APPLICATION NOTE 936A

The Do's and Don'ts of Using Power HEXFETs®

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Summary

In common with all power semiconductor devices, power MOSFETs have their own technical subtleties, which must be properly understood if the designer is to get the most out of them. In this article, some of the most common "Do's and Don'ts" of using power HEXFETs are explained.

Introduction

Power HEXFETs offer many advantages over conventional bipolar transistors, in both linear and switching applications. These advantages include very fast switching, absence of second breakdown, wide safe operating area, and extremely high gain. Typical applications are high frequency switching power supplies, chopper and inverter systems for DC and AC motor speed control, high frequency generators for induction heating, ultrasonic generators, audio amplifiers, AM transmitters, computer peripherals, telecommunications equipment, and a host of special military and space needs.

There are several basic types of power MOSFETs available. Original designs used so-called V-groove or U-groove structures, while the trend today is towards vertical D-MOS technology, with a closed cellular source configuration. This technology was first embodied in the HEXFET structure, shown in Figure 1.

Current flows vertically through the silicon from the drain, through the body of the device, then horizontally through the channel region, and vertically out of the source, as illustrated. The flow of transistor current is controlled by the voltage applied between the gate and source terminals; the applied gate voltage sets up a field in the channel region, which modulates the resistance of the device. The gate is isolated electrically from the body; as a result, the power HEXFET has a very high, almost infinite, DC gain.

A feature of power MOSFETs is that they inherently have built into them an integral reverse body-drain diode. The existence of this diode is explained by reference to Figure 1. When the source terminal is made positive with respect to the drain, current can flow through the middle of the source cell, across a forward biased P-N junction. In the "reverse" direction, the power HEXFET thus behaves like a P-N junction rectifier.

The integral body-drain diode is a real circuit element, and its current handling capability is typically as high as that of the transistor itself. Some circuits require an "inverse" rectifier to be connected across the switching device, and in these circuits it will often be possible to utilize the body-drain diode of the HEXFET, provided the proper precautions are taken.

In this application note, some of the most common do's and don'ts of using power HEXFETs are described. The objective is to help the user get the most out of these remarkable devices, while reducing "on the job" learning time to a minimum.

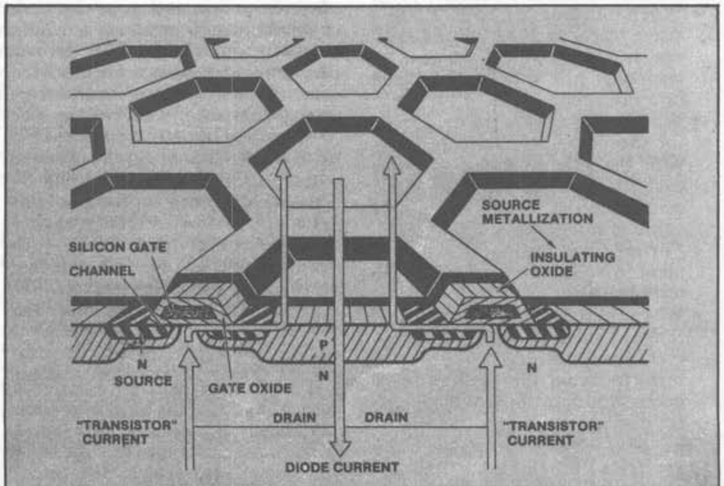


Figure 1. Basic HEXFET Structure

Be Careful When Handling & Testing Power HEXFETs

The user's first "contact" with the power HEXFET could be a package of parts arriving on his desk. Even at this stage, it behooves one to be knowledgeable about some elementary precautions.

