

# Raman Channel Temperature Measurement of SiC MESFET as a Function of Ambient Temperature and DC Power

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**Abstract** — Raman spectroscopy is used to measure the junction temperature of a Cree SiC MESFET as a function of the ambient temperature and DC power. The carrier temperature, which is approximately equal to the ambient temperature, is varied from 25 °C to 450 °C, and the transistor is biased with  $V_{DS}=10V$  and  $I_{DS}$  of 50 mA and 100 mA. It is shown that the junction temperature is approximately 52 and 100 °C higher than the ambient temperature for the DC power of 500 and 1000 mW, respectively.

**Index Terms** — Junction Temperature, MESFET, Raman Spectroscopy, SiC.

## I. INTRODUCTION

High temperature wireless sensor systems are becoming increasingly desired for aircraft engine control systems to reduce pollution, decrease noise, and increase fuel economy. These sensors are expected to operate at an ambient temperature between 500 and 650 °C [1]. NASA is planning science missions to Venus that will require communication systems and wireless sensors that operate at an ambient temperature of 500 °C [2]. Sensors for oil drilling and mining must operate at 300 °C, and automobile sensors for engine, exhaust, and brake monitoring are required to operate at 125 °C [3].

Wide bandgap, SiC transistors are widely used for these applications. High temperature wireless sensor systems have been developed and demonstrated. Operation of a pressure sensor integrated into a 30 MHz oscillator based on a commercial, Cree Inc. CRF24010 SiC transistor has been demonstrated at a carrier temperature of 400 °C [4]. An oscillator based on the same Cree SiC MESFET with an output power of 4.9 dBm at 453 MHz and a carrier temperature of 475 °C was demonstrated [5]. Lastly, the Cree CRF24010D SiC transistor was used to demonstrate a 1 GHz oscillator that operated at a carrier temperature of 200 °C [6].

Cree has conducted accelerated life tests of the CRF24010 using a maximum junction temperature of 410 °C [7]. These tests show the device has an activation energy,  $E_a$ , of 0.90 eV and a Mean Time to Failure (MTTF) of  $2 \cdot 10^6$  hrs at 175 °C junction temperature. Furthermore, self-heating decreases the transistor's saturation current and current gain [8], [9]. Since transistor reliability and performance are dependent on the junction temperature, it is critical that it be measured under operational conditions.

Various methods have been used to measure or extract the junction temperature, including extraction from measured

current/voltage characteristics, direct contact with thermocouples, infrared camera, and Raman spectroscopy [10]. Raman techniques have become preferred because they permit higher resolution and, therefore, a better measurement of the peak temperatures along the channel [11]. Raman spectroscopy has been used to measure the junction temperature of GaN transistors and SiC Light Emitting Diodes [12]-[15].

In this paper, we measure for the first time the channel temperature of a SiC MESFET over a very wide ambient temperature range (25 to 450 °C). These measurements are made at DC power levels of 500 and 1000 mW. Section II describes the experimental method used, and Section III presents the measured results. Finally, Section IV gives a brief summary and conclusion.

## II. EXPERIMENT DESCRIPTION

A Cree CRF24010D SiC MESFET is attached to a 3 mm by 8 mm by 10 mil thick alumina substrate with electrically conductive epoxy, which have thermal conductivities of 0.34 and 0.072 W/(cm K), respectively. The alumina substrate is mounted on a tantalum metal sheet (0.54 W/cm K) and a thermocouple is attached to the Ta metal. This is mounted onto a 2 inch by 1 inch rectangular ceramic heater, which is mounted on a piece of thermal insulating space shuttle tile. Thus, the Ta metal sheet, alumina substrate, and the SiC MESFET are thermally isolated except for radiative heat transfer to still air.

