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Characterization of power MOSFET bipolar switches at high temperature

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Abstract

The power MOSFET analog switch is a bipolar switch often used in solid state relays. The circuit consists of two power MOSFETs connected gate to gate and source to source. The gate and source terminals float and are driven through a transformer or photodiode isolation circuit. The circuit conducts drain-to-drain through the MOSFETs when the switch is turned on. This paper will characterize the performance of such analog switches at temperatures up to 220 °C. As temperature increases, the threshold voltage of the switch decreases, its leakage current increases, and its on resistance increases. In the off state, the switch experiences problems at high temperature with high dV/dt signals. When high speed signals cross through zero volts, one of the FETs latches temporarily and conducts a current spike through the switch. This paper will present a simple model of switch behavior as a function of temperature and will compare that model to experimental measurements.

Keywords: analog switch, high temperature electronics, power MOSFET, solid state relay

1.0 Introduction

Typically, in open hole well logging, logging while drilling (LWD), and measurement while drilling (MWD) applications, engineers are limited to adapting commercial electronic parts to high temperature environments. Such environments range in temperature from 150 °C to 200 °C. Such temperatures are beyond the performance limits of manufacturer's specifications, so the engineer is required to test the performance of any selected electronic parts to the upper limit of the temperature range of the tool that is being designed. Such test results are rarely published. Because of this, engineers are often in the dark about expected performance of many common circuits at temperatures beyond manufacturer's specifications.

That situation is particularly true of circuits that use power MOSFETs. There are a few MOSFETs that are specified for operation at junction temperatures up to 175 °C., but there are no silicon power MOSFETs available with temperature specifications up to 200 °C and beyond. Honeywell has an SOI power MOSFET that is commercially available [1], but cost is prohibitive and the current carrying capacity and maximum drain to source voltage is limited in that device. There is some information on using commercial power MOSFETs up to 200 °C from Johnson, *et al* [2]. Additionally, switching performance of sampled commercial power MOSFETs up to 300 °C has been reported by Habchi, *et al* [3].

When using power MOSFETs, there are several operational limits that must be considered. MOSFETs have a positive temperature coefficient of on resistance, a condition, often touted in manufacturer's literature, that aids design in parallel operation of MOSFET switches. When operated as linear devices, however, MOSFETs can develop thermal runaway phenomena, similar to second breakdown in bipolar devices [3]. Further, parallel operation of MOSFET switches can lead to current hogging phenomena because of variations of the negative temperature coefficient of MOSFET

