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Automotive MOSFETs in Linear Applications: Thermal Instability

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Automotive Power

Never stop thinking.

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1. Introduction

The choice of MOSFETs is important criteria for applications that use MOSFETs in linear mode operation. This application note is intended to provide an overview of the phenomenon of "hot spotting" under linear mode operation which can be found in automotive applications such as HVAC (Heating, Ventilation, and Air-Conditioning) and auxiliary heater diesel engine (pre-heater).

Figure 1 below, is a typical method of using a MOSFET in HVAC fan application. The MOSFET is used to linearly control the load like variable resistor for lower cost solution.

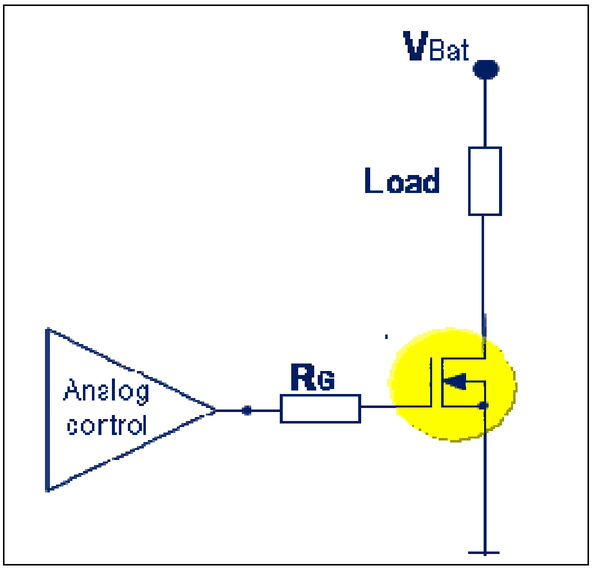

Figure 1. Pictorial diagram low side MOSFET for linear control of load

2. Power MOSFETs

Every new power MOSFETs generation have distinct advantages over previous MOSFET technologies. This has resulted in power MOSFETs that are able to achieve lower on-resistance, $R_{DS(on)}$, as well as lower gate charge, Q_g, performance when compared with older technologies. To improve the MOSFET on-resistance ($R_{DS(ON)}$), there are trade offs with the optimization of MOSFET geometry. One of the most significant consequence of improved on-resistance resides in the performance of Safe Operating Area (SOA).

Every power MOSFET is based upon a unit "cell" design structure. MOSFET geometries are specific to each manufacturer, but the MOSFET electrical operations are basically the same. Every MOSFET device is made up of millions of MOSFET "cells", which are electrically paralleled together. The greater the number of paralleled cells, the lower the device's on-resistance, $R_{DS(on)}$, and the greater the device's current carrying capability. $R_{DS(on)}$, is one of the most important factors for most of the power MOSFETs used today, in order to reduce conduction losses in the application.

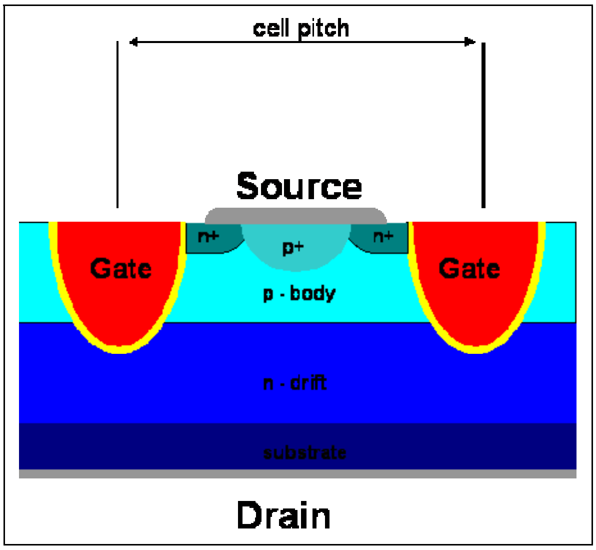

Figure 2. Pictorial Diagram of a Trench MOSFET

Figure 2 shows a simplified pictorial diagram of a trench N-channel power MOSFET. When applying a positive voltage to the MOSFET gate (the "P- body" region or "channel"), the channel is inverted and the current flows between the source and the drain. The more positive this gate voltage, the lower the device's on-resistance resulting in increased current flow. As a result the power MOSFET device makes an excellent semiconductor switch. When the MOSFET transitions through the linear mode of operation (see Figure 3), the gate voltages can be typically just above the threshold, $V_{GS(th)}$ value. While operating in this mode, the channel resistance will be much greater than the data sheet $R_{DS(on)}$ rating (usually rated at V_{GS}=10V) and the resulting drain voltage will modulate between the supply voltage and ground (see Figure 3).

