

# RF HYBRID LINEAR AMPLIFIER USING DIAMOND HEAT SINK

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## ABSTRACT

This paper will address the applications and methods used for a high power output RF linear small signal amplifier using diamond heat sink. Comparison and the benefits of using diamond heat spreaders will be reviewed. A growing number of researchers, engineers and scientists are looking into the applications of diamond's unique properties such as physical, electrical and optical.

## INTRODUCTION

High reliability space and military applications produce a very big demand continuously for high reliability RF amplifiers and other electronic circuits. These devices have been limited by the heat that they must dissipate during the normal operation. Today the circuit density is limited by the heat generated by the closely packaged and packed electrical devices and components. The problem has been how to get the heat out. This is not a problem with the diamonds, which have the highest thermal conductivity of any known material on the earth (Figure 1).

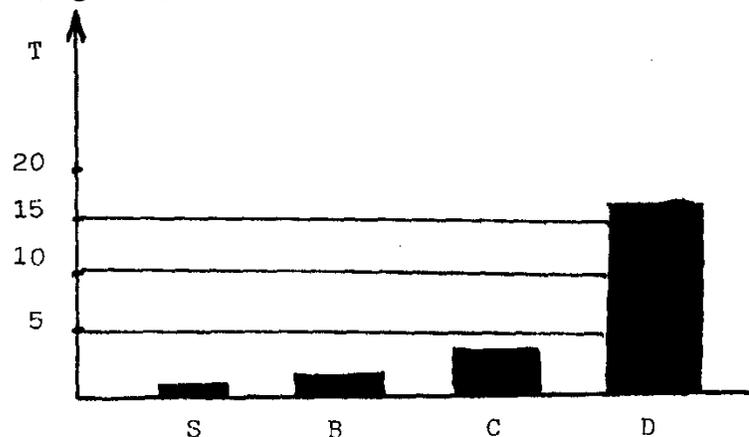


Figure 1.

T : thermal conductivity @ 100 degrees C  
S : silicon  
B : beryllium oxide

C : copper  
D : diamond (type 2A)

## WHY DIAMOND

Diamond is the best known insulator which has a thermal conductivity about five times better than pure copper at 100 degrees Centigrade and outperforms BeO by even a greater margin. Diamond heat sinks could eliminate the need for refrigeration systems to cool the avionics of the missiles and the aircrafts. It could reduce weight, create more compact devices and simplify the designs. Diamond is one of the few materials that both an electrical insulator and a thermal conductor. Diamonds feature a dielectric constant half that of silicon, thermal conductivity 20 times that of silicon, saturated electron velocity 2.7 times that of most common semiconductors, and a breakdown voltage 50 times that of most semiconductors. Diamonds can handle much more electrical power and heat than silicon. Silicon's bandgap, the distance electrons have to jump to make it into the material's conduction band, is only 1.3 eV. When a lot of electrical energy or heat goes through silicon semiconductors, the electrons become too energetic and jump right through the bandgap. This causes silicon devices leak and fail. Diamond's electron gap is 5.45 eV so it has the potential for high energy operation. This gives diamond a significant advantage over the other elements. But of course, diamond costs more than the others.

## BASIC DIAMOND PROPERTIES

The purest diamonds have the highest thermal conductivity, and the presence of nitrogen (a common impurity in diamond) can easily affect the thermal conductivity by reducing it. Diamonds are classified as type 1 or type 2, according to whether nitrogen is present or not. Also these types are subcategorized as A or B according to the specific forms in which impurities are present. In our studies, we are considering type 2A diamonds. This type diamonds have very low nitrogen contents and the highest heat conductivities. A comparison is given for the difference between type 2A diamond and copper thermal conductivities in Figure 2.

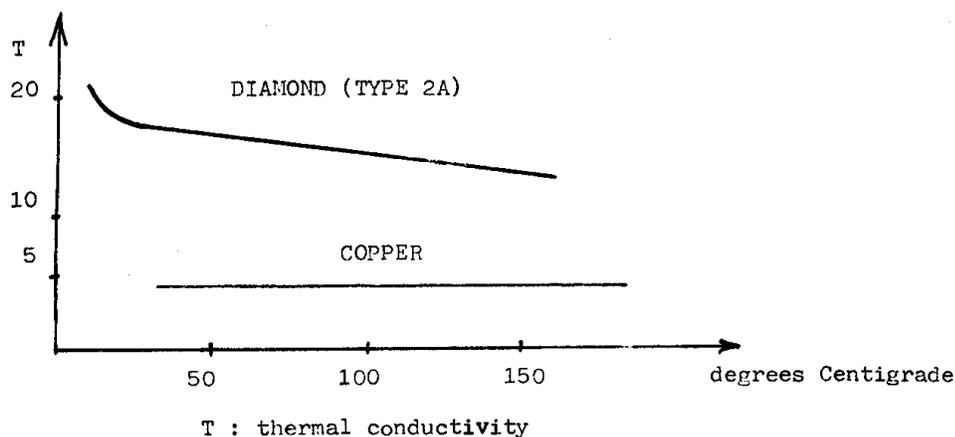


Figure 2.