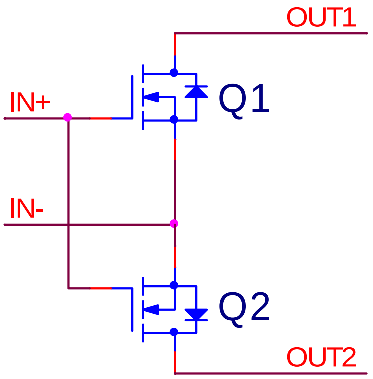

Figure 1. MOSFET bipolar switch

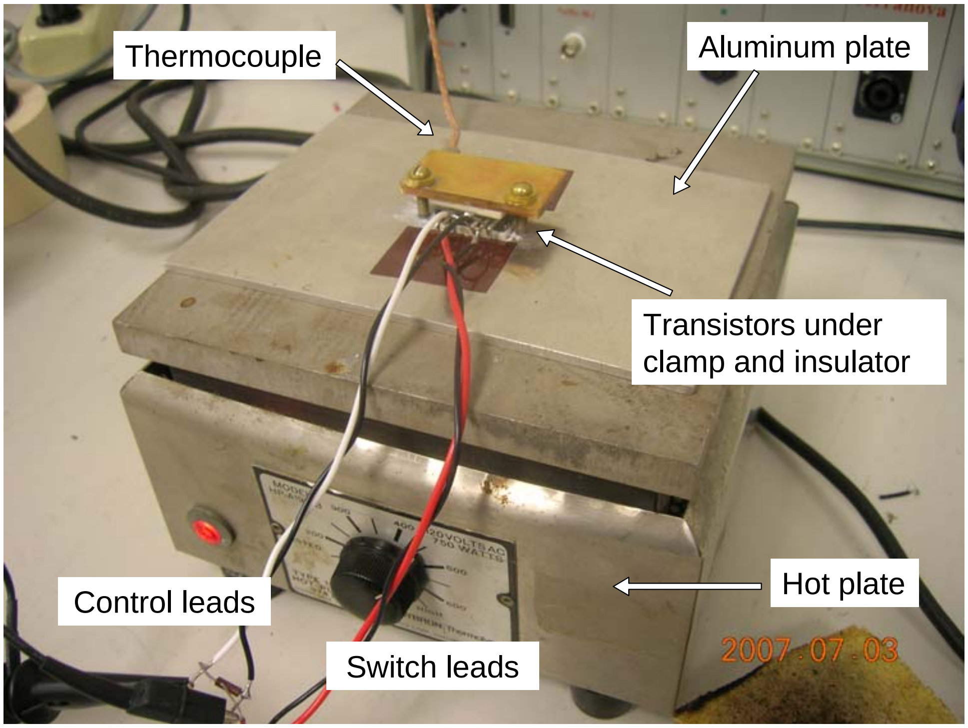

Figure 2. Hotplate setup for experimental measurements

threshold voltage [4].

Another limitation of power MOSFETs is dV/dt induced latchup of the parasitic bipolar transistor in the vertical MOSFET structure. High dV/dt from drain to source may cause sufficient voltage drop across the base resistance of the parasitic transistor to turn it on, resulting in on-state latchup [6]. While the manufacturer typically supplies a specification for maximum drain to source dV/dt, the limitations of dV/dt beyond the device's maximum temperature specification are not well defined.

One of the most useful circuits for downhole electronics is the high voltage bipolar analog switch, commonly referred to as the 'solid state relay.' This circuit is built by connecting two power MOSFETs source to source and gate to gate. The MOSFETs are turned on by using a floating drive from gate to source, and switch current is conducted from drain to drain. See Figure 1. This circuit can be used in many applications, such as switching AC power to motors and actuators, or in active damping circuits of sensor antennas.

This paper reports on experiments conducted to test operation of the switch circuit at temperatures up to 220 °C. The experiments focus particularly on the effect of temperature on dV/dt limits. The experiments were conducted using several types of power transistors rated at 1000 volts maximum drain to source voltage, and maximum drain current of about 4 to 10 amps. The intended application of the switch circuit was in a transmit-receive switch of a sensor antenna.

The results of the experiment show that up to 220 °C, the individual transistors have leakage currents that double every 15 °C, MOSFET threshold voltage changes at about -7.7 mV per °C, and on resistance increases at a rate of about 11 mΩ per °C. When the switch was turned off and its output terminals submitted to a high dV/dt voltage, the switch conducts transient currents which worsen with increasing temperature. At temperatures approaching 200 °C, the switch exhibits a transient latching phenomenon which has deleterious effects in the application circuit.

2.0 Hotplate experiments.

A hot plate was used to heat the transistors for testing. The transistors comprising the switch were clamped to a ¼ inch aluminum plate which was heated by the hot plate. A thermocouple was attached to the hot plate to monitor temperature. An electrically insulating, but thermally conducting ceramic spacer was sandwiched between the transistors and the aluminum plate. The experiments that were conducted did not dissipate appreciable power in the transistors. Because of this, it was assumed that the

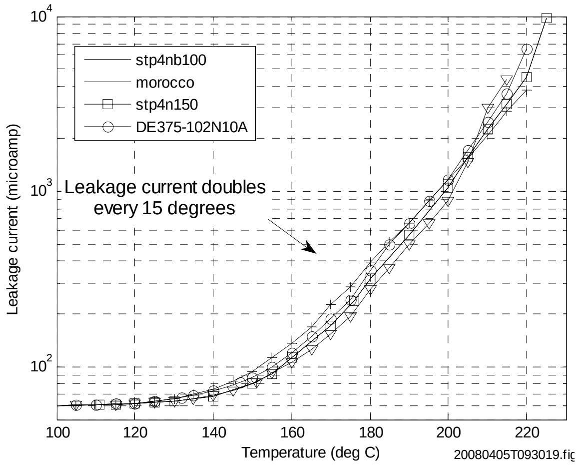

Figure 3. Leakage current of MOSFETs as a function of temperature.

