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An Introduction to the HEXSense™ Current-Sensing Device

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Introduction

This application note will acquaint the designer with International Rectifier's new family of HEXFET power MOSFET devices. Designated the HEXSense "C" Series, they are essentially HEXFETs with an added current-sense capability.

HEXSense Characteristics

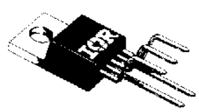
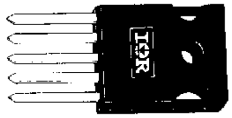
The HEXSense family extends the present HEXFET matrix. This matrix consists of a number of die sizes, HEX Z to HEX 5, arranged in geometric progression of power handling capability, i.e., each die size has approximately twice the power handling capability of the next smaller die and half that of the next larger one. Each die size is available in a range of voltage ratings. A variety of standard packages and a custom packaging capability complete the matrix.

The Figure 1 table maps out the HEXSense extension to this matrix. The HEXSense device is "downward compatible" with its corresponding HEXFET device. Current-sense capability can be obtained in existing designs without affecting power device performance.

The root IRC in the part number identifies the device as being a HEXSense device. The die size is identified by next to last digit of the part number. Other alphanumeric characters identify voltage grade, package, etc.

Figure 2 shows the first available HEXSense packages and the device symbol.

HEXSense "C" Series Current-Sensing Power MOSFETS

	TO-220 Package Style			TO-247 Package Style		
						
	Die Size			Die Size		
Voltage	HEX-2	HEX-3	HEX-4	HEX-3	HEX-4	HEX-5
50V	IRCZ20	IRCZ30	IRCZ40	IRCP030	IRCP040	—
100V	IRC520	IRC530	IRC540	IRCP130	IRCP140	IRCP150
200V	IRC620	IRC630	IRC640	IRCP230	IRCP240	IRCP250
250V	IRC624	IRC634	IRC644	IRCP234	IRCP244	IRCP254
400V	IRC720	IRC730	IRC740	IRCP330	IRCP340	IRCP350
500V	IRC820	IRC830	IRC840	IRCP430	IRCP440	IRCP450

NOTE: The die size is indicated by the last-but-one digit of the part number. For example:

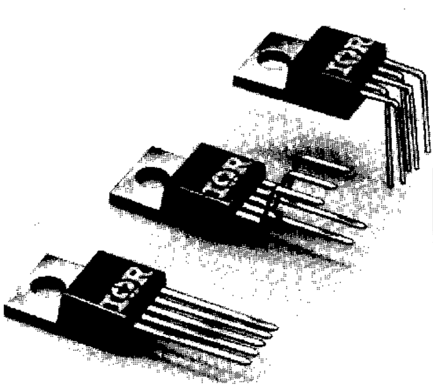
IRC530 ↑ HEX-3

IRC720 ↑ HEX-2

IRCP240 ↑ HEX-4

IRCP350 ↑ HEX-5

Figure 1. HEXSense Product Matrix



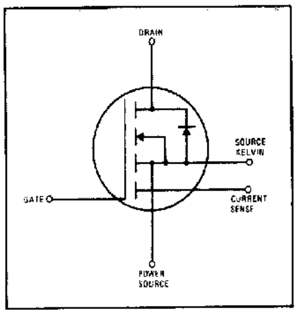


Figure 2. Five Lead TO-220 HEXSense Packages and Device Symbol

HEXSense Fundamentals

A HEXFET die is made of many transistor cells acting in parallel (Figure 3). When the device is on, current flows from drain to source via a narrow channel region around the edge of each cell. Since current is carried by majority carriers in the channel region, the drain current is distributed relatively evenly among cells and varies little from device to device of the same type. Therefore, drain current can be determined by measuring the current passing through a small number of cells and multiplying it by a scaling factor which is known for the particular device type. Little power loss is involved and thus HEXFET drain current can be determined in an almost lossless manner.

The source region of the sensing cells is covered with an isolated metallization which is connected to an external pin via a separate bonding pad and bonding wire and is referred to as the *sense terminal* or *sense pin*. The subscript C is used in symbols representing the various electrical quantities associated with the current sense function, e.g., V_{DC}, I_{DC} or I_C, etc.

