HIGH PULSE ENERGY F-BAND TRAPATT DIODE AMPLIFIERS

J. H. Bowen, M. E. Breese, V. A. Mikenas, A. Schwarzmann, M. Weiss
RCA, Missile and Surface Radar Division
Moorestown, N.J. 08057

and

S. G. Liu, H. Sobol*
RCA, David Sarnoff Research Center, Princeton, N.J. 08540

Abstract

Design considerations in building high-power wide-pulse-width TRAPATT diode amplifiers are outlined. Diode characteristics, package parasitics, and circuit impedance levels are discussed. Analytical and experimental investigations of the transient thermal behavior of TRAPATT diodes are presented. Performance characteristics of several MIC alumina substrate amplifiers are described.

Introduction

Solid-state phased array radar designs frequently require transmitter module power outputs in the order of hundreds of watts with corresponding pulse widths of 50 microseconds and greater. Although the TRAPATT diode is ideally suited for operation in a pulsed mode, pulse widths were, until recently, limited to approximately 1 microsecond with maximum output powers in the order of 100 to 200 watts[1,2]. This paper describes some recent work in which pulse widths were extended to 50 microseconds at a power output level of 150 watts, and to 30 microseconds at a power output of 500 watts.

These performance improvements were a result of several factors, including improved wafer processing techniques and advanced circuit design, as well as a more comprehensive understanding of the thermal limitations and characteristics of TRAPATT diodes. This paper describes both analytic and experimental techniques for determining the transient thermal characteristics of TRAPATT diodes.

All circuits were designed and built using MIC techniques on alumina substrates and are directly compatible with modern solid-state module and radar design concepts. The results reported in this paper were obtained with both fundamental mode as well as harmonic mode extraction techniques. In the fundamental mode of operation, RF power is extracted at a frequency which corresponds to the trapped plasma cycle within the TRAPATT diode. On the other hand, in the harmonic mode of operation, RF output power is typically extracted at the second or third harmonic of this trapped plasma frequency.

Thermal Studies

Since the TRAPATT diode is ideally suited for high-power pulsed operation, a transient junction temperature investigation was of immediate interest. Two basic approaches to the problem were pursued. One approach consisted of an analytic and a computer model analysis, whereas the second approach made use of experimental techniques. The primary goal of this investigation was to evaluate techniques for the determination of the thermal characteristics of TRAPATT diodes and not in the establishment of maximum operational limits. The techniques presented here also apply to other semiconductor devices used in pulsed applications.

An accurate analytical model of the thermal characteristics of a TRAPATT diode is essential in gaining an insight into the parameters controlling the heat flow and resultant temperature distribution within the diode. A simple one-dimensional model has been found to give excellent results which corroborate well with data obtained using a three-dimensional computer analysis as well as with experimentally derived data.

*H. Sobol is presently with Collins Radio, Dallas, TEX.

The diode configuration that was modelled is schematically shown in Fig. 1. This thermal model assumed that the TRAPATT diode was in intimate contact with the heat sink and that a "heat capacitor" was intimately attached to the other terminal as shown in Fig. 1. A "heat capacitor" is basically an ungrounded heat sink that stores thermal flux during the heating cycle and discharges this heat through the diode into the heat sink during the off-time. It was assumed that the duration of the heating pulse was sufficiently short to prevent saturation of the heat capacitor; therefore, this heat capacitor can be considered as a second heat sink for the diode.

A simple one-dimensional diode model was generated and a closed form expression derived for the rise in junction temperature above the heat sink, as follows:

$$\Delta T_j = 0.314 \frac{P\sqrt{\tau}}{A} f(a) \qquad (1)$$

where P/A is the dissipated power density in watts per square centimeter, τ is the length of the heating pulse in seconds, and f(a) varies between 0.5 and 0.75 as the thickness of silicon between the junction and heat capacitor.

A three-dimensional computer model was also generated with sufficient flexibility to permit evaluation of several different types of diode configurations. This computer model has provisions for varying all physical dimensions, the silicon thermal conductivity, and the type of heat sink material. Some computed temperature profiles at several points within a typical TRAPATT diode are shown in Fig. 2. These data are for a diode with a diameter of 500 microns and a thickness of 43 microns, with a copper heat capacitor of 100 micron thickness, when dissipating 1.35 mW per square micron. It is seen that the effective thermal "time constants" of these devices can be much greater than 50 microseconds, since the temperatures in Fig. 2 are still rising sharply at the end of the pulse.

