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Current sensing power MOSFETS

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Document information

Info	Content
Keywords	Current sensing, PowerMOS, senseFET, sense ratio, sense resistor, virtual earth
Abstract	Current sensing power MOSFETs provide an effective means of protecting automotive electronic circuits from overcurrent conditions. This application note describes the principles of operation using virtual earth current sensing and sense resistor current sensing techniques.

founded by Philips

Revision history

Rev	Date	Description
02	20090624	Updated to meet NXP Semiconductors house style and rewritten.
01	20040909	Initial version

Contact information

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1. Introduction

Current sensing power MOSFETs provide an effective means of protecting automotive electronic circuits from overcurrent conditions. They offer a low loss method of measuring the load current, eliminating the need for a current shunt resistor.

NXP Semiconductors has developed a range of current senseFET products to address the requirements of the automotive market as shown in Table 1. All devices are based on low R_{DSon} TrenchMOS PowerMOS technology.

Table 1. NXP senseFET range

Device	Maximum R_{DSon} (mΩ)	Sense ratio
BUK7105-40AIE	5	500:1
BUK7905-40AI	5	
BUK7C06-40AITE	6	
BUK7108-40AIE	8	
BUK7107-55AIE	7	
BUK7C08-55AITE	8	
BUK7109-75AIE	9	
BUK7C10-75AITE	10	

2. Principle of operation

Current senseFET technology depends on the close matching of transistor cells within the PowerMOS. A TrenchMOS device comprises many thousands of transistor cells in parallel. Elements within the device are identical and the DRAIN current is shared equally between them. The more cells that are in parallel for a given MOSFET chip area, the lower its on-state resistance will be. This principle has been the key driving force for automotive PowerMOS for many years and is well understood by both suppliers and customers.

It is possible to isolate the SOURCE connections of several cells from those of the majority and bring them out onto a separate SENSE pin. The PowerMOS can now be thought of as two transistors in parallel with a common GATE and DRAIN but separate SOURCE pins; see Figure 1. When the devices are turned on, the load current will be shared as a ratio of their on-state resistances.

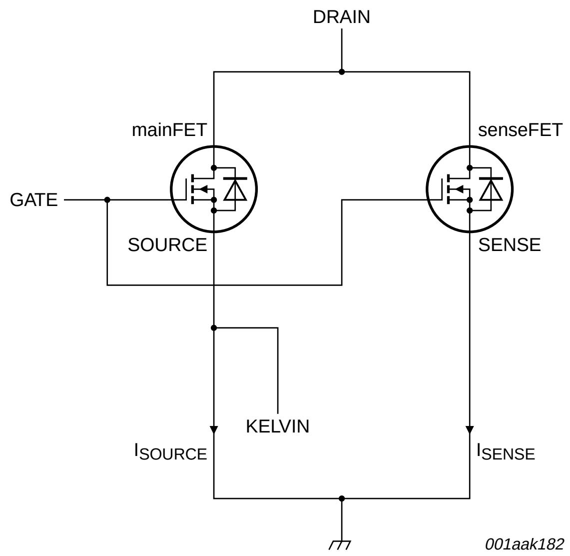


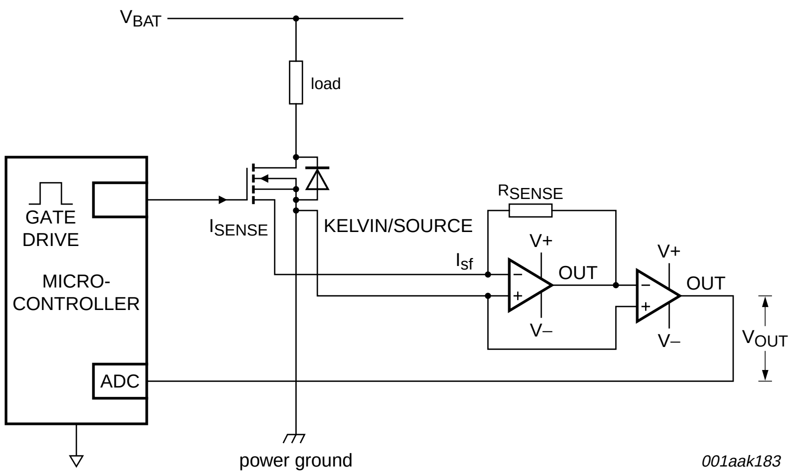
Fig 1. SenseFET equivalent circuit

The sense cells pass only a small fraction of the total load current in proportion to the ratio of their areas. This ratio is typically 500:1.

The ratio of current through the mainFET to the current through the senseFET is known as the sense ratio (n). This ratio is defined for the condition where the SOURCE and SENSE terminals are held at the same potential. An additional KELVIN connection to the SOURCE metallization enables accurate determination of the SOURCE potential.

3. Virtual Earth current sensing

The virtual Earth current sensing technique gives the best performance in terms of accuracy and noise immunity over the full temperature range of the device. This method is illustrated in Figure 2.



