Thermal Characterization of Microwave Power FETs Using Nematic Liquid Crystals

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Abstract

A method of measuring the thermal characteristics of microwave power FETs using temperature sensitive nematic liquid crystals is described. Measurements performed using this technique show thermal resistance not to be invariant, as often assumed.

Introduction

Thermal limitations play an important role in microwave power FET operation. Channel temperature affects both RF performance and service lifetime (MTTF).

Accurate device thermal characterization is essential both during design and end use. A commonly used parameter, thermal resistance (θjc) may be used to determine device operating temperatures. Many workers commonly assume thermal resistance to be a constant. The measurements described here show thermal resistance to be a function of several factors, including operating temperature and bias conditions.

The measurement technique described has temperature accuracy within $\pm.5$ degrees Celsius, and spatial resolution better than two microns. This latter property makes the liquid crystal method an especially powerful thermal analysis tool.

Theory of operation

The liquid crystal technique makes use of the properties of several types of temperature sensitive nematic crystals (1). As shown in Fig. 1, below a critical temperature, the so-called

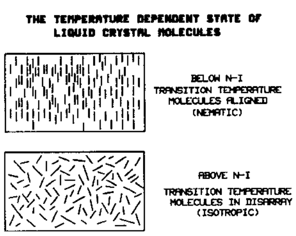

Fig. 1

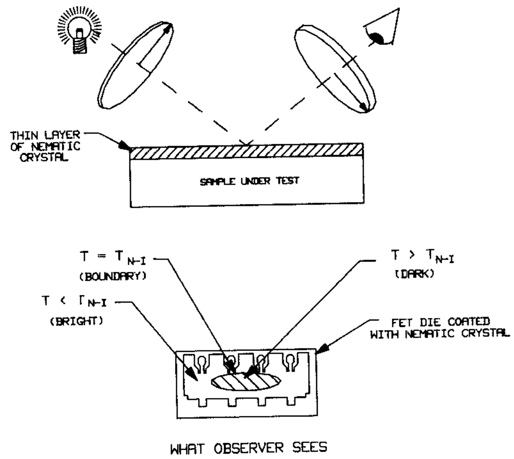

Fig. 2

nematic-isotropic (N-I) transition temperature, the molecules which make up the material form an orderly (nematic) array. When the transition temperature is reached or exceeded the molecules take on random (isotropic) orientations. Crystals having N-I transition temperatures ranging from 25 to 300 degrees Celsius may be obtained from several manufacturers, including Eastman Organic Chemicals and E. Merck.

If uniformly polarized light is directed towards the device under test (DUT) and viewed through a correctly oriented polarizing plate (analyzer) as shown in Fig. 2, a difference will be noted between points on the sample which are below and above the N-I transition temperature respectively. The DUT will appear bright in areas which are below the N-I temperature, and dark in areas which are either at or above the transition temperature.

The principle of operation is as follows: Below the N-I transition temperature the crystal material is birefringent. Light reflected from the DUT will contain components polarized in two directions, making complete cancellation by the analyzer impossible. Above the transition temperature, the reflected light is uniformly polarized and near total cancellation is possible when the analyzer is properly oriented.

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Using the liquid crystal technique

Nematic crystal material is usually supplied in powdered form. To use it, one dissolves a small quantity of the powder into a carrier liquid such as acetone. The resulting solution is then applied to the surface of the DUT using a pipette. The carrier liquid is allowed to evaporate completely, leaving behind a thin film of the nematic crystal. Fig. 3 summarizes this procedure.

