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THERMAL CONSIDERATIONS IN HIGH AVERAGE POWER MICROWAVE PIN DIODE SWITCHES

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ABSTRACT

The temperature sensitivity of PIN diode chip parameters responsible for the absorption and removal of heat in high average power switches is discussed.

The absorption of heat is controlled by the temperature sensitive forward and reverse bias resistances. The removal of heat is dominated by the variation in thermal impedance as a function of temperature. These variables combine in high power PIN diode switches to produce a phenomenon commonly called thermal runaway.

Using an empirical relationship derived from the data presented, a nonlinear model for temperature rise as a function of input power is generated. Reasonable correspondence between the empirical model and measured junction temperature was observed using a 1 KW CW SPDT waveguide switch.

Part of this work was performed as part of an Air Force contract[1].

INTRODUCTION

Little has been written in the literature concerning diode failure due to excessive junction heating in high average power PIN diode switches. A detailed understanding of the relationship between the incident RF power and the junction temperature rise for a given PIN diode is essential for reliable operation of a high average power diode switch. With this information, the switch design engineer can determine the reliability of the device for normal as well as fault mode conditions, such as high system VSWR or excessive ambient temperature.

The analysis of junction temperature rise is divided into two sections: temperature dependency of the heat absorption mechanism (the forward and reverse bias resistances of the diode) and the temperature dependency of the heat dissipation mechanism (the diode thermal impedance).

An empirical model for the relationship between junction temperature and the incident average RF power is generated using the experimental data for thermal impedance, forward bias resistance and reverse bias resistance. This model was verified at 5 GHz with power levels up to 1000 Watts using a SPDT waveguide switch.

MEASUREMENT OF TEMPERATURE SENSITIVE PARAMETERS

The parameters of the diode used in these measurements are listed in Table I. The thermal impedance for the diode listed is the typical value for this device when mounted on a large heat sink.

TABLE I
DIODE CHIP SPECIFICATIONS AT 25 C

Forward Bias Resistance (50 mA), Rf max	0.4 Ohms
Junction Capacitance (-40 V), Cj	0.20-0.24 pFd
Breakdown Voltage (10 uA), Vb min	1000 Volts
Carrier Lifetime min	3 usec
Thermal Impedance (Chip), θj,	4 C/W
Thermal Impedance (Package),θj	4 C/W
Thermal Impedance (Total), θj,	8 C/W
Diode Thickness:	.005 in.
Diode Diameter:	.022 in.

The reverse bias resistance of the diode was measured at approximately 4 GHz using the isolation resonance technique described schematically in Figure 1. The diode was mounted at the end of a low loss quarter wave coaxial line. The level of the isolation peak was recorded as a function of bias level and temperature. This was then compared with the level of the isolation peak without the diode (approximately 50 dB). From this isolation number, the actual reverse bias resistance of the diode was calculated. A similar procedure was used for the diode under forward bias, with the exception that the line length was one half wavelength.

Figures 2 and 3 are plots of the equivalent forward and reverse bias resistance of the diode across a 50 Ohm line. We see from the data that the resistance varies significantly over the temperature range of interest (25 to 150 degrees C). This technique of measuring the device resistance was selected because of its high sensiti-

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vity and simplicity compared to direct RF measurement of insertion loss in either coaxial or waveguide structures.

From these two Figures, we may write an empirical expression that describes the forward (Rf) and reverse (Rr) bias resistance as a function of temperature at bias conditions of -30 Volts and +80 mA per diode. This relationship will be useful later in predicting the junction temperature rise as a function of RF power. The resistance is expressed as the product of the room temperature resistance in Ohms and a thermal scaling factor:

(1) $Rr(T) = 14{,}700 / [\ 1 + (0.0097)(T-25)\ ]$

(2) $Rf(T) = 0.38\ [\ 1 + (0.00341)(T-25)\ ]$

where: $25\ C < T < 150\ C$

The temperature dependance of the thermal impedance of bulk silicon is shown in Figure 4 [2]. The change in thermal impedance over the range of interest is greater than 50%. As above, the thermal impedance of silicon can be expressed as the product of the room temperature value and a thermal scaling factor:

(3) $\Theta(T) = .651\ [\ 1 + (.00544)(T-25)]$ C-cm/W

where: $25\ C < T < 150\ C$

The thermal impedance of the packaged diode can be represented as follows:

(4) $\Theta(T) = \Theta c + \Theta j(T)$
$= \Theta c + \Theta jo\ [\ 1 + (.00544)(T-25)]$

Where Θjo is the chip thermal impedance at room temperature and Θp is the thermal impedance of the package and solder interface. The thermal impedance of the packaged diode was measured over this temperature range. The increase in thermal impedance of the mounted diode was approximately 2 degrees C/W. This is consistent with the change that would be calculated from equation 4.

HIGH POWER RF MEASUREMENTS

A SPST and a SPDT waveguide switch were built to test the model. The performance of these switches are summarized in Table II. Each switch section employed 2 diodes mounted in series in the waveguide as shown schematically in Figure 5. This provided low thermal resistance mounting of the diodes in a low loss RF structure.