The Raman spectra of the SiC transistor were acquired using a microscope-coupled Raman spectrometer (Renishaw System 2000 Raman Microscope) with the microscope stage replaced by a heating stage mounted on an xyz translation stage. The excitation was produced by a continuous argon ion laser ( $\lambda = 514.5$  nm). The laser excitation was transmitted through a 20x long-working-distance objective (working distance = 20 mm, NA = 0.42) that focused the laser to an approximately 10  $\mu$ m diameter spot on the SiC transistor. The laser power exiting the objective was 3.5 mW. The center of the middle gate of the SiC transistor was positioned beneath the objective and brought into focus using the xyz translation stage. At high heater stage temperatures, thermal convection introduced some errors in focusing the laser. The scattered light was collected in a back-scattering geometry through the same long-working-distance objective. The scattered light

collected by the objective was transmitted into the Raman spectrometer where the elastically scattered (Rayleigh) laser light was removed by a pair of holographic notch filters and then dispersed within a 0.25 m focal length spectrograph by a 1800 groove/mm holographic reflection grating and detected by a Peltier-cooled CCD detector providing a spectral resolution of about  $2 \text{ cm}^{-1}$ . All spectra were acquired in 100 sec. A neon emission lamp was positioned to reflect off the specimen into the objective in order to incorporate a temperature-independent neon emission reference spectrum into every Raman spectrum. Peak positions were determined by applying a nonlinear least-squares curve fitting routine (GRAMS) over the spectral range from  $650$  to  $815 \text{ cm}^{-1}$  that fits each peak to a mixture of Lorentzian and Gaussian lineshapes. In particular, the temperature dependence of the position of the Raman peak corresponding to the SiC transverse optical (TO) mode (at  $776 \text{ cm}^{-1}$  shift at room temperature) was selected for temperature measurement of the SiC transistor gate. To compensate for possible drift in spectral offset, a corrected SiC TO peak position was always determined by adding the separation between the SiC TO peak and the neon emission reference peak at  $676.3 \text{ cm}^{-1}$  to the known position of the neon emission peak. The Raman peak shift was temperature-calibrated by fitting a second order polynomial to the dependence of the thermocouple temperature measurement on the position of the SiC TO peak obtained from the SiC transistor gate at zero current. Figure 1 shows the test fixture under the Raman instrument.

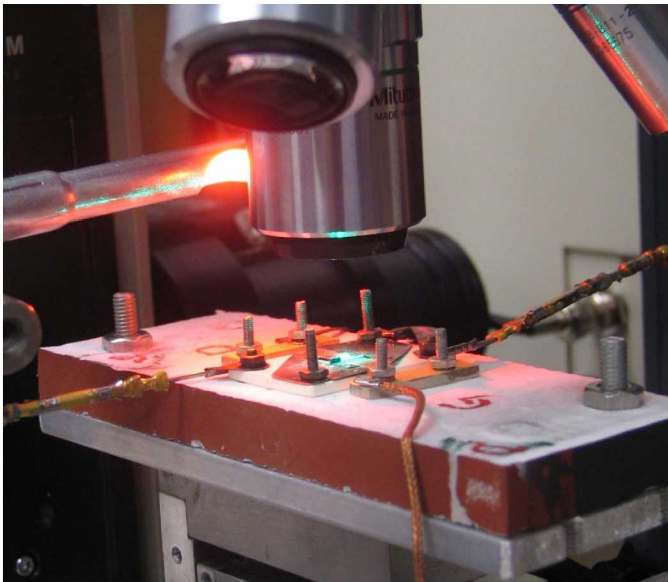


Fig. 1: SiC MESFET mounted on alumina substrate on a tantalum metal sheet, ceramic heater, and thermal isolating ceramic. The thermocouple mounted to the metal sheet and the bias lines for the transistor and the ceramic heater are seen. A thermally insulating cover with a hole in it to permit the Ne and Ar light to strike the transistor is not shown.

The recommended maximum operating junction temperature of the CRF24010 is  $255 \text{ }^\circ\text{C}$ . Since the operating temperatures of the perceived uses of the transistor are greater than  $255 \text{ }^\circ\text{C}$ , the operating bias conditions are backed off to  $V_{DS} = 10\text{V}$  and  $I_{DS}$  of 50 and 100 mA to limit the increase in junction temperature. These bias conditions have been used for high temperature oscillators [5], [6]. During the Raman spectroscopy measurements, the ceramic heater temperature is first set with no bias on the transistor and the system is allowed to stabilize for 15 min. The Raman measurements with no transistor bias are used for temperature calibration. The gate bias,  $V_{GS}$ , is decreased until  $I_{DS} = 50 \text{ mA}$ , and the system is allowed to stabilize for 10 min. before the Raman measurement is made. This is repeated for  $I_{DS} = 100 \text{ mA}$ . Preliminary measurements determined that the 15 and 10 min. stabilization times are adequate.