The experimental technique pursued to verify the analytical and computer model results consisted of an indirect temperature measurement whereby the breakdown voltage of the junction was observed and the junction temperature determined from a previously established calibration curve. Excellent agreement was found with the analytical and computer model data with that obtained by this technique.

Some experimentally derived junction temperature data are shown in Fig. 3 for pulsewidths between 5 and 25 microseconds as a function of peak dissipated power. These data are for a diode with a diameter of 865 microns, and agree within reasonable experimental accuracy with Equ. (1).

Circuit Design Considerations

A successful high-power wide-pulse-width TRAPATT diode amplifier design was found to be dependent on a number of important factors including diode type and size, diode package design with its inherent parasitics, circuit impedance levels, as well as basic circuit design concepts. Complementary "p" type diodes were used in this work because of their lower inherent thermal resistance[3]. The use of large diameter (≈900) diodes ensured that high powers could be generated over wide pulse widths. To minimize package parasitics, the diodes were mounted in the rectangular microstrip package shown in Fig. 4. By adjusting the length of the inductive ribbon shown in Fig. 4, the package-plus-diode resonance was adjusted to occur at the second harmonic of the extraction frequency. This technique minimized external circuit tuning requirements, and thus decreases both circuit losses and Q-factor, thereby increasing amplifier bandwidth.

The impedance level of the external circuitry also plays an important role in TRAPATT diode amplifier performance. A series of experimental tests were made in which the circuit characteristic impedance level was varied between Z_O = 10 and 50 ohms and the effect on TRAPATT amplifier performance was noted. From these results it was determined that maximum efficiency was found at an impedance level of approximately 10 to 15 ohms. These tests were performed in standard reflection type amplifier circuits[2].

Circuit Performance Results

Based on the above TRAPATT diode amplifier design considerations, several high-power wide-pulse-width amplifiers were designed and built.

Some typical performance data for a second-harmonic-extraction amplifier are shown in Fig. 5. Operations at a 50 microsecond pulse width was achieved over a 100 MHz bandwidth. At a pulse width of 10 microseconds, a bandwidth of 160 MHz was measured. Alumina substrates, 6.35 mm thick, were used and an integral circulator was incorporated as part of this amplifier resulting in a very small circuit size of 2.5 by 10.0 cm.

In order to increase the total RF output power, two diodes were mounted in series electrically but in parallel thermally. The diode pair was placed and tested in a circuit similar to that used for the single diode. However, because of the relatively high overall diode impedance (roughly twice that of a single diode), the circuit performed better as a fundamental-mode-extraction amplifier circuit than as a second-harmonic-extraction amplifier. Typical performance characteristics of this amplifier are shown in Fig. 6.

The 1 dB bandwidth was in excess of 200 MHz. Larger bandwidths were obtained by applying profiled RF input power and drive current. Maximum circuit efficiency and gain were 27 per cent and 6 dB respectively. At 500 watts output power level, the pulse width was successfully extended to 30 microseconds over a narrow portion of the bandwidth. This amplifier has also been operated in a Class "C" mode in which no bias current is drawn when the RF input drive is removed.

Conclusions

Analysis of the thermal characteristics of a typical TRAPATT diode has shown that the effective thermal time constant is considerably in excess of 50 microseconds. Operation with 50 microsecond pulse widths has been demonstrated using an alumina substrate MIC circuit over a 100 MHz bandwidth at a 150 watt output level. At a 500 watt level, a pulse width of 30 microseconds has been demonstrated over a narrower bandwidth, using series diodes.

Acknowledgement

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References

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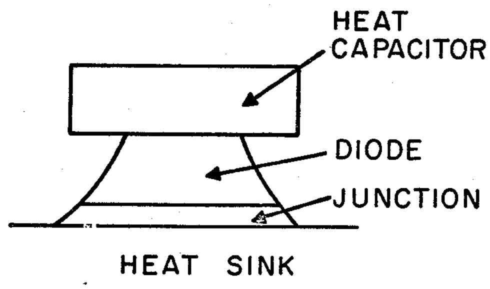