PREPARATION AND APPLICATION OF LIQUID CRYSTAL SOLUTION

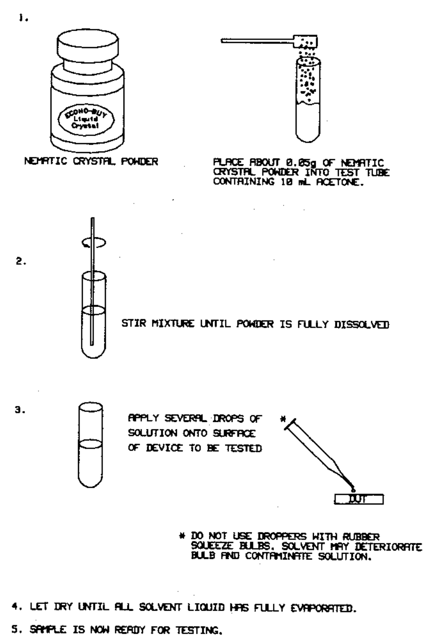


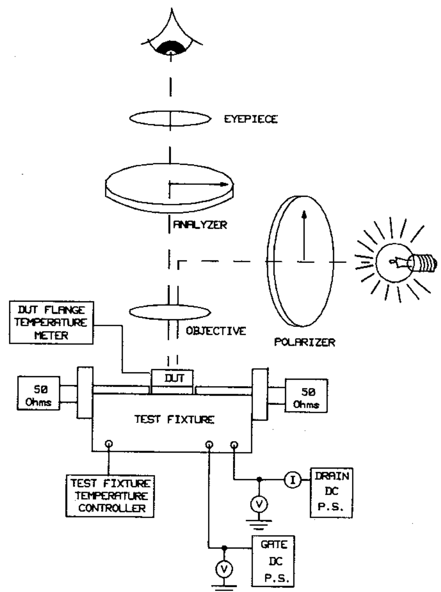
Fig. 3

Following preparation as outlined above, the DUT is placed on a temperature controlled stage as shown in Fig. 4 and DC bias is applied. By noting the point at which the first spot on the device begins to go dark and the associated case temperature, which may be measured using a thermocouple, one may calculate the thermal resistance using:

$$\theta jc = \frac{Tch - Tc}{Pdiss} \qquad (1)$$

where

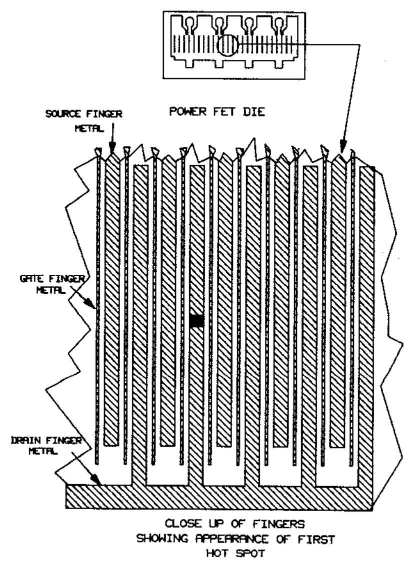
θjc = channel-to-case thermal resistance ($^{\circ}C$ per watt)
Tch = maximum channel temperature ($^{\circ}C$) Equal to the N-I temperature of the crystal in use.
Tc = case temperature ($^{\circ}C$)
Pdiss = DC bias power + RF input power - RF output power (watts)



BLOCK DIAGRAM OF LIQUID CRYSTAL TEST SETUP

Fig 4

The superior spatial resolution of the liquid crystal method permits measurements of device thermal resistance under conditions commensurate with the appearance of the first hot spot on the channel as shown in Fig. 5. Since the device will most likely fail at it's hottest point, this "hot-spot" value of thermal resistance is useful when performing calculations for accelerated life testing or MTTF determination.



CLOSE UP OF FINGERS SHOWING APPEARANCE OF FIRST HOT SPOT

Fig. 5

Some results

The sequence of photographs in Fig. 6 shows the heating pattern of an Avantek M114 power FET (2-watt, X-band device). As the case temperature is increased in succeeding photographs, the channel becomes hotter and the size of the darkened area increases. Photo number 2 shows the appearance of the first hot spot, on a drain finger. The spot is about six microns square, and as one would expect, appears at the center of the die.