A separate set of measurements were made on a similar test setup, but with a thermocouple placed in contact with an unbiased SiC MESFET. The heater temperature was set and the system allowed to stabilize for 15 min. Then, thermocouples on the Ta sheet and the SiC MESFET were compared. Across the entire temperature range, the two thermocouples agreed to within  $10 \text{ }^\circ\text{C}$ . This indicates that thermal radiation and conduction from the ceramic heater is sufficient to raise the SiC MESFET to the same temperature as the Ta carrier, so that the presented thermocouple temperature may be considered as the ambient temperature,  $T_A$ .

### III. MEASURED RESULTS

Figure 2 shows the Raman spectra for four ambient temperatures with no DC bias applied to the MESFET. It is seen that the SiC TO line shifts to lower wave numbers and the peak Full Width to Half Maximum (FWHM) increases as the ambient temperature increases. Figure 3 shows the calibration curve based on the Raman spectra with no DC bias.

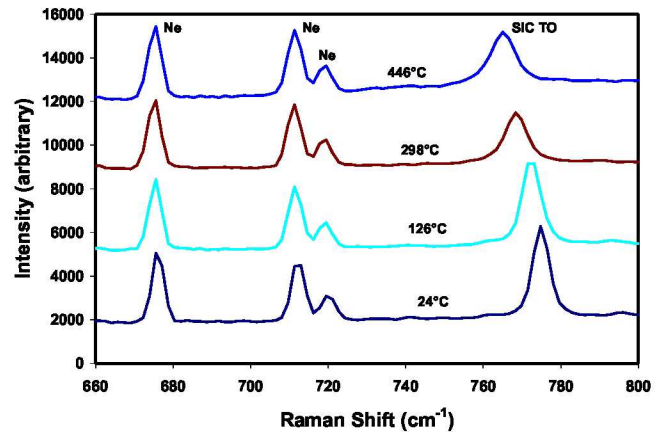


Fig. 2: Raman spectra for SiC MESFET channel with no DC current applied to the transistor.

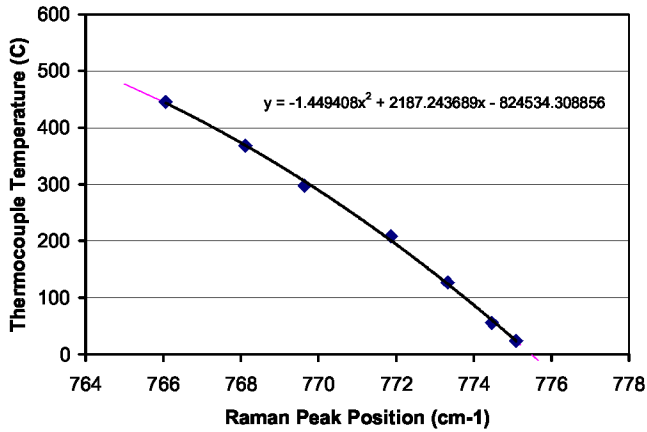


Fig. 3: Raman spectra calibration curve. Symbols are experimental data and line is curve fit.

When the MESFET is biased with  $V_{DS}=10$  V and  $I_{DS}=50$  and 100 mA (DC power of 500 and 1000 mW), the temperature of the Ta metal sheet measured by the thermocouple increases due to heat generated by the MESFET. With the ceramic heater at room temperature, the Ta metal sheet increases to 42 and 60 °C for DC power of 500 and 1000 mW, respectively. As the ceramic heater temperature is increased so that Ta metal sheet is 450 °C with no MESFET bias, the increase in temperature due to transistor self-heating is less than 5 °C. In all results reported, the ambient temperature,  $T_A$ , is the thermocouple temperature before DC power is applied to the MESFET.