Power MOSFET consists of millions of individual unit "cells" making up the total device structure. These unit "cells" are thermally coupled due to their physical proximity to each other. As a result, they tend to current share because as junction temperature increases so does $R_{DS(on)}$. As indicated previously, to decrease $R_{DS(on)}$ without increasing the die size, the physical distance (cell pitch) between adjacent MOSFET "cells" becomes smaller and smaller, allowing more and more active cells per unit area. The down side of "cell" densification is a phenomenon known as "hot spotting". As newer technologies are developed which increase the "cell" density, the "hot spotting" effect can occur at both lower drain voltages and possible through switching transitions than previous MOSFET generation.

The MOSFET positive temperature coefficient does not represent all the factors that contribute to a stable thermal operation. Using MOSFET manufacturer's latest technology of power MOSFETs exhibit higher current densities in order to decrease $R_{DS(on)}$ over previous generations. To achieve these higher current densities the MOSFET will have a higher gain (transconductance - g_{fs}). The MOSFETS transconductance can be defined as follows [1]:

$$g_{fs} = \left[\frac{\partial I_D}{\partial V_{GS}} \right]_{VDS=constant}$$

A MOSFET that has a higher transconductance will have a higher current handling capability at lower gate source voltages and thus a higher zero temperature coefficient point (see Figure 4) on the device transfer curve [2]. While the higher zero temperature coefficient can often be neglected when the applied gate voltage far exceeds the device threshold voltage. This can not be neglected for applications that fall within the "linear mode" of operation as in Figure 3. The circuit designer must give some attention to selection of the MOSFET when operating in this area.

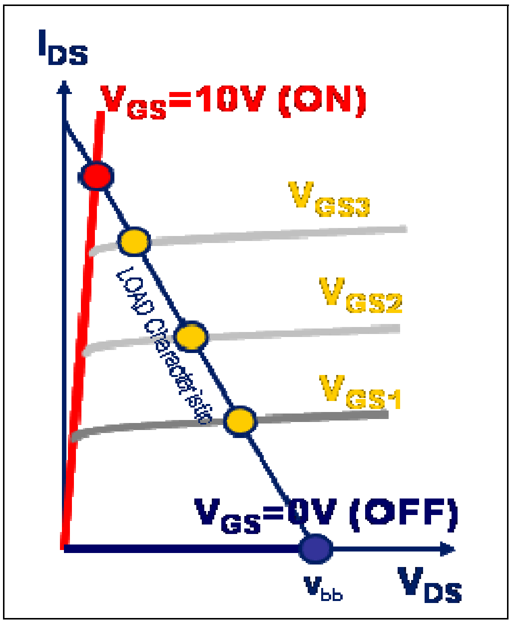

Figure 3. MOSFET operation through linear mode operation.

3. MOSFET Thermal Instability

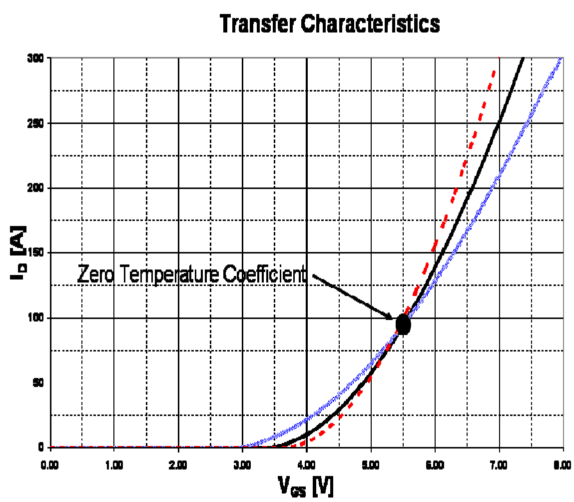

Figure 4. Typical MOSFET transfer characteristic curves over temperature.

Figure 4 above, shows a MOSFET transfer curves where drain current, I_D, is a function of gate voltage, V_{GS}, at fixed junction temperatures. The "zero temperature coefficient" is the point where the temperature lines intersect. Another way to depict the "zero temperature coefficient" is to take the $\Delta Id / \Delta T = \alpha$, where α is defined as the drain current temperature coefficient[2].