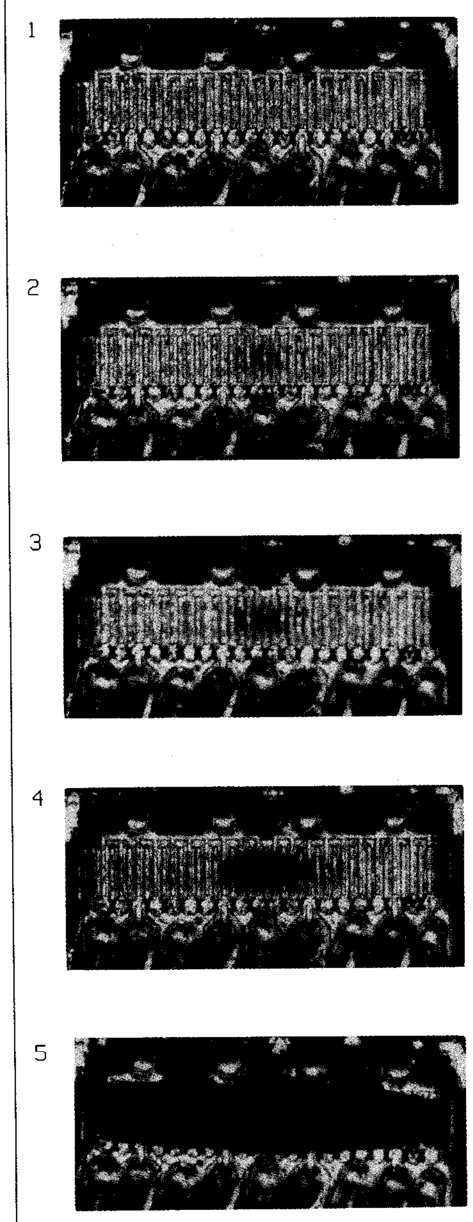


Fig. 6

The oval pattern shown in succeeding photographs is characteristic of good attachment between the backside of the FET die and its carrier. A device exhibiting poor die attachment would exhibit a number of isolated hot spots or an asymmetrical pattern.

The variation of thermal resistance as a function of temperature for the M114 was studied by performing hot spot thermal resistance measurements using five different nematic crystals, each having a different N-I transition temperature. The result of these measurements is shown in Fig. 7. This data was found to give excellent agreement with the values computed using Kirchoff's transformation (2).

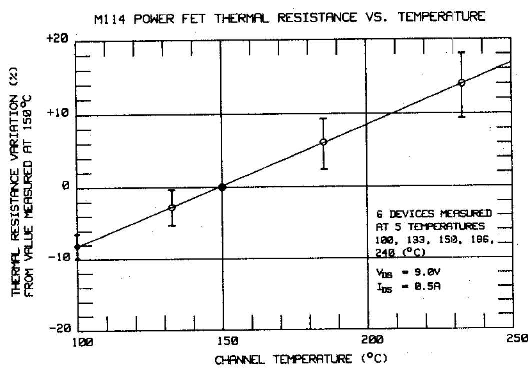


Fig. 7

The effect of varying drain current on thermal resistance was investigated by performing hot spot thermal resistance measurements while holding drain voltage constant. Drain current was varied by a factor of three, and case temperature was adjusted to keep the size of the hot spot constant at each value of Ids. The variation of θjc due to the case temperature change was computed and subtracted from the total variation observed, yielding no net variation of thermal resistance with drain current.

An experiment was performed to determine the variation of thermal resistance as a function of drain voltage. Vds was varied over a range spanning from 2 to 11 volts and Ids appropriately adjusted to keep the power dissipated by the DUT constant. The case temperature was set as required to keep the hot spot size constant at each set of Vds, Ids values. The variation of θjc due to the change in case temperature was calculated and subtracted from the thermal resistance measured, giving the variation due to changing values of Vds. The results of this experiment are given in Fig. 8.