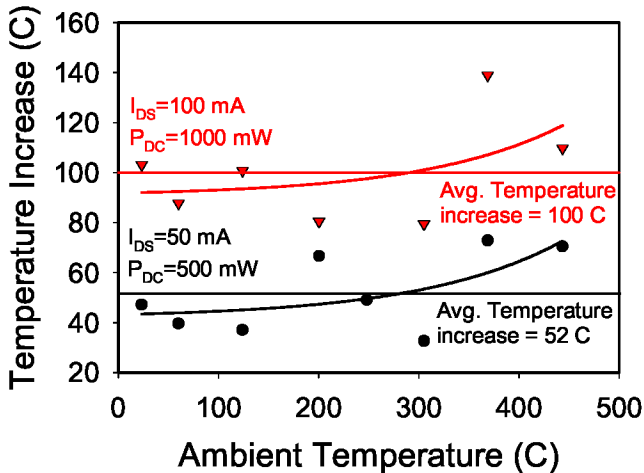


Fig. 4: Measured increase in the channel temperature as a function of the ambient temperature and applied DC power.

Figure 4 shows the measured increase in the channel or junction temperature compared to the ambient temperature ( $\Delta T_j = T_j - T_A$ ) as a function of the thermocouple temperature,  $T_A$ , and DC power. The average temperature increase is 52 and 100 °C for the transistor bias powers of 500 and 1000 mW, respectively. Note that the increase in temperature is close to the expected factor of 2 caused by a doubling of the DC power. An additional, non-physical curve fit equation has

been added to Fig. 4 that better approximates the measured data:

$$\Delta T_j(P_{DC}) = T_0(P_{DC}) + ae^{bT_A} \quad (1)$$

where  $T_0$  is a constant temperature increase dependent on the DC power,  $a$  and  $b$  are fitting parameters, and  $T_A$  is the ambient or carrier temperature in °C.  $T_0$  is 41.9 and 90.7 °C for DC power of 500 and 1000 mW, respectively. Fitting parameters  $a$  and  $b$  are approximately equal for both DC power curves;  $a \approx 1.245$  and  $b \approx 7.143 \cdot 10^{-3}/^\circ\text{C}$ . Thus, it is found that the increase in channel temperature is directly dependent on the transistor bias DC power, but the variation in junction temperature with ambient temperature is not strongly dependent on DC power.

#### IV. DISCUSSION

Wireless sensors for aircraft engines, Venus science missions, automobile engines, and mining and drilling bits requires the RF circuits to operate at high ambient temperatures. While the circuit designer can back off on the recommended bias conditions to minimize the increase in the MESFET junction temperature, there is a trade off with lower current and RF power gain. The  $V_{DS}$  used in this paper is close to the minimum that can be used because the transistor knee voltage is close to 5 V at the 100 mA  $I_{DS}$  [5] at room temperature. Throughout the tests, the gate current was zero until the ambient temperature approached 400 °C, at which point it increased to 3 mA. Higher temperatures caused the current to increase further and the tests were terminated.

If the ambient temperature is 500 °C and the DC power is 1000 mW, the predicted channel temperature from (1) is 635 °C. Using the published Arrhenius plot for the CRF24010 MESFET [7], the predicted MTTF is 15 hours. If the DC power is reduced to 500 mW, the predicted channel temperature is 586 °C and the MTTF is 28 hours. Unfortunately, these MTTF values are too low for most applications. For a MTTF of 1000 hours, which is considered to be the minimum for the aircraft engine application, the ambient temperature cannot be higher than 300 °C with 1000 mW DC power. Furthermore, it is not clear if the Arrhenius plot is valid at these channel temperatures because the reported maximum temperature used to derive it is 410 °C, and gate diffusion was not seen through 410 °C, which may occur at higher junction temperatures.

#### V. Conclusion

This paper presented the measured junction temperature of a SiC MESFET over a wide range of ambient temperatures. It is shown that the increase in junction temperature is directly related to the applied DC power, but that the variation with ambient temperature is not strongly dependent on the DC power. Further measurements are required to confirm these results and to determine the equation for predicting the increase in temperature as a function of the ambient temperature and DC power. For the additional measurements,

a smaller spot size and a method of focusing with the distortions caused by thermal convection are required.

#### ACKNOWLEDGEMENT

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