TABLE II
PERFORMANCE OF THE WAVEGUIDE SWITCH

Frequency range, operational:	5.0 - 5.8 GHz
high power test:	5.0 GHz
Power, CW:	1000 Watts
VSWR:	1.2:1
Isolation:	19 dB
Insertion loss:	0.15 dB
Switching speed:	2.0 usec
Forward Bias per diode:	50 mA
Reverse Bias:	-30 V
Waveguide:	WR-187 Reduced Height

The SPDT switch was operated at power levels up to 1000 Watts. The rise in junction temperature was measured under both forward and reverse bias conditions in the following way. The RF was applied to the switch as a square wave of 50 Hz. The resultant long pulse width of 10 ms insured that the diode had come to thermal equilibrium. At the end of the RF pulse, the change in forward bias diode voltage was measured on an oscilloscope and compared to the steady state value with the RF off. Using a calibration chart of temperature vs. bias voltage at the proper operating current of the diode, the junction temperature rise was then determined.

The junction temperature rise under reverse bias was measured in a similar way. At the end of the RF pulse, the bias on the diodes was changed from reverse bias to forward bias within 3 usec. The junction temperature rise was then measured as described above. The monitoring circuitry employed allowed measurement of the forward bias voltage with a ressoolution of plus minus 2 degrees C.

The measured junction temperature for reverse bias is shown in Figure 7 and for forward bias in Figure 8.

MODEL VERIFICATION

In oorder to compare the calculated and measured junction temperature, the loss characteristics of a SPDT switch must first be examined. The reverse bias insertion loss of a diode pair in series across the transmission line is:

(5) $Lr(T) = Z / 2\ Rr(T)$
$= Z\ [\ 1 + (.0097)(T-25)\ ] / 29400$

The insertion loss for a diode pair under forward bias mounted in series at the junction of a SPDT switch is:

(6) $Lf(T) = 2\ Rf(T) / Z$
$= 2\ \{0.38\ [\ 1 + (.00273)(T-25)\ ]\} / Z$

Where Z = 120 Ohms at the frequency of operation. The relationships for insertion loss have been modified to account for the fact that the waveguide switch employed two diodes in series. The dissipated power, in either forward or reverse bias, may now be calculated from:

(7) $P_{dis}(T) = P_{in}\, L(T)$

The junction temperature can be expressed in terms of the ambient temperature (Tamb), the thermal impedance and the resistance of the diode:

(8) $T_j = T_{amb} + P_{dis}(T)\, \theta_j(T)$

(9) $T_{jf} = T_{amb} + 2\, P_{in}\, R_f(T)\, \theta_j(T) / Z$

(10) $T_{jr} = T_{amb} + Z\, P_{in}\, \theta_j(T) / 2\, R_r(T)$

where the empirical relationships for the temperature dependance of resistance and thermal impedance are given in equations (1) through (4).

Tj was solved using an iterative process. The empirical relationship and the data are plotted in Figures 6 and 7 for forward and reverse bias respectively. As can be seen, there is reasonable correspondence between the data and the empirical model that has been generated.

It is of interest to compare the change in the slope of the non linear model above 120 C with the linear model on each graph. The plot was extended above 1000 Watts CW to clearly show the phenomenon of thermal runaway. At temperatures above 175 C, the curve is such that a small variation in input power will cause substantial variations in junction temperature.

CONCLUSION

It has been shown that the phenomenon of thermal runaway can be explained by the thermal sensitivity of thermal impedance and resistance. The non linear model presented can be used to a produce a more reliable high power PIN diode switch.

ACKNOWLEDGEMENTS

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[1] Rome Air Development Center, Air Force Systems Command, Griffiss Air Force Base, NY 13441-5700; Airforce Contract # F19628-83-C-0035.

[2] M. Neuberger and S. J. Welles, "Silicon", Air Force Contract # F33615-68-C-12 25, Hughes Aircraft, October 1969.

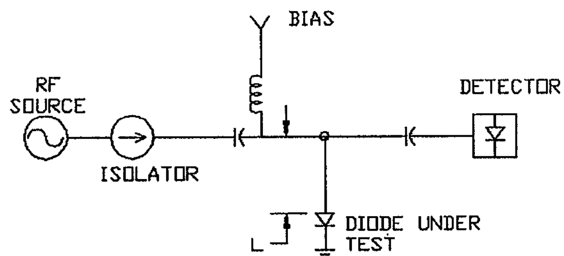

FIGURE 1
TEST SETUP FOR MEASURING FORWARD AND REVERSE BIAS RESISTANCE

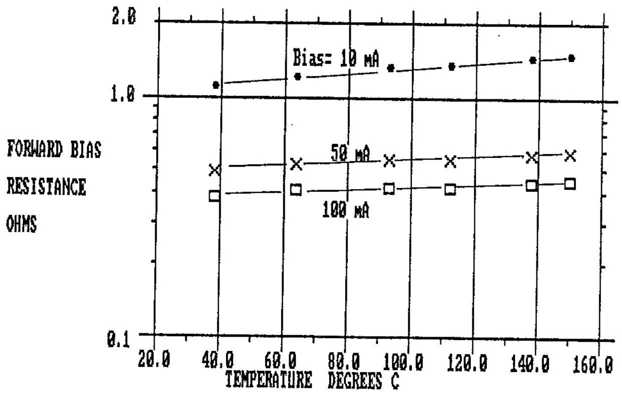

FIGURE 2: Forward Bias Resistance as a Function of Junction Temperature and Bias Current