transistors' junction temperature was the same as the measured temperature of the aluminum plate. Figure 2 shows a photo of the hot plate experiments.

Four different N-channel transistors were tested as candidates for use in the application:

- STP4Nb100, 1000 volt, 3.8 amps, 4Ω
- STP4Nb100 from a lot marked by the manufacturer as "Made in Morroco".
- STP4N150, 1500 volt, 4 amp, 5Ω
- DE375-102N02A, 1000 volt, 10 amp, 7.8Ω

The maximum specified drain source voltage, drain current, and on resistance are noted.

3.0 Leakage current.

Figure 3 shows the leakage current for four different transistor parts. As shown in the plot, the leakage current in these transistors follows the same general curve over the range of temperatures in the experiment. The maximum temperature produced by the hot plate is about 220 °C. Leakage current remains close to leakage current at room temperature until the junction temperature reaches about 120 °C. After this the leakage current doubles about every 15 degrees, up to a value of about 10 mA at 220 degrees. Device leakage current will determine the leakage current of the switch. For this applications Figure 3 can be used to assess whether switch leakage will come within specifications at rated temperatures.

4.0 Threshold voltage.

In Figure 4, the dependence of threshold voltage on temperature is shown for a sample DE375-102N10A transistor. This curve is representative of the other transistors that were tested. The threshold voltage at 25 °C was 4.2 volts. Freeze spray was used on the aluminum plate to get a test temperature below 25 °C, as seen in the figure. The coefficient of threshold voltage variation with temperature is -7.7 mV per °C. This produced a 1.5 volt drop in threshold voltage from 25 °C to 220 °C.

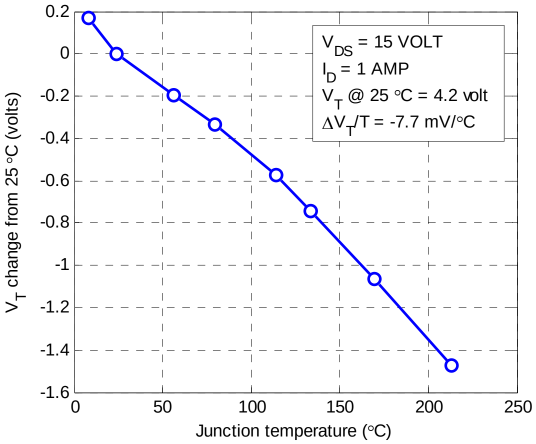

Figure 4. Variation of threshold voltage with temperature for DE375-102N10A.

As a design parameter, the threshold voltage must be taken into account when designing the switch driver. It is particularly important that when turning off the switch by lowering the gate source voltage on the transistors, the driver circuit must reliably reduce gate to source voltage below the threshold voltage that is expected at the maximum rated design temperature. Otherwise, there is a danger that the switch will not turn off when operated at high temperatures.

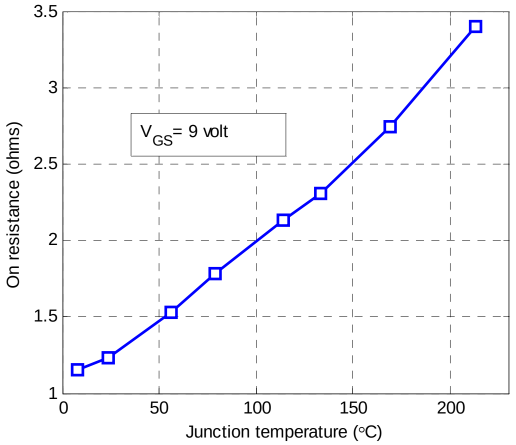

Figure 5. Variation of on resistance with temperature for DE375-102N10A.