FIG. 1 TRAPATT diode thermal model

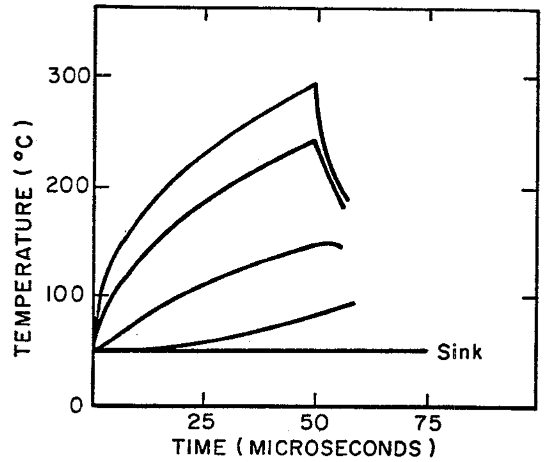

FIG. 2 Calculated temperatures

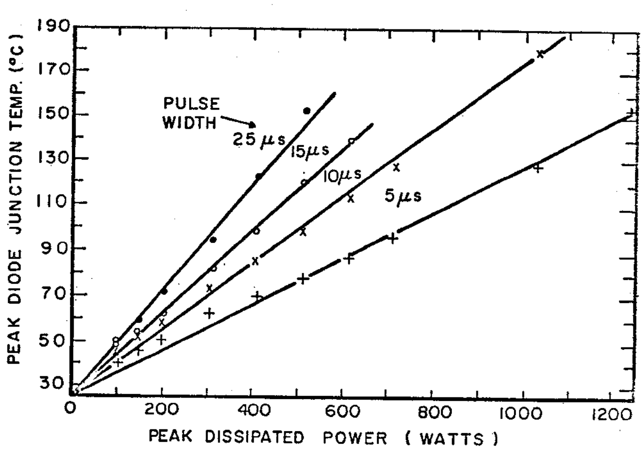

FIG. 3 Measured peak junction temperature

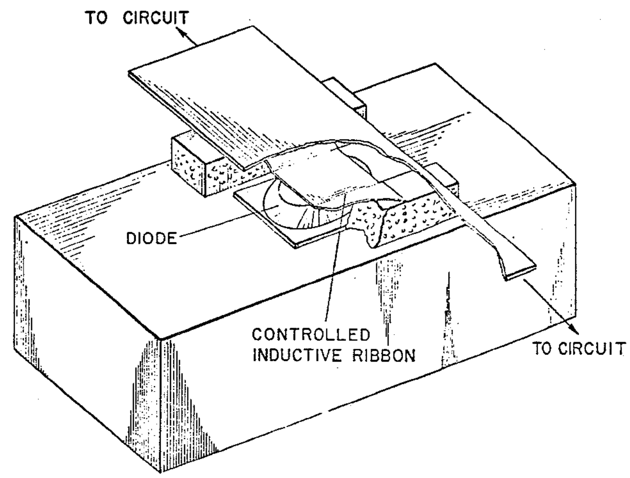

FIG. 4 Rectangular microstrip diode package

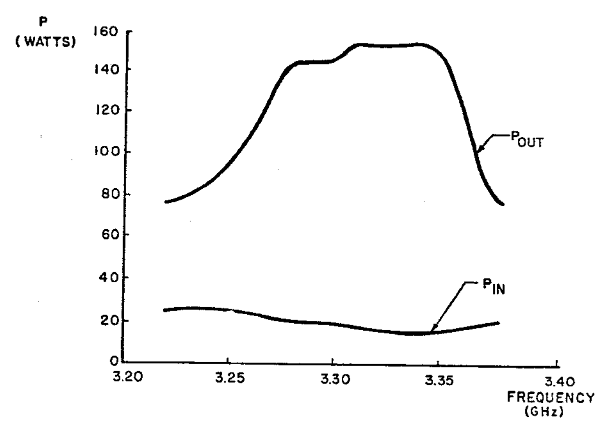

FIG. 5 Performance characteristics of second harmonic extraction TRAPATT diode amplifier

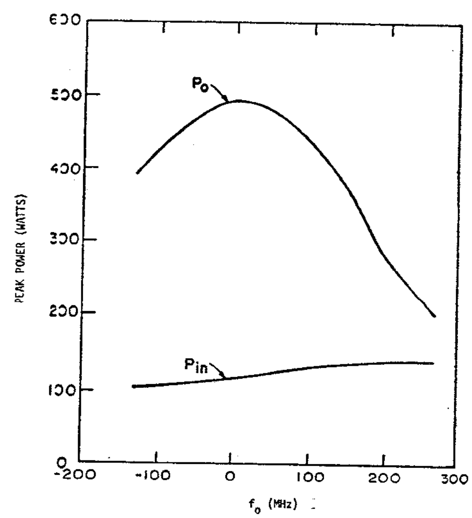

FIG. 6 Performance characteristics of series diode circuit