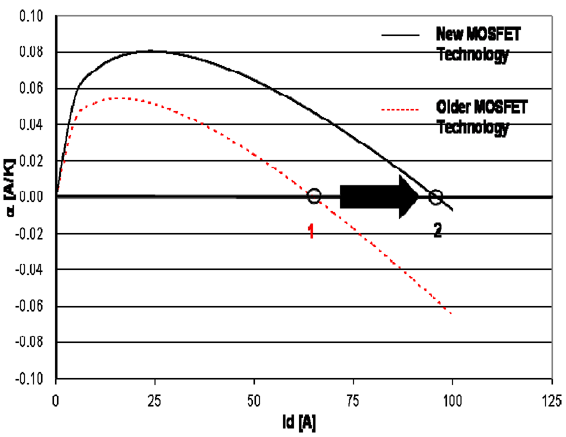

Figure 5. ΔId/ΔT versus Id for new versus old MOSFET technology

α is the drain current temperature coefficient which is the result of several competing effects:

\+ Positive temperature, which has a dependence of carrier generation

\- Negative temperature, which has a dependence of carrier mobility

For $\alpha > 0$ a hotter "cell" will carry **more** current and get even hotter which can possible lead to thermal runaway

For $\alpha < 0$ a hotter "cell" will carry **less** current and is cooler, which leads to thermal stabilisation.

The SOA graph from SPP_B_I80N06S-08 data sheet describes the boundary conditions of safe operation. Between the boundary conditions exists a set of sloping lines that show SOA limitations as a function of a time. These lines are "constant" power lines representing the power it takes to raise the device junction temperature to maximum rated junction temperature (175°C) while maintaining a constant 25°C case temperature (ideal cooling). The constant power lines are derived directly from the MOSFET transient thermal impedance curve.

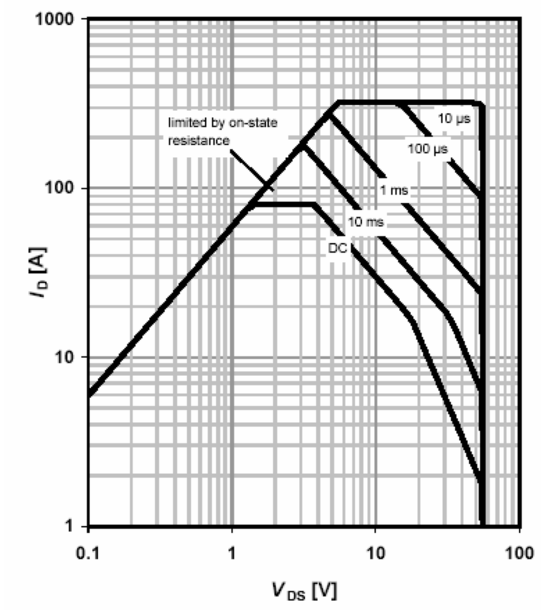

Figure 6. SOA of SPP_B_I80N06S-08 data sheet

Hot spot generation within the MOSFET die can happen below the zero temperature coefficient point (when $\alpha > 0$, see Figure 5) and when the temperature distribution across the die is not uniform. Unfortunately, temperature distribution across the die is never uniform under bias. Even with a perfectly mounted die that has no solder voids or any other other manufacturer imperfections, the die will always be warmer in the center than around the edges.

Hot spotting can begin with a constant V_{GS} across the die and a small group of cells that are hotter than their neighbors. Below the zero temperature coefficient point these cells due the transfer characteristic begin to take more current compared with other cells. This will further increase the temperature. As shown in Figure 5, this mechanism is regenerative and has the potential of leading to intrinsic thermal runaway within the MOSFET. Thus, under the right combination of conditions a catastrophic device failure can result. Hot spotting can possible occur due to imperfections in the die attach process (voids) or voids degradation over device lifetime. This local area void can produce hotter cells than other neighboring cells. Which can lead to theses hotter cells to take more current compared to its neighbors and thus further increases its temperature until possible failure.

4. Conclusion

There are four points which can influence a MOSFET's susceptibility to the hot spotting phenomenon.

1. MOSFET cell density: As the cell density of the MOSFET is increased the thermal coupling between adjacent cells is increased.
2. MOSFET transconductance gain (*gfs*): The higher the device's gain, gfs, the higher the current intersection point on the transfer curve (see Figure 4)
3. Drain voltage: The higher the drain-source voltage while the MOSFET is its "linear mode of operation", the greater the susceptibility for hot spotting.
4. Time: The longer the MOSFET operating within an area of potential hot spotting (linear mode of operation), the higher the probability of hot spotting will likely occur.

Infineon has chosen to modify the SOA graphs on certain automotive qualified MOSFETS and eliminate suspect constant power lines. Some SOA graphs have a dual slope in the region of hot spotting thereby acknowledging and demonstrating the device's SOA constraints. In general, hot spotting should not a problem when a MOSFET is switched full "on," quickly.

Reference

[1] Ducan A. Grant and John Gowar, "*Power MOSFETS Theory and Applications"*, John Wiley & Sons Publications, 1989.

[2] P. Spirito, G. Breglio, V. d'Alessandro, N. Rinaldi, "Thermal Instabilities in high Current Power MOS Devices: Experimental Evidence, Electro-thermal Simulations and Analytical Modeling", MIEL 2002, 23rd International Conference on Microelectronics, Vol. 1, May 12-15, 2002, pp. 23-30.

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