Two terminal connections are made to the source metallization of the main cells via separate bonding wires. These are the *power source pin* and the *Kelvin source pin*. The appropriate use of the Kelvin pin is very important for an accurate measurement of device current, as will be explained later.

In practice, a HEXSense device consists of two paralleled MOSFETs with isolated sources (Figure 4), commonly referred to as "power device" and "sense device." The key parameter of this combination is the *current sensing ratio* (r). This is the ratio between the current in the source pin and the current in the sense pin (I_{source}/I_{sense}). This ratio will, of course, be slightly different in terms of drain current, which is the sum of both currents:

$$I_D = (r+1)\,I_C$$

Under the ideal conditions of equal enhancement of all cells and perfect source metallization, the current sensing ratio would be the ratio of the number of cells in the power device to the number of cells in the sense device.

The *output capacitance* of the sensing cells $(C_{oss})_c$ is higher than would be expected from the area ratio alone because of the relative large capacitance of the bonding pad for the sense pin. Its effects would be felt at the inception of the fully enhanced operation (as an excess of current due to its discharge) and at its end (as a reduction of the same). However, in practice these effects are minor compared to the likely slew rate limitations of the sensing operational amplifier.

Dependence of Current Ratio on Temperature, Gate Voltage and Drain Current

The current ratio, r, varies slightly with temperature, gate voltage and drain current. These variations have a number of causes including variations in the resistivity of the silicon from which the devices are made, temperature gradients across the die and voltage drop in the source metallizations. Typical variations in the current ratio that can be expected with variation of T_j, V_{GS} and I_D are shown for each device in the data sheet. In each case one parameter is varied while the other parameters are held constant.

The effects are cumulative so that if all three parameters vary, each will contribute to a variation in r.

Practical Implementation of the Current Sense Function

Virtual Earth Sensing

The circuit that gives the best performance in terms of speed, accuracy and noise immunity is shown in Figure 5. In a slightly modified version it was chosen for data sheet characterization and is detailed in Appendix I.

For fully enhanced operation the accuracy of this circuit may be estimated directly from the data sheets and the tolerance of r. Neither the offset nor the bias current of the operational amplifier should have any significant effect on the overall static performance.

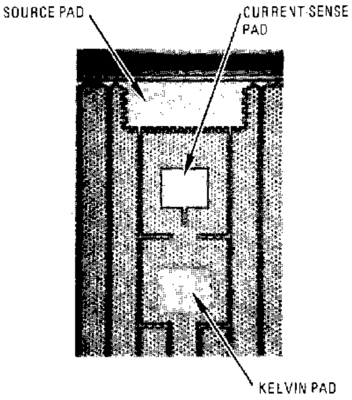


Figure 3. HEXSense Die

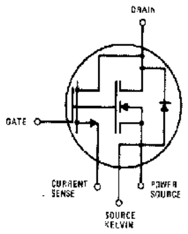


Figure 4. Schematic Representation of HEXSense Device

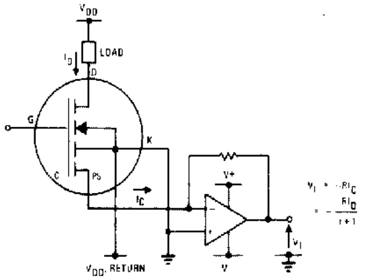


Figure 5. Virtual Earth Sensing Circuit

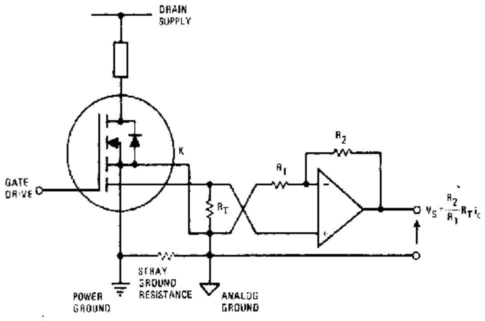


Figure 6. Resistor Sensing Circuit

However, this is not the case when it comes to dynamic performance. Current swings of 10A in 100 nsec are common in switch mode power supplies (SMPS) and similar applications. For a 5 volt output at 10A this translates into a required slew rate of 50 V/μs which is an order of magnitude above that which commonly available operational amplifiers are capable of. The settling time of high slew-rate operational amplifiers will also affect the dynamic performance of this circuit.