5.0 On resistance.

The variation of on resistance of a DE375-102N10A is shown in Figure 5. As expected, the on resistance increases with temperature. The temperature coeffience of the on resistance is 11 mΩ per °C.

6.0 Dynamic off state operation transients

Figure 6 shows the test circuit for testing dynamic operation of the switch in its off state. At the control input to the switch, a 50 ohm resistor ties the gates to the sources of the transistors, turning the transistors off. A signal generator with a 50 ohm output impedance is used to drive the output of the switch. This drive voltage is a square wave which ranges from -20 volts to 20 volts, with transition dV/dt of 1.4 volt per ns when unloaded.

Figure 7 shows the response of the switch in the off state, using STP4NB100 transistors. Plot A shows the response to a rising signal at 25 °C. The 10 to 90 percent transition time is 21 ns. Plot B shows the response to a rising signal at 185 °C. Note that the initial rise of the signal remains similar to the 25 °C waveform, but as the signal approaches its final maximum value, the approach is slowed considerably. The transition time is 40 ns, twice the value for 25 °C. Plot C shows the response of the switch to a rising signal at 205 °C. There is a significant 'tail' that occurs in the signal after it passes through zero volts. This tail extends the transit time of the signal to 147 ns. Plot D shows the response to a falling signal for the switch. In this case there is a plateau in the signal near the transition through zero volts, and the transition time is extended to 202 ns. For the transistors tested, this plateau typically occurs when the switch is operated above 200 °C, and can occur for both rising and falling signals. It indicates that the parasitic NPN transistor in one of the MOSFETs is being activated during signal transition.

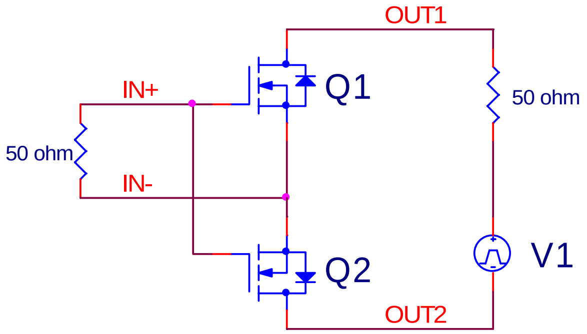

Figure 6. Test circuit of dynamic off state response.

In the off state, and for slow signals, the switch can be modeled as a pair of back to back body diodes, as shown in Figure 8. For fast signals it is useful to model the back to back diodes as parasitic NPN transistors as was explained by Barkhordarian [6]. This model is shown in Figure 9. Normally, the base resistance, Rbase, is very small, so the base emitter junction is effectively shorted and the transistor base collector junction appears as a simple body diode. During high dV/dt conditions, however, the body capacitance, Cbody, can conduct enough current to produce a sufficient drop across Rbase to turn on the parasitic NPN transistor. In many power MOSFET circuits this can lead to transistor latchup, leading to device failure.

For signals with low dV/dt, the following mechanism is postulated to explain the switch behavior shown in Figure 7. Assume that a falling signal is experienced by the switch. Before the transition, Q1's body diode

