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Thermal Imaging of Power MOSFETs under Thermal Runaway Conditions

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Abstract

The Metal Oxide Semiconductor Field Effect Transistor (MOSFET) has become one of the world's most manufactured items, but with success and the drive to make a better part come new problems. Whereas older power MOSFETs would share internal power, newer MOSFETs grab the current, causing thermal runaway. Using a thermal camera and an oscilloscope to look at the voltage and current internal to the MOSFET, we can gain an understanding of how a hot spot develops on the surface of the MOSFET. We have used thermal imaging in an attempt to understand the problem so that better predictions could be made as to when the problem will occur.

Introduction

The National Aeronautics and Space Administration's (NASA's) Goddard Space Flight Center (GSFC) became aware of the thermal runaway problem in October 2008 when a protection circuit design failed. Thinking that the failure was due to a test setup problem, the Metal Oxide Semiconductor Field Effect Transistor (MOSFET) was replaced. However, when a new test was run, it also failed within a few seconds. An independent expert was called in and the thermal runaway problem was quickly identified. Interestingly enough, while the problem had been around for years, and was in some areas a known issue, the manufacturer's Safe Operating Area Charts and application notes did not mention the problem or the associated cause.

An IEEE paper by P. Spirito gave the physics and math behind the problem. GSFC, in an attempt to better understand the thermal runaway problem, carried out further testing in order to develop a set of non-destructive tests. Figure 1 shows a microscopic image of a MOSFET that had failed from the thermal runaway problem. It also shows an image from a scanning electron microscope (SEM) of the same area. Note that the SEM shows a smaller area of destruction.

It has been argued in Wikipedia that the modern MOSFET is the most manufactured item in the history of mankind. Its function is as a simple electrical switch and as a voltage controller. As a switch, it is the fundamental building block for electronic logic gates, which in turn are the building blocks for the modern computer. The MOSFET can also be used to store information in the form of "on" or "off", better known as 1's and 0's. A single storage bit is one MOSFET, and a contemporary memory stick contains more than 1,000,000,000 (1 billion) individual MOSFETs. The second area where a MOSFET is used is in the control of voltages where a device starts with one voltage and a second lower voltage is required.

Thermal problems arise inside of the MOSFET because –the MOSFET consumes power. When the MOSFET is used as a voltage controller, it transforms the power it consumes into heat; the MOSFET consumes the

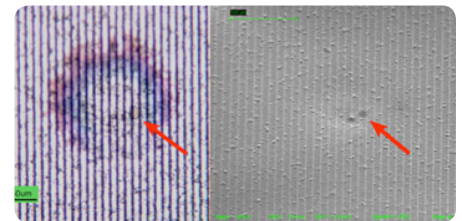


Figure 1. Microscope and Scanning Electron Microscope image of failed MOSFET. Background into the Thermal Runaway Effect of a Metal Oxide Semiconductor Field Effect Transistor.

extra power and transforms it into heat. The standard formula for power would apply and is:

$$P = IV$$

Equation 1.

Where I is the current through the MOSFET and V is the voltage. When the MOSFET is used as a switch, it loses power in two ways. First, through resistive losses when the switch is turned on as expressed by the following formula:

$$P_1 = I^2 R_{on} D$$

Equation 2.

Where R_{on} is the on-resistance, and D is the Duty Cycle On Time divided by the Cycle Time.

The second instance in which a MOSFET may lose power occurs during its transition from fully off to fully on as expressed by the following equation:

$$P_2 = IVT_r f$$

Equation 3.

where T_r is the time to turn on and f is the switching frequency.

Thus, combined power losses are:

$$P_T = I^2 R_{on} D + IVT_r f$$

Equation 4.

The final part of the thermal problem is in how much power is in a given area and is referred to as power density or watt density. Power can be dissipated with little temperature change given a large enough area, and as the area goes down, the temperature will go up. An example of power density is seen in figure 2, which shows a set of 39 ohm resistors in parallel with one another. The voltage is the same across all of the resistors, and the power in each resistor is 0.4 watts.

When a MOSFET is used as a switch, as is most typical, the heat inside of the part is the limiting factor for how fast the part can be used. It is possible to reduce the heat internal to a MOSFET by increasing the size of the part, or by cooling the part. In many cases, cooling is not practical, or only partially useful. So to keep a MOSFET from overheating, only items found in equation 4 can be varied.