Two disadvantages of this circuit are the dual power supply requirement for the operational amplifier and the negative polarity of the output voltage.

Resistor Sensing

A second circuit, shown in Figure 6, overcomes these disadvantages at a significant penalty in accuracy and performance.

In this circuit the current-to-voltage translation is performed by the sensing resistor R_T, while the operational amplifier provides the necessary amplification. Input and output voltages are both positive and no negative supply is required, provided the the common mode input range of the operational amplifier includes ground (CA3130, CA3140, LM324, LM358, TLC271, etc.).

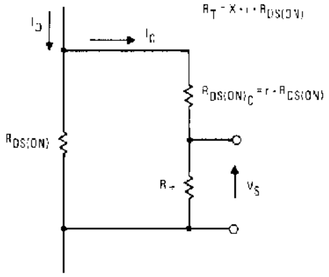


Figure 7. Evaluation of Error Introduced by R_T

The sense ratio of the circuit will vary from the nominal sense ratio due to the introduction of R_T. With reference to Figure 7, assuming that R_T is a share of (X) of the on-resistance of the sensing cells, which, in turn, is r times the $R_{DS(on)}$ of the main device,

$$\frac{I_D}{I_C} = 1 + r\,(1+X)$$

The voltage across the sensing resistor will be:

$$V_S = \frac{X}{X+1} R_{DS(on)}\, I_D$$

Ideally, it should be:

$$V_S = X \cdot R_{DS(on)}\, I_D$$

This error, $1/(1+X)$, can be compensated for by increasing the gain of the operational amplifier by the same coefficient. However, it should be remembered that the coefficient X is not a constant because the $R_{DS(on)}$ of the device (and of the sensing cells) is a function of temperature, current, gate voltage and production spread.

The value of R_T should be such that the voltage across its terminals at the lowest level of current at which the prescribed measurement accuracy is still required should be significantly higher than the offset of the operational amplifier. Figure 8 shows the minimum values of R_T assuming an offset of 3 mV and a minimum voltage of 20 mV, with a drain current of 10% of rated I_D at 25°C. Furthermore, if it is necessary to amplify the sense signal over a wide voltage range then the output voltage range of the operational amplifier may pose a limitation. An operational amplifier with a low output saturation voltage will be necessary if low level drain currents are to be sensed, or a negative supply may be required.

Changes in MOSFET on-resistance with temperature have an adverse effect on the overall accuracy of the sensing circuit of Figure 6. It can be shown, however, that sensitivity of V_S to temperature changes becomes negligible as R_T tends to values in the order of 10% of $R_{DS(on)c}$.

With reference to Figure 7,

$$V_S = \frac{R_T}{R_T + R_{DS(on)c}} \cdot I_D \cdot R_{DS(on)}$$

$$\simeq \frac{R_T}{R_{DS(on)c}} \cdot I_D \cdot R_{DS(on)}$$

$$= R_T \cdot I_D \cdot \frac{R_{DS(on)}}{R_{DS(on)c}}$$

Since $R_{DS(on)}$ and $R_{DS(on)c}$ should change by the same factor for a given change in temperature, the ratio $R_{DS(on)}/R_{DS(on)c}$ should remain constant. Therefore, provided $R_T \ll R_{DS(on)c}$, V_S should not be greatly affected by changes in the device temperature.

In final analysis the value of R_T will be the lowest compatible with the offset of the operational amplifier and the noise immunity requirements of the circuit.