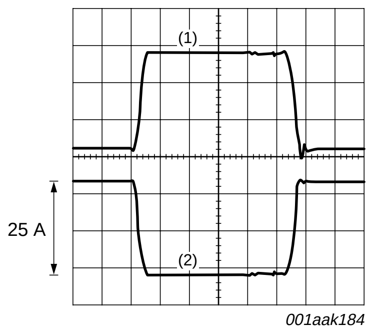
I_{sf} = senseFET current.

Fig 2. Virtual Earth current sensing

Current feedback to the virtual Earth of the operational amplifier ensures that the SENSE and KELVIN terminals are held at the same potential so that the geometric ratio is measured as shown by Equation 1.

$$V_{SENSE} = \frac{(-I_D)R_{SENSE}}{n} \quad (1)$$

A typical senseFET response is shown in Figure 3. The sense signal closely mirrors the DRAIN current throughout the whole pulse duration.



(1) SenseFET response: 20 µs; 10 V/div.

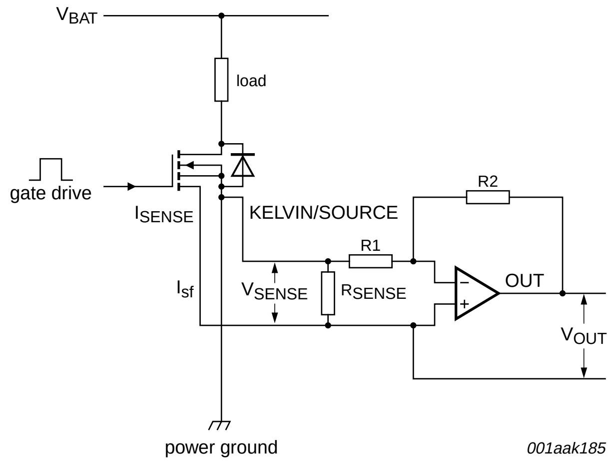
(2) DRAIN current: 20 µs; 10 A/div.

Fig 3. SenseFET virtual earth response

Tolerances of ± 5 % can be achieved with this circuit over temperature. The main advantage of this method is that the sense signal is independent of temperature and linearly proportional to load current. Note that when the MOSFET is used in the low side of the circuit, a negative supply is required for its operational amplifier.

4. Sense resistor current sensing

The use of an external sense resistor in series with the SENSE pin offers a simpler technique for monitoring the current through the device; see Figure 4 and Figure 5.



I_{sf} = senseFET current.

Fig 4. Sense resistor circuit

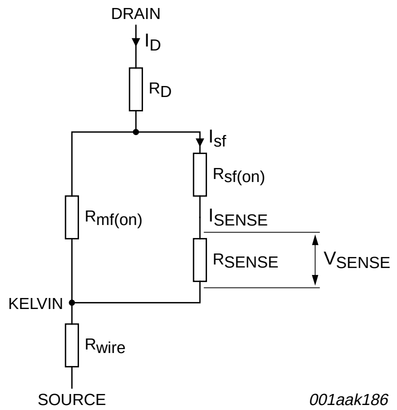


Fig 5. Equivalent sense resistor circuit in the ON state

In Figure 4, an external operational amplifier is used to amplify the sense signal. In the equivalent circuit shown in Figure 5, the resistance of the FET is separated into active and passive components, with a common DRAIN resistance. The active channels are modelled by the mainFET on-state resistance ($R_{mf(on)}$) carrying the majority of the current and the senseFET on-state resistance ($R_{sf(on)}$). The passive contribution from the wire resistance is denoted by R_{wire}. The circuit operates as a potential divider with design equations Equation 2 and Equation 3.

$$V_{out} = \left(\frac{R_2}{R_1}\right) R_{SENSE} I_{sf} \tag{2}$$

$$V_{SENSE} = I_D R_{mf(on)} \frac{R_{SENSE}}{R_{SENSE} + R_{sf(on)}} \tag{3}$$

The inclusion of R_{SENSE} increases the resistance of the mirror leg, and the sense ratio now becomes as shown in Equation 4.

$$n' = n \cdot \left(1 + \frac{R_{SENSE}}{R_{sf(on)}}\right) \tag{4}$$

The maximum voltage seen on the I_{SENSE} terminal occurs when R_{SENSE} is infinite i.e. an open-circuit condition. This is known as the compliance voltage V_{comp} as shown in Equation 5.

$$V_{comp} = V_{DSon} \times \left(\frac{R_{mf(on)}}{R_{mf(on)} + R_D}\right) \tag{5}$$

Therefore the mirror terminal only samples a proportion of the full DRAIN-SOURCE voltage. Fortunately, for low voltage PowerMOS the contribution from the DRAIN resistance (R_D) is a small proportion of the total R_{DSon} and so the compliance ratio is high. This will deteriorate in higher voltage devices.