In the development of the electronic computer, manufacturers have done a remarkable job of increasing the speed and lowering power requirements of the computer. The market has driven the need for faster (SF Hz), smaller, more efficient parts, and the pressure continues to maintain this trend. While manufacturing has reduced the size of the parts and increased the switching speed of the MOSFETs, the quest for speed and size continues.

While a computer needs only one MOSFET per memory bit, we now expect billions of bits of memory in a small computer. The modern power MOSFET may still be used as a single part that has many smaller MOSFETs tied in parallel internally. The number of single MOSFETs inside of a power MOSFET is now around 100,000,000 (100 million) per square inch. By increasing the total number of MOSFETs, the "On" resistance is effectively lowered.

Unfortunately, the market demand for faster, smaller, more efficient parts is plagued by fact that small, fast parts tend to run hot, reducing efficiency. In the race to manufacture "better" power MOSFETs, parts manufacturers have exhausted simple modifications quite quickly. Newer modifications have come at a price, and tradeoffs have been made that have contributed to failure rate.

MOSFETs designed up until 1997 were designed as mobility-dominant

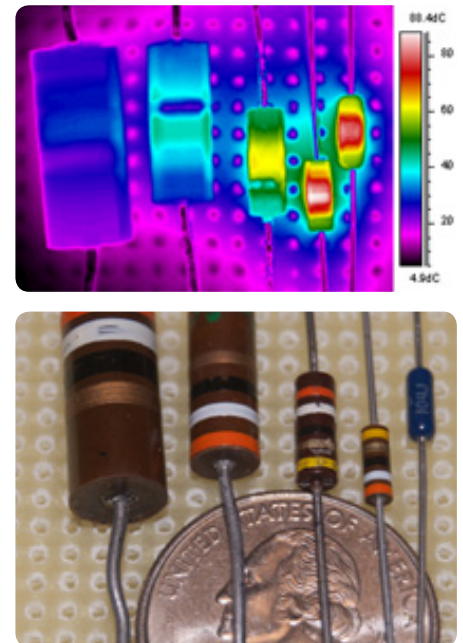


Figure 2. Thermal and visible image of five 39 ohm resistors with 0.4 watts of power in each resistor. Emissivity of resistors is 0.95 with the exception of "Gold" bands. (The emissivity of gold bands is unknown.) The thermal image has the background temperatures subtracted to indicate a delta temperature.

carriers where the flow of electrons was limited as the temperature of the device went up. The effect was to force current away from the hottest cells and into the cooler cells and is a form of negative feedback. This effect was true if the MOSFET was used as a switch or as a voltage controller.

After 1997, MOSFET designs began to change as the push for faster switching forced the manufacturers to go to a design using a charge-dominant carrier. These newer designs allow for faster switching and lower ON-resistance. The design is not a problem when the MOSFET is used as a switch—the most common usage. However, when they are used as voltage controllers, the trade-offs quickly become apparent. Charge-dominant carriers allow more current to flow as the temperature goes up. The hotter an area gets, the more current that wants to flow in the hot region. This is a positive feedback situation, and the current quickly becomes out of control. While the power MOSFET may have 25,000,000 (25 million) individual cells internal to the part, it only takes one cell to fail for the part to fail.

Work on the problem was done and an IEEE paper was produced by Spirito et al [1].

Looking Into the Thermal Runaway Problem

After the first few readings of the Spirito paper, it was determined that testing was necessary to better understand what was being said. The formulas under investigation were:

$$\alpha = \frac{dI_d}{dT}$$

Equation 5.

$$\beta = \frac{dI_d^2}{dT^2}$$

Equation 6.

$$\Delta_T = \frac{R_T V_{ds} I_d}{1 - R_T V_{ds} \alpha} + \frac{\beta}{I_d} \left(\frac{R_T V_{ds} I_d}{1 - R_T V_{ds} \alpha} \right)^3$$

Equation 7.

It was determined that a commercial MOSFET would be used because of the price and availability of the parts. As it happened, GSFC's Power Branch, Code 563, had a small stock of IRF2910 power MOSFETs in hand, so they were chosen for the testing. The IRF2910 part is in a plastic case, and it was necessary to remove the plastic so that the MOSFET could be viewed during the testing. The MOSFET part is based on silicon, and as such has a very low emissivity when viewed in the IR. In order to see the thermal image of the MOSFET, a fine layer of talc was applied.