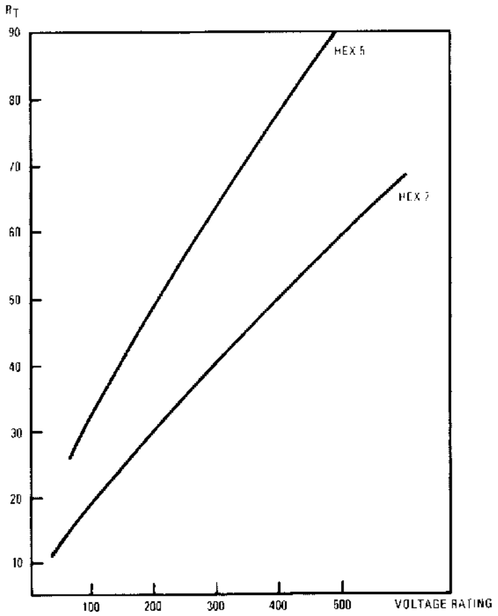
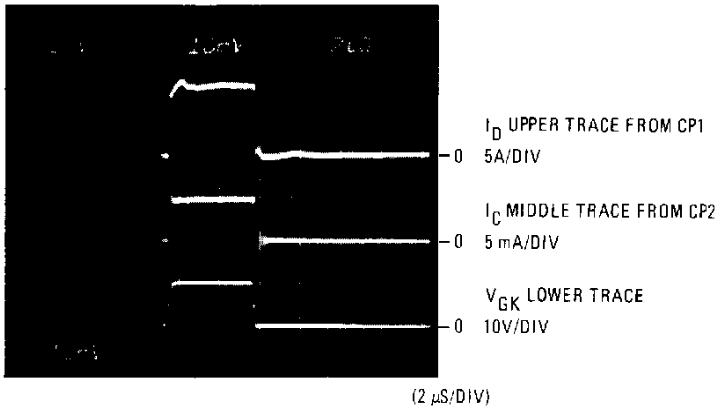
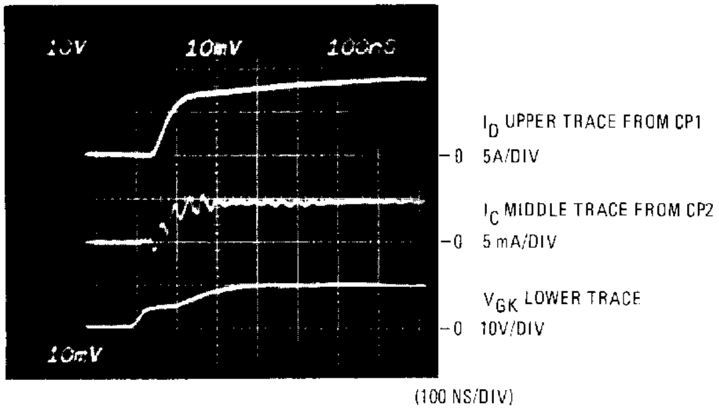


Figure 8. Minimum Value of R_T to Achieve 20 mV at a Drain Current of 10% of Rated I_D @ 25°C

TURN-ON AND TURN-OFF



TURN-ON



TURN-OFF

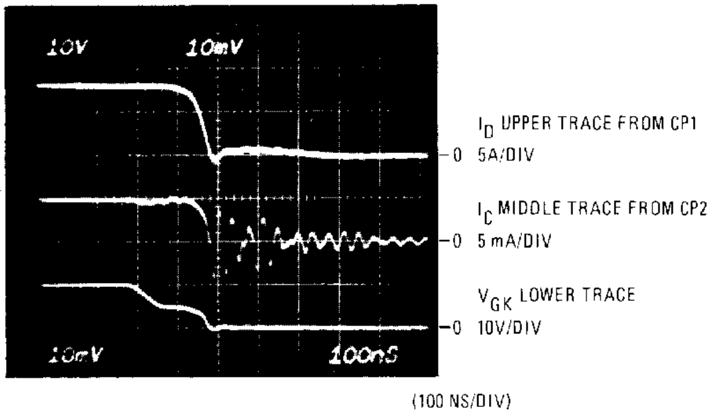


Figure 9. Dynamic Test Waveforms I_D, I_C and V_{GK} for IRC530

Using the Main Device as the Sense Resistor

If R_T is very large compared with the $R_{DS(on)}$ of the sense cells, the voltage that appears across the sense resistor will be very nearly equal to the voltage developed across the main device. In this case, therefore, the $R_{DS(on)}$ of the main device acts as the current sensing resistor and the sense cells acts as a switch which disconnects the current sense output from the sensing resistor (the main device) during the period when the HEXFET is switched off. During the off-period the current sense output is pulled low by the sense resistor rather than being pulled up to the power rail voltage. Thus, the current signal processing circuit is relieved of the necessity to withstand high voltages during a time when no useful information is available to it. The drawback with this mode of operation, of course, is that $R_{DS(on)}$ varies considerably with temperature and this must be allowed for when interpreting the current sense output.