Diamond has an extremely low coefficient of friction and also is an excellent electrical insulator (except for semiconducting type 2B). It will start to graphitize at temperatures in the region of 873 degrees K in air. At the same time diamond film is hard and strong. It can transmit light from the far infrared through the ultraviolet. Diamond film can easily overcome the problem of falling apart under stress for optical window materials.

## GENERAL CONSIDERATIONS

A power hybrid amplifier can be described as a high power dissipating microcircuit. Every circuit dissipates power depending on the specifications. But for the high power circuits, some other and special design techniques must be considered. This must be done to ensure and improve the circuit performance characteristics. In the high reliability aerospace and military applications the operating temperature limits requirements are different than the industrial applications. Minimum extremum goes down to -54 degrees C and maximum extremum goes up to + 125 degrees C. In the very low and high temperature environments, the circuit performance varies from the expected or designed to. This situation requires special considerations in design and processes for the fabrication of the devices. Some basic factors which must be considered during the power hybrid circuit design are as follows; 1) substrates, 2) packaging materials, 3) semiconductor die attach, 4) heat spreaders, 5) interconnections of the components and 6) circuit layout. Table 1 gives the details of the various materials for the substrates.

MATERIAL	DIELECTRIC LOSS TANGENT	DIELECTRIC CONSTANT @ 1MHz 25 <sup>0</sup> C	SPECIFIC GRAVITY G/cm <sup>3</sup>
ALUMINA (99.6 %)	0.0001	9.9	3.90
BeO (99.5 %)	0.0004	6.5	2.85
FUSED SILICA	0.000015	3.7 - 4.0	2.20
ALUMINUM NITRIDE	0.001	8.8	3.28
TFE	0.0001	2 - 10	2.20

Table 1.

## THERMAL BASICS

The variation of the failure rate, of any circuit, with temperature is an exponential function. A junction temperature change from 90 degrees C to 125 degrees C may increase the failure rate 4 to 9 times. The thermal resistance,  $\theta_{ca}$ , of a heat sink is a measure of how

fast and effectively dissipating the heat which is being developed in the transistor. The lower the thermal resistance is the cooler the transistor.

$$T_c = T_a + P \theta_{ca} \quad (1)$$

where,  $P$  : power dissipated in the device (Watt)  
 $\theta_{ca}$  : thermal resistance (degrees C/W) case-to-ambient  
 $T_a$  : ambient temperature (degrees C)  
 $T_c$  : case temperature (degrees C)

The temperature of the transistor collector-to-base junction,  $T_j$ , is important. Thermal resistance junction-to-case,  $\theta_{jc}$ , is needed to determine  $T_j$ . Usually  $\theta_{jc}$  is given in the transistor data sheet.

$$T_j = T_a + P \theta_{ja} \quad (2)$$

$$T_j = T_a + P (\theta_{jc} + \theta_{ca}) \quad (3)$$

where,  $\theta_{ca} = \theta_{ch} + \theta_{ha} \quad (4)$

where,  $P$  : power dissipated in the device  
 $T_j$  : junction temperature  
 $\theta_{jc}$  : thermal resistance, junction-to-case  
 $\theta_{ch}$  : thermal resistance, case-to-heat sink  
 $\theta_{ha}$  : thermal resistance, heat sink-to-ambient

The dissipated power in a transistor is non-linear with respect to the surface and the junction temperature. Because of the different currents on the semiconductor chip, there may be an occurrence of thermal runaway which can damage the semiconductor chip permanently. In the production of the hybrid circuits there is an inverse proportion between the cost and the heat (thermal resistance).

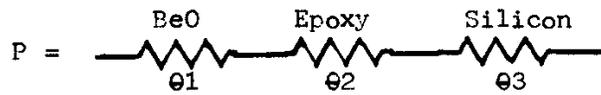
## THERMAL MODEL

A thermal model of a basic heat source ( semiconductor transistor chip) is given in Figure 3.

The basic equation for the thermal resistance is:

$$\theta = t / k \cdot A$$

where,  $\theta$  : thermal resistance  
 $t$  : length of thermal path  
 $A$  : area of thermal path  
 $k$  : thermal conductivity



$$t = X1 + X2 + X3$$

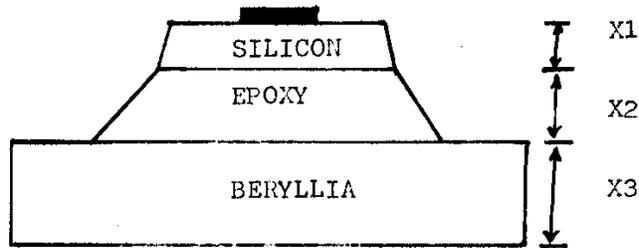


Figure 3.

