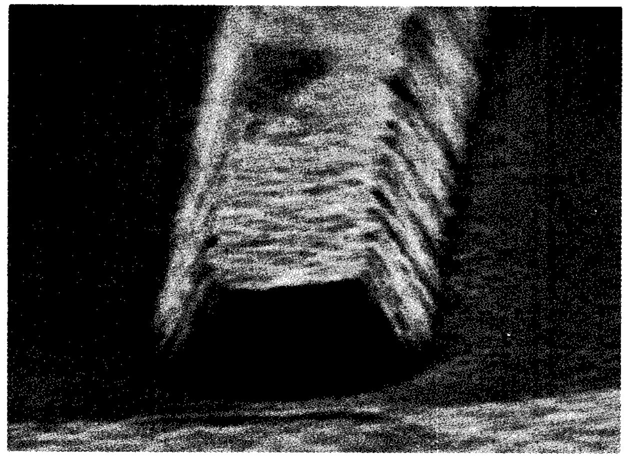

Fig. 6. SCANNING ELECTRON MICROPHOTO SHOWING THE HIGH THICKNESS TO WIDTH RATIO OF METALLIC CONDUCTOR (1 MICRON WIDE, 0.8 MICRON THICK).

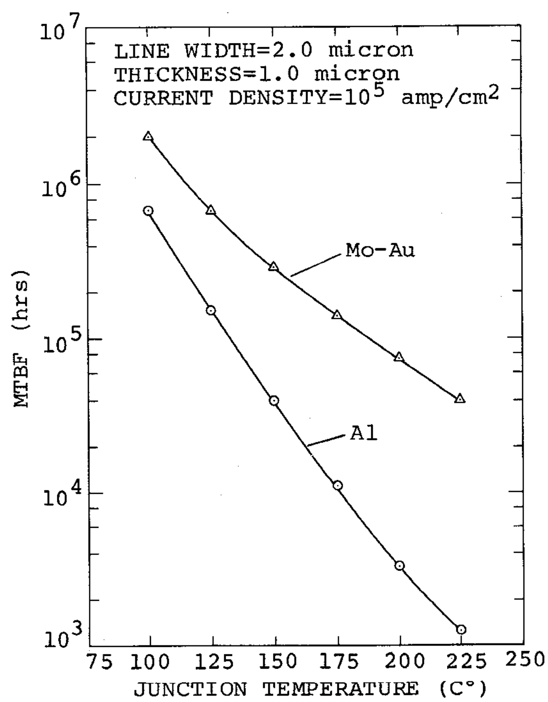

Fig. 7. MTF VS JUNCTION TEMPERATURE OF RF SPUTTERED Mo-Au AND Al.