Switching Performance

The circuit of Figure 5 will also yield a better switching performance than would otherwise be obtained with most schemes (see Figure 9) . Figure 10 shows the test circuit used to obtain these waveforms. It can be seen that the switching performance is in line with the fast switching capabilities of HEXFETs. No significant delays are evident. The sense current follows the drain current during switching with no large peaks noticeable. The ringing on the current waveform is introduced by the measurement probes and is not actually present in the circuit.

Notes on the Use of the Kelvin Pin

The measurement accuracy is somewhat degraded by some parasitic resistance elements that upset the current partitioning between the power device and the sense device. As shown in Figure 11, the metallization, bonding wire and pin contribute additional resistance that is not in the same ratio as the $R_{DS(on)}$ of the sense cells and the $R_{DS(on)}$ of the main cells.

To minimize the effect of the metallization resistance, the Kelvin contact has been placed at the center of the die, close to the current sense pin.

PARTS LIST:

C1	425 μF	450V WORKING VOLTAGE
C2	0.22 μF	600V WORKING VOLTAGE (HIGH FREQUENCY CAP.)
R1	4Ω	NON-INDUCTIVE RESISTOR
DUT	IRC530	

EQUIPMENT LIST:

CP1, CP2	CURRENT PROBES TEKTRONIX A6302 (BW: 50 MHz)
P.G.	PULSE GENERATOR WAVETEK 187

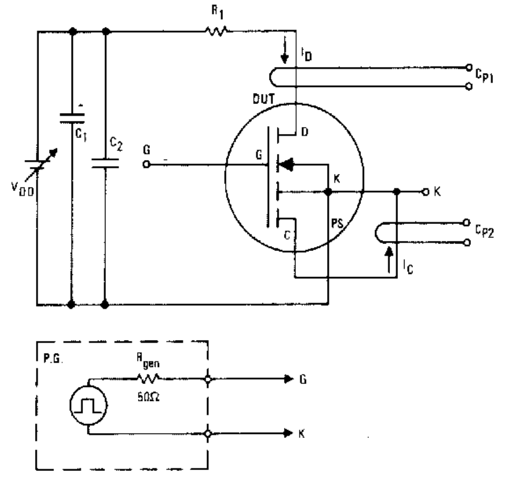


Figure 10. Test Circuit for Switching Performance

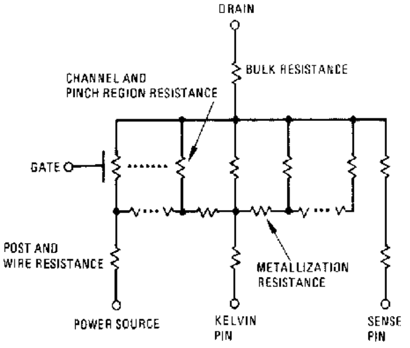


Figure 11. HEXSense Model Showing the Different Components of On-Resistance

In the sensing circuit of Figure 5, this effect can be compensated for by returning the Kelvin to the non-inverting input of the operational amplifier, so that the sense terminal, connected to the inverting input, is raised above ground by a voltage drop that approaches the drop across the parasitic resistances.

For the same reason, in the Figure 6 circuit, the sensing resistor R_T should be connected between the sense and the Kelvin pins so as to minimize the unbalancing effects of the metallization and the wire and post resistances. In practical circuits ground loops and voltage differentials between the control ground and the power ground make the use of the Kelvin contact essential.

In those power circuits in which very fast switching of the HEXFET is required, the Kelvin contact represents a useful method of bypassing the "common source inductance" which is one of the main limitations in switching speed. Inductance that is common to the drain circuit and to the gate circuit establishes a feedback into the gate drive circuit that is proportional to L_s x di/dt. This voltage reduces the net available gate voltage and slows down the switching. By applying the gate drive signal between the gate and the Kelvin contact, the source inductance is no longer "common" and therefore has no effect on the switching speed of the HEXFET.