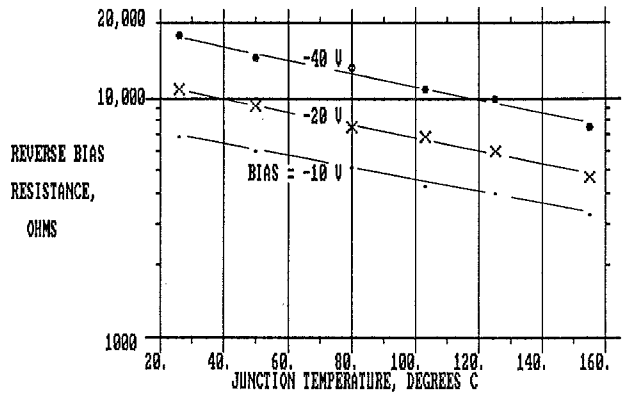

FIGURE 3: Revrese Bias Resistance as a Function of Junction Temperature and Bias Voltage

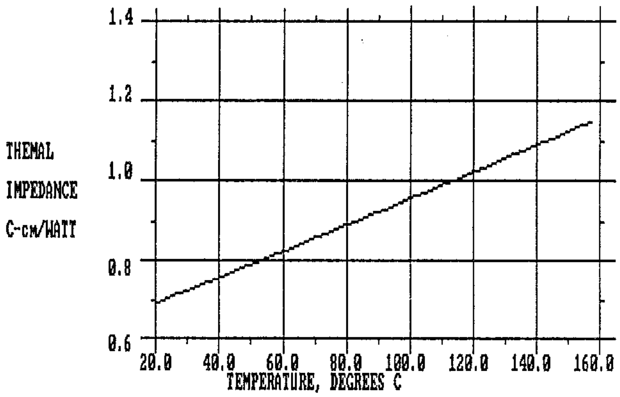

FIGURE 4: Variation of Thermal Impedance of Silicon as a Function of Temperature

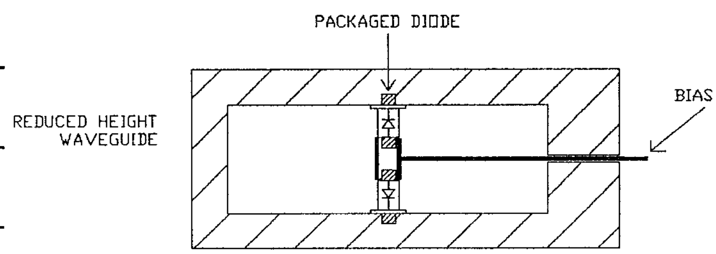

FIGURE 5
CROSS SECTION OF SWITCH SHOWING DIODE CONFIGURATION

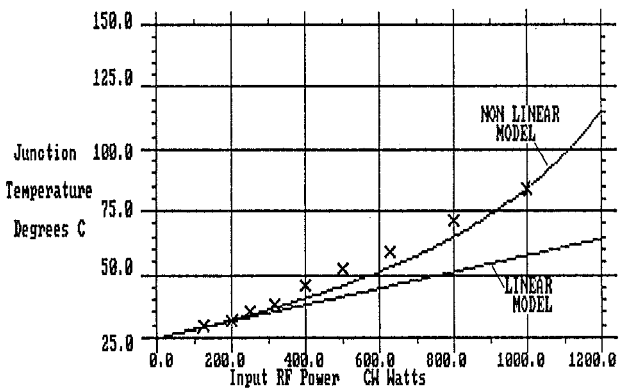

FIGURE 6: Junction Temperature vs Input Power Under Reverse Bias

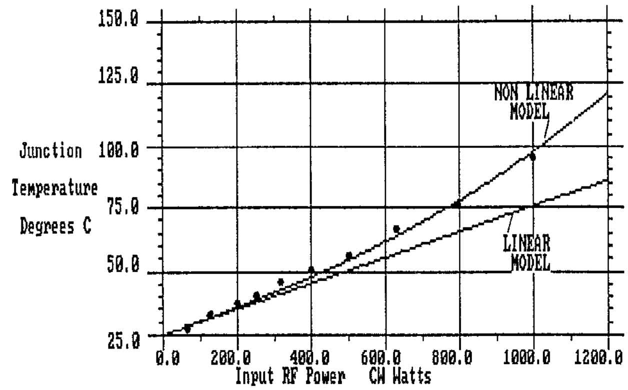

FIGURE 7: Junction Temperature vs Input Power Under Forward Bias of 80 mA/Diode