## AMPLIFIER DESIGN

Our transistor is a silicon bipolar transistor. The amplifier circuit will consist of an active biased single stage, operating into a 50 ohm load and driven by a 50 ohm source, where frequency range is 5 to 500 MHz. This is a broadband linear small signal RF amplifier. Small signal means that the amplifier is operated in the linear region. This also means, in linear area, output power is not compressed. In the linear small signal region, the ratio of the output power to the input power is constant. As the input power is increased, the output power reaches to its limits. Above this limit the amplifier has a “compressed output” power. This is shown in Figure 4.

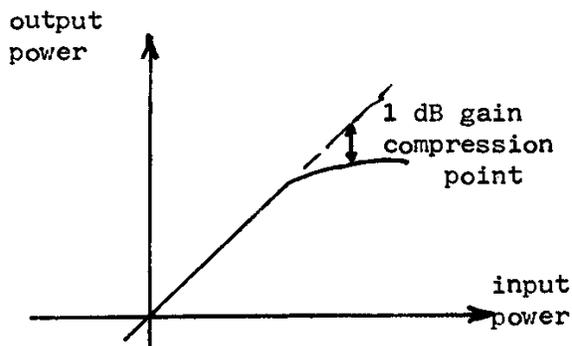


Figure 4.

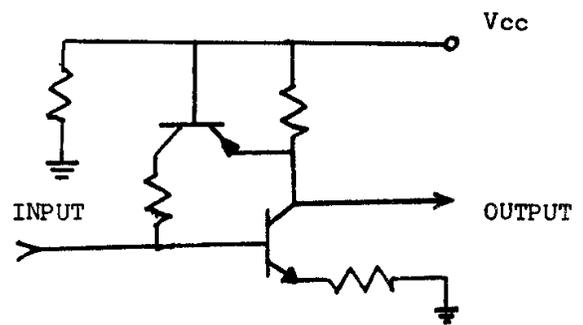


Figure 5.

In our design goal, the power output of the amplifier at 1 dB small signal gain compression point is almost + 30 dBm. which is 1 Watt. And the gain flatness of +/- 1 dB in the operating frequency range.

## **DESIGN STEPS**

First we select the appropriate transistor for our design goals. The optimum bias points is advised and given in the data sheets by the transistor manufacturer. According to this data, a biasing circuit is designed. In this case our bias circuit is an active bias circuit which provides better DC current stability against the fluctuations. As seen in Figure 5, active biasing is achieved by another transistor. This biasing circuit enables the RF transistor operates in the active region. After bias circuit design is completed, we design the RF circuitry of the amplifier. This amplifier is an active biased common-emitter transistor circuit. We use S-parameters (scattering parameters) of the transistor to design the RF circuitry. This data also given in the data sheets by the transistor manufacturer.

If the transistor is stable at the operating frequencies, input and the output of the circuit can be simultaneous conjugate matched. This means we can design necessary input and output matching circuits for the gain and the output power desired. Therefore our final circuit design is ready after the integration of the bias and the RF circuitry sections.

## **PRODUCTION ASSEMBLY**

Active devices are attached using eutectic bond to the heat sink. Heat sink is solder-down attached to the substrate or directly to the header surface. Substrate attachment is achieved by solder where gold plating of the package and metallization of the back side of the substrate are required for reflow. Interconnections are made by gold wire bonds. Sealing of the package is done in a dry nitrogen chamber where sealing of the lid to the case is hermetically performed by seam or projection welding.

## **THERMAL TESTING**

There are several ways to verify the thermal analysis. Some of them are probing the circuit with using a thermocouple, infrared (IR) microscope measurement, etc .The useful semiconductor lifetime is strictly related to the junction temperature. And also the power dissipation (maximum allowable in a semiconductor device is limited by its junction temperature. An easy way measurement is base-emitter junction voltage drop testing. Any change in a semiconductor die temperature affects base-emitter voltage drop difference which is measured first at low power dissipation and then high power dissipation. This measurement can report the relative heat dissipation of the circuit.

## **CONCLUSION**

In the aerospace and military power applications the circuit density is limited by the heat generated; which closely packaged components can cause much more limitations.

Dissipating heat out of the circuit is not a problem with diamond heat sinks. This heat spreaders provide high heat transfer by conduction and dissipate the heat fast enough before any damage occurs in the circuitry. In the future, even another application would be to dope the parts of the diamond layer and use this as both insulator and semiconductor. So maybe integrated circuits can be made of diamond.

## **ACKNOWLEDGEMENT**

The RF hybrid power amplifiers both with and without diamond heat sinks are designed. These are being fabricated at Aydin Vector Division. So this paper covers up-to-date studies for this application. Diamonds are metalvized and provided from Dubbeldee Diamond Corporation.

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