APPENDIX I — Sense Ratio Characterization

This Appendix details a test method used for characterization of the nominal sense ratio under static conditions. The test circuit schematic is shown in Figure A1.

The Kelvin source pin is connected to signal ground and also acts as a return for the gate-source drive voltage. The sense pin is connected to the virtual signal ground. The power source pin floats with respect to signal ground. Under static conditions and with sufficient gate overdrive the requirements of equal cell enhancement and zero appreciable stray source resistances are met. For characterization purposes the nominal sense ratio (r) is defined as the ratio between drain and sense current as measured with this circuit in the prescribed manner. The ratio r will vary with T_j, I_D and V_{GS} as indicated in the data sheets.

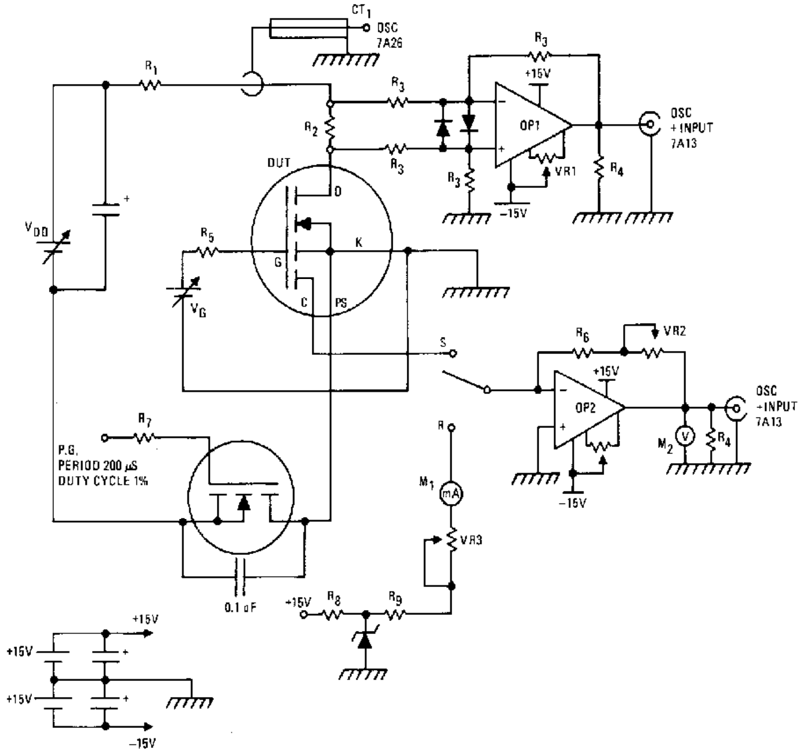


Figure A1. Nominal Sense Ratio Measurement Circuit

Parts List:

R1	2Ω	3%	5W
R2	0.1Ω	0.1%	2W
R3	10k	0.1%	¼W
R4	200k	3%	¼W
R5	1k	3%	¼W
R6	100Ω	0.1%	¼W
R7	100Ω	0.1%	¼W
R8	3k	3%	¼W
R9	9.1k	3%	¼W
VR1	20kΩ		
VR2	100Ω	10 turn pot.	
VR3	1k	10 turn pot.	
OP1, OP2		LM741	

Test Equipment:

Oscilloscope — Tektronix 7603
Pulse Generator (P.G.) — Wavetek 187
Multimeter (M1, M2) — Fluke 8012 Digital Multimeter
Operational amplifier (OP1, OP2) outputs to Differential Comparator — Tektronix 7A13
Current transformer (CT1) output to Dual Trace Amplifier — Tektronix 7A26

Test Procedure:

1) Switch in S, Use CT1 to monitor I_D.
Adjust V_{DD} to obtain required I_D.
Ensure V_G adjusted to provide gate overdrive.
2) Set 7A13 differential Volts/div to 10 mV/div.
3) Adjust VR2 until differential voltage is zero.
4) Turn off V_E and V_G.
5) Place switch in R,
Adjust M1 current with VR3 to read 1.000 mA.
Read M2 voltage (200 mV range).
M2 reading = (R6 + VR2) x 1 mA,
Calculate VR2

$$\text{Nominal sense ratio (r)} = \frac{R6 + VR2}{R2}$$

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