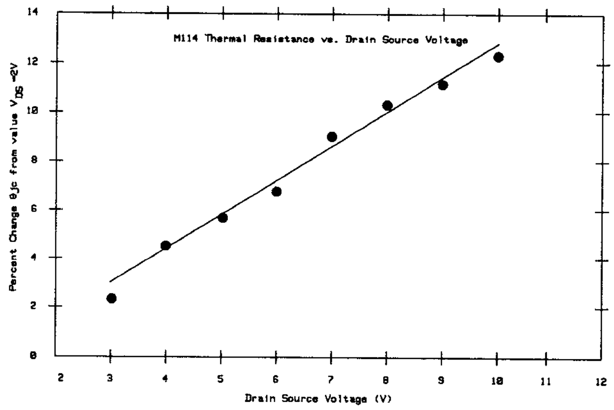


Fig. 8

Fig. 9 gives a plot showing contours of constant channel temperature. These isotherms are determined as follows: DC bias is applied to the DUT and the case temperature adjusted to show the first hot spot on the channel. The case temperature is then increased in small increments. As the channel temperature increases, the darkened area expands.

The boundary between the light and dark areas will be at the transition temperature of the crystal in use, and the temperature difference between the hottest part of the die and the boundary will be given by:

T = Tcase2 - Tcase1

where
Tcase2 = DUT case temperature when hottest point measured
Tcase1 = DUT case temperature

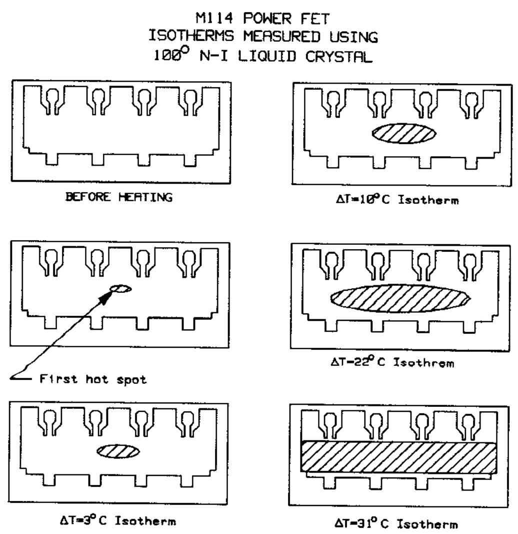


Fig. 9

This formula assumes that the thermal resistance of the DUT is constant over temperature, a valid assumption for temperature differences on the order of several tens of degrees. Using the liquid crystal technique, it is possible to plot a series of isotherms with temperature differences between adjacent contours differing by less than one degree Celsius.

Measurements have been performed on several types of interdigitated finger-type power FETs both with and without RF applied. Observations show little or no change in thermal resistance or isothermic contour shapes due to the presence of RF.

Comparison with other techniques

Several other techniques, including infrared microscopy and delta Vgs testing are commonly used to measure power FET thermal resistance. IR microscopy typically gives values of hot spot thermal resistance about ten percent lower than those obtained using the liquid crystal technique. This is due to the poorer spatial resolution of the IR method. The delta Vgs technique makes use of the temperature dependent voltage drop across a forward-biased gate-source diode. Delta Vgs measurements may differ from liquid crystal measurements by a factor of two or more, depending on measurement conditions.

Conclusion

The liquid crystal technique of thermal profiling has been applied to microwave power FETs. Contrary to the common assumption taking thermal resistance to be a constant, variations with both temperature and bias conditions have been observed. A method for the determination of channel isothermic contours has been given. The superior spatial resolution afforded by this technique makes possible the detection of very small hot spots, useful in device thermal profiling and reliability studies.

References

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(2) W. B. Joyce, "Thermal Resistance of Heat Sinks with Temperature-Dependent Conductivity", Solid-State Elect., Vol. 18, pp. 321-322, 1975