Points to be monitored using an oscilloscope (Agilent Infiniium 54832B) during the test were:

1. Voltage across the MOSFET "Drain to Source" (Vds)
2. Current through the MOSFET (Ids)
3. Control Voltage (Vgs)
4. Reverse Voltage "Source to Drain" (-Vds)

In addition to the electrical parameters, a thermal image was also needed. The thermal images were taken with a FLIR ThermaCAM S-60 camera, set to a rate of 60 frames per second.

The circuit used to test the MOSFET was designed to handle high current pulses and had a second MOSFET as a power switch ahead of the part under test. Two voltages were required to run a single test. The first voltage was the voltage placed across the MOSFET from "Drain to Source" (Vds), the second voltage was applied onto the controlling "Gate" pin (Vgs). When the test circuit was activated, the switching MOSFET was fully turned



Figure 3 Test MOSFET with burned spot. Plastic casing has been etched away to reveal MOSFET die, and lead wires.

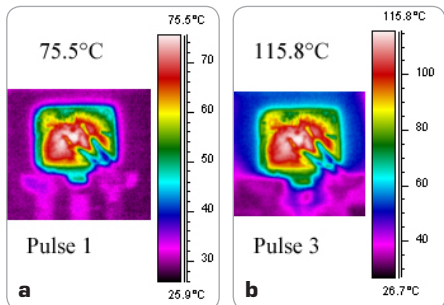


Figure 4 A, B, C, D Thermal images of MOSFET under test. ($V_{ds} = 20$ Volts, $V_{gs} = 2.35$ Volts). Images show hottest frame for each 100 millisecond pulse. The pulses were 2 seconds apart. There were 10 pulses total. Images shown are A. Pulse 1 at 75.5°C, B. Pulse 3 at 115.8°C, C. Pulse 6 at 187.0°C, and D. Pulse 9 at 254.3°C. Emissivity of MOSFET = 0.95.

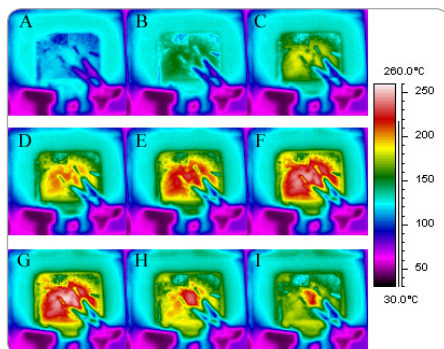


Figure 5 A, B, C, D, E, F, G, H, I. Sequence of thermal images of a MOSFET under test during a single pulse. Images are 16 milliseconds apart. Test voltages were: $V_{ds} = 20$ Volts, $V_{gs} = 2.35$ Volts. Emissivity of MOSFET = 0.95

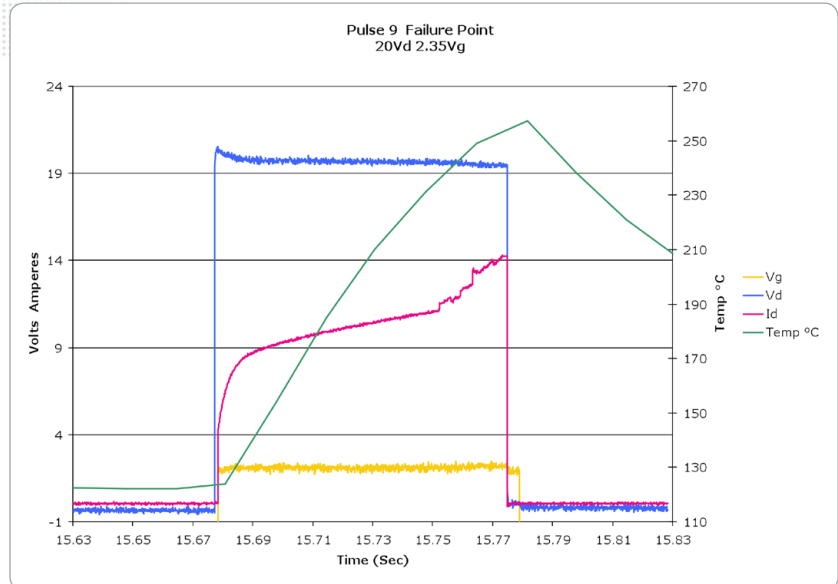


Figure 6 Plots are a combination of the oscilloscope data and the thermal data. V_{ds} is Blue, V_{gs} is Yellow, I_d is Pink, Temp °C is Green. Note that at time 15.75 the current becomes unstable, i.e. loss of control and loss of MOSFET.