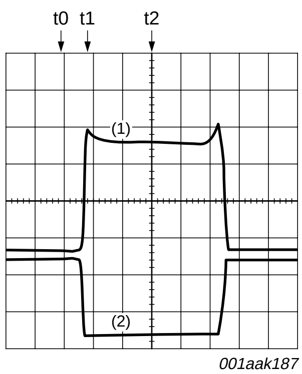
As an example, the BUK7905-40AIE $R_{mf(on)}$ = 3 mΩ, $R_{sf(on)}$ = 1.1 Ω and has a nominal sense ratio of 500:1. If R_{SENSE} = 1 Ω, when 10 A load current flows through the load this will generate V_{SENSE} ≈ 14 mV. In the low side, a single rail amplifier can be used to amplify this signal to a more useful level.

The KELVIN connection to SOURCE is essential for accurate current sensing. Otherwise, voltage drops over R_{wire} that are caused by load current will add to the sense voltage and introduce a source of error. In the past this was less of an issue as a R_{wire} of 2 mΩ was only a small fraction of a 200 mΩ mainFET. But modern PowerMOS products can have on-state resistances as low as 1 mΩ, comparable with the parasitic resistances. Referencing to the KELVIN pin eliminates the wire contribution.

The main disadvantage of the sense resistor technique is that the inclusion of R_{SENSE} introduces a temperature dependence.

Imagine the case where R_{SENSE} is 0 Ω. The on-state resistance of both the mainFET and senseFET track together over temperature and the ratio of the two stays constant. In this case the current sense ratio also stays constant over temperature.

Conversely, if R_{SENSE} approaches infinity, V_{SENSE} in Equation 3 now becomes $V_{SENSE} = I_D R_{mf(on)}(T)$, and will follow $R_{mf(on)}$ over temperature (T). The mainFET on-state resistance almost doubles between 25 °C and 175 °C thus eroding the tolerance of the measurement. For values between the two, a balance must be struck between signal magnitude and accuracy. We normally recommend maintaining $R_{SENSE} << R_{sf(on)}$ and amplifying the V_{SENSE} signal accordingly. A typical senseFET response is shown in Figure 6.



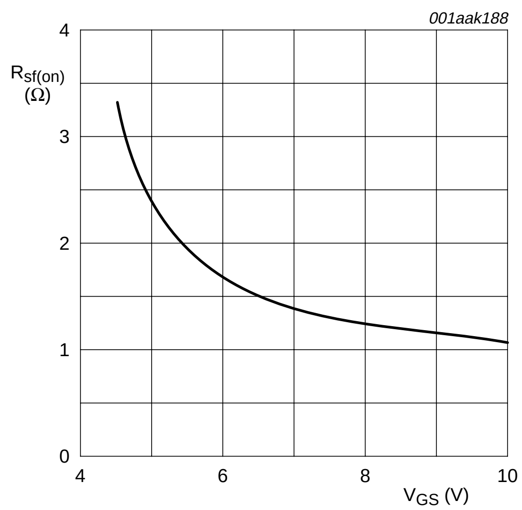
(1) SenseFET response: 100 µs; 500 mV/div.

(2) DRAIN current: 100 µs; 5 A/div.

Fig 6. SenseFET response in resistor circuit

The response shown in Figure 6 appears to show that the senseFET reacts instantaneously to changes in the DRAIN current, and that the sense signal contains false peaks at turn-on and turn-off. These are due to a difference in the current ratio between the linear and the fully enhanced operating regions and are largely circuit related. This becomes more clear if we evaluate the response in terms of an effective sense ratio (n'), which is dependent on the ratio of $R_{SENSE}/R_{sf(on)}$ from Equation 4. Assume that R_{SENSE} = 1 Ω.

At t0 the GATE-SOURCE voltage is zero and no current flows. Once a GATE voltage is applied, a channel forms and current begins to flow through the device, although the on-state resistance is still very high. At this point $R_{sf(on)}$ >> R_{SENSE} and the geometric sense ratio (n) is measured. This yields the maximum sense signal at t1. As the GATE is overdriven, the on-state resistance of the senseFET falls and the $R_{SENSE}/R_{sf(on)}$ factor becomes more significant as shown in Figure 7. This continues until the final level of V_{GS} and sense ratio are reached at t2. During turn-off, the process is reversed. Note that if R_{SENSE} = 0 Ω, no false peaks are observed and the sense signal is similar to the virtual earth response shown in Figure 3.



I_{SENSE} = 25 mA.

Fig 7. On-state resistance of senseFET as a function of V_{GS}

Normally, designers choose to blank out the false peaks, and to sense the current once the device is fully enhanced.

5. Conclusion

SenseFET devices are an effective means of protecting automotive applications. They are a low loss and cost-effective alternative to traditional current shunts whilst retaining realistic tolerances.

6. References

[1] **N. Zommer and J. Biran “Power current mirror devices and their applications” —** Proc. Power convers. Int. Conf. June, pp275-283 (1986).

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8. Contents

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