Power HEXFETs, being MOS devices, can potentially be damaged by static charge when handling, testing or installing into a circuit. The problem is rather slight by comparison with that experienced with low level MOS devices. Power HEXFETs are, after all, *power* devices; as such, they have much greater input capacitance, and are much more able to absorb static charge without excessive build-up of voltage. In order to avoid possible problems, however, the following procedures should be followed as a matter of good practice, wherever possible:

- HEXFETs should be left in their anti-static shipping bags, or conductive foam, or they should be placed in metal containers or conductive tote bins, until required for testing or connection into a circuit. The person handling the device should ideally be grounded through a suitable wrist strap, though in reality this added precaution is seldom essential.
- HEXFETs should be handled by the package, not by the leads.

When checking the electrical characteristics of the power HEXFET on a curve tracer, or in a test circuit, the following precautions should be observed:

- Test stations should use electrically conductive floor and table mats that are grounded. Suitable mats are available commercially.
- When inserting HEXFETs into a curve tracer or a test circuit, voltage should not be applied until all terminals are solidly connected into the circuit.
- When using a curve tracer, a resistor should be connected in series with the gate to damp spurious oscillations that can otherwise occur on the trace. A suitable value of resistance is 100 ohms.
- For repeated testing, it is convenient to build this resistor into the test fixture.
- When switching from one test range to another, voltage and current settings should be reduced to zero, to avoid the generation of potentially destructive voltage surges during switching.

The next step is to connect the power HEXFET into an actual circuit. The following simple precautions should be observed:

- Work stations should use electrically grounded table and floor mats.
- Soldering irons *should be grounded.*

Now that the power HEXFET has been connected into its circuit, it is ready for the power to be applied. From here on, success in applying the device becomes a matter of the integrity of the circuit design, and of what circuit precautions have been taken to guard against unintentional abuse of the HEXFET's ratings.

The following are the interrelated device and circuit considerations that lead to reliable, trouble-free design.

Beware of Unexpected Gate-to-Source Voltage Spikes

Excessive voltage will punch through the gate-source oxide layer and result in permanent damage.

This seems obvious enough, but it is not so obvious that transient gate-to-source overvoltages can be generated that are quite unrelated to, and well in excess of, the amplitude of the applied drive signal. The problem is illustrated by reference to Figure 2.

If we assume that the impedance, Z, of the drive source is high, then any positive-going change of voltage applied across the drain and source terminals (caused, for example, by the switching of another device in the circuit) will be reflected as a positive-going voltage transient across the source and the drain terminals, in the approximate ratio of:

$$\frac{1}{1 + \frac{C_{gs}}{C_{dg}}}$$

The above ratio is typically about 1 to 6. This means that a change of drain-to-source voltage of 300V, for example, could produce a voltage transient approaching 50V between the gate and source terminals. In practice this "aiming" voltage will not appear on the gate if the dv/dt is positive because the HEXFET goes in conduction at approximately $V_{gs} = 4V$, thereby clamping the dv/dt at the expense of a current transient and increased power dissipation. However, a negative-going dv/dt will not be clamped. This calculation is based upon the worst case assumption that the transient impedance of the drive circuit is high by comparison with the gate-to-source capacitance of the HEXFET. This situation can, in fact, be quite easily approximated if the gate drive circuit contains inductance — for example, the leakage inductance of an isolating drive transformer. This inductance exhibits a high impedance for short transients, and effectively

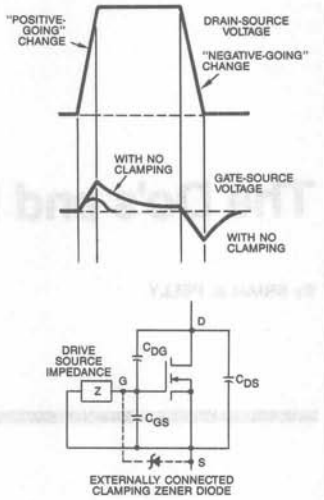


Figure 2. A Rapidly Changing Applied Drain-Source Voltage will Produce Gate-Source Voltage Transients