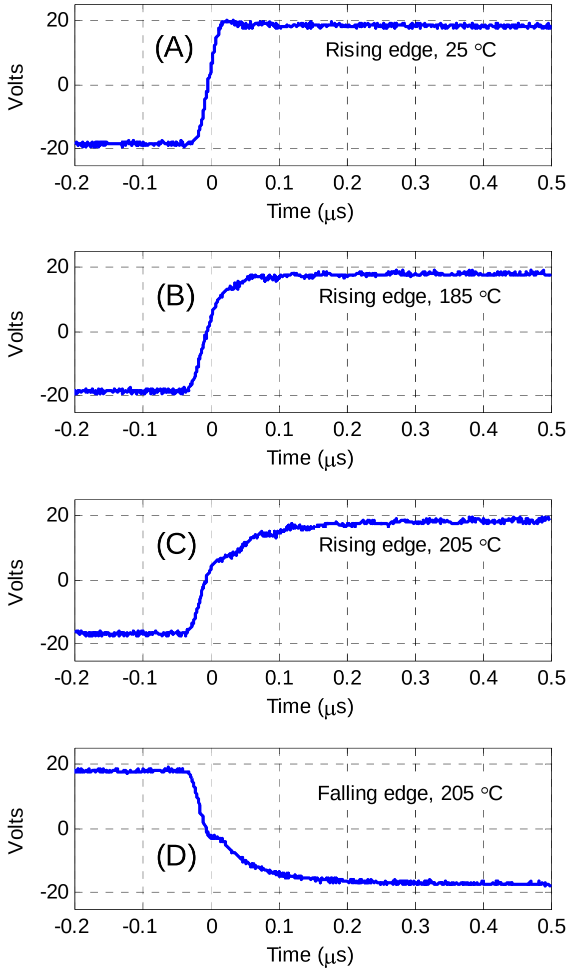

Figure 7. Dynamic response of switch in off state as a function of temperature.

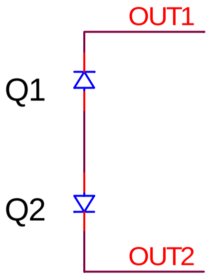

Figure 8. Model of switch in off state as back to back body diodes.

will be reversed biased, while Q2's body diode will be biased slightly below cut-in, holding some reverse recovery charge. At high voltage, the capacitance of Q1 is small, because of the non-linear characteristic of reversed biased junctions. As the signal voltage initially falls, the charge across Q1 is quickly removed, allowing the switch voltage to fall rapidly. As the voltage across Q1 approaches zero volts, however, the capacitance of Q1 increases, and the rate of charge removal declines. At close to zero volts across the switch, the reverse recovery charge on Q2 is moved to Q1 at a rate much slower than the initial discharge rate of Q1. This phenomenon accounts for the asymmetric charging curves noted in Figure 7. As reverse recovery charge increases with temperature, the asymmetry of transition also increases, as shown in Figure 7.

For signals with high dV/dT, it is possible that during movement of charge from Q2 to Q1 that the drop across the base resistance of Q2 is sufficient to turn on the Q2's parasitic NPN transistor. In this case, the switch voltage will be clamped briefly until charge transfer (current) declines, allowing the parasitic transistor to turn off. After that, the charge transfer continues normally. This sequence of phenomena can explain the plateau effect shown in Figure 7D.

7.0 Conclusion

As reported, the switch circuit experiences predictable increases in on resistance, increase in leakage current, and decrease in threshold voltage. However the dynamic behavior of the switch in the off state is difficult to model. The phenomenon may depend heavily on the amount of reverse recovery charge on the body diode, and on that charge's dependence on temperature. These are parameters that are not typically available from manufacturer's data sheets.

The transient phenomenon noted is important in some applications. As a transmit-receive switch, for example, the transient currents in the switch's off state may cause overloading or ringing at the receiver input, lengthening the receiver dead time, or possibly destroying the receiver input stage. There is a need to further investigate this phenomenon to develop modeling and design techniques to help avoid its occurrence.

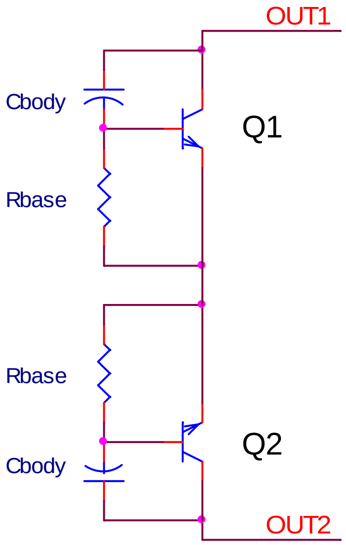

Figure 9. Off state switch showing parasitic bipolar transistors.

8.0 References

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