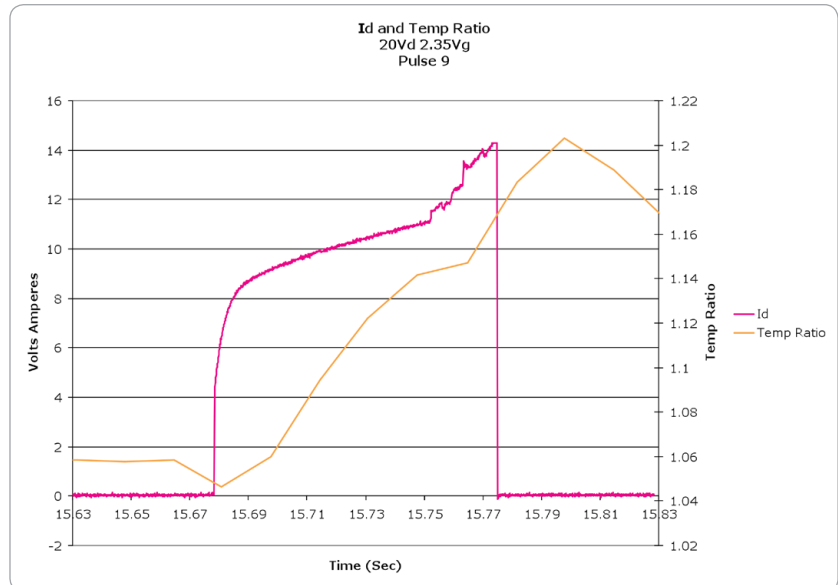


Figure 7 Plots are a combination of the oscilloscope data and the thermal data. I_d is Pink, Temp Ratio from hot spot to cold spot on MOSFET.

on one millisecond before the test unit was turned on so that the voltage would be present during the test pulse. At the end of the test pulse, the switch MOSFET was turned off first, and then the test unit's gate voltage was turned off. The reason for the switch pulse was to be able to apply a negative voltage across the test MOSFET in the hopes of determining its temperature through the use of the intrinsic diodes in the MOSFET.

The test was set up to pulse the MOSFET for 100 milliseconds on and 2 seconds off for 10 full cycles.

Data recording began by initializing the oscilloscope, starting the thermal camera including the Researcher software, and then turning on the test circuit. Each test ran for 23 seconds, with the oscilloscope generating 100 million bits of data with 1.2 million data points per test point and the thermal software generating 230 million bits of data with 1380 frames of data. Both data sets included time tags.

Although a single test run lasted for only 23 seconds, many hours were spent analyzing the results. Each run generated upwards of 50 graphs examining each pulse for thermal rise times, current changes as the temperature changed, and changes in the thermal gradient. Below are selected images and graphs from the testing.

Conclusions

- 1 Among the early questions was "what would generate a thermal runaway faster?" Was a part more likely to have a runaway if it started out cold or if it started out hot? While the gain of the MOSFETs is higher at lower temperatures, the lack of headroom became the dominant factor, so a hot MOSFET is more prone to a thermal runaway event than a cold one.
2. The use of the intrinsic diode internal to the MOSFET as a temperature monitor was only partly useful. The method was very accurate if the MOSFET was isothermal, but when a hotspot occurred the diodes indicated a temperature higher than the bulk temperature, but lower than the hot spot's temperature.
3. Advanced prediction of where a hot spot will occur within the group of cells is elusive. Prediction of when a hot spot will occur was consistent with the models developed by P. Spirito. Alpha was consistent over temperature and was easily derived from the thermal data.

Acronym List

α	= Alpha or Change in Current / Change in Temperature or $\delta I / \delta T$
β	= Beta or Change in Current Squared / Change squared in Temperature or $\delta I^2 / \delta T$
ΔT	= Change in Temperature
D	= Duty Cycle On Time / Cycle Time
f	= Frequency (Hertz)
GSFC	= Goddard Space Flight Center
I	= Current (Amperes)
I _d	= Drain Current
IEEE	= Institute of Electrical and Electronics Engineers
MOSFET	= Metal Oxide Semiconductor Field Effect Transistor
NASA	= The National Air and Space Administration's
P	= Power (watts)
R _{on}	= Resistance of MOSFET when it is ON (Ohms)
R _t	= Thermal Resistance
SEM	= Scanning Electron Microscope

Trt = MOSFET Rise Time time from off to on (Seconds)
V = Volt
Vds = Voltage drain to source
Vgs = Voltage Gate to Source

References

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