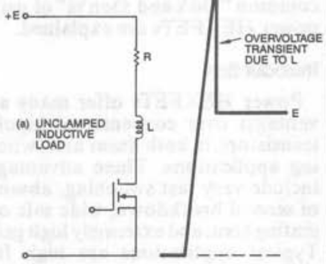


Figure 3. Drain-Source Overvoltage Transient when Switching Off with Unclamped Inductive Load

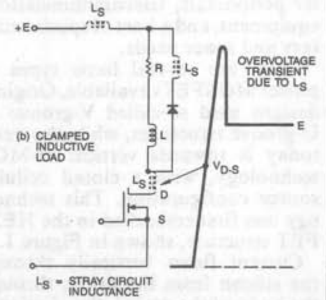


Figure 4. Drain-Source Overvoltage Transient Produced by Stray Circuit Inductance When Switching Off with Clamped Inductive Load

decouples the gate from its drive circuit for the duration of the transient.

The negative-going gate-to-source voltage transient produced under the above circumstances may exceed the gate voltage rating of the device, causing permanent damage.

It is, of course, true that since the applied drain transient results in a voltage at the gate which tends to turn the HEXFET device ON, the overall effect is to an extent self-limiting so far as the gate voltage transient is concerned. Whether this self-limiting action will prevent the voltage transient at the gate from exceeding the gate-source voltage rating of the device depends upon the impedance of the external circuit. Spurious turn-on is of itself undesirable, of course, though in practical terms one may grudgingly be able to accept this circuit operating imperfection, provided the safe operating area of the device is not violated.

As a minimum solution to the problem, the gate-source terminals must be provided with a voltage clamp (a conventional zener diode is suitable for this purpose) to prevent the gate-source voltage rating from being exceeded. A more fundamental solution, of course, is to make the impedance of the gate circuit low enough that not only is the gate-source voltage rating not exceeded, but also the voltage transient at the gate is contained to a level at which spurious turn-on does not occur.

It should be remembered that a collapse of voltage across the HEXFET (i.e., a negative-going dv/dt) will produce a transient negative voltage spike across the gate-source terminals. In this case, of course, there will be no tendency for the device to turn ON, and hence no tendency for the effect to be self-limiting. A zener diode connected to clamp positive transients will automatically clamp negative-going transients, limiting them to the forward conduction voltage drop of the zener.

Beware of Drain-Source Voltage Spikes Induced by Switching

The uninitiated designer is often not aware that self-inflicted overvoltage transients can be produced when the device is switched OFF, even though the DC supply voltage for the drain circuit is well below the V_{DS} rating of the HEXFET.

Figure 3 shows how a voltage spike is produced when switching the device OFF, as a result of inductance in the circuit. The faster the HEXFET is switched, the higher the overvoltage will be. Inductance is always present to some extent in a practical circuit, and therefore, there is always danger of inducing overvoltage transients when switching OFF. Usually, of course, the main inductive component of the load will be "clamped", as shown in Figure 4. Stray circuit inductance still exists, however, and overvoltage transients will still be produced as a result — to say nothing of the fact that the clamping diode may not provide an instantaneous clamping action, due to its "forward recovery" characteristic.

The first approach to this problem is to minimize stray circuit inductance, by means of careful attention to circuit layout, to the point that whatever residual inductance is left in the circuit can be tolerated. If the device has an inductive energy rating, use can be made of this rating for this situation. Generally, however, such ratings do not yet exist for power HEXFETs, and a clamping device should be connected, physically as close as possible to the drain and source terminals, as shown in Figure 5. A conventional zener diode, or a "transorb" clamping device, are satisfactory for this purpose. An alternative clamping circuit is shown in Figure 6. The capacitor C is a reservoir capacitor and charges to a substantially constant voltage, while the resistor R is sized to dissipate the "clamping energy" while maintaining the desired voltage across the capacitor. The diode D must be chosen so that its forward recovery characteristic does not significantly spoil the transient clamping action of the circuit.

A simple RC snubber can also be used, as shown in Figure 7. Note, however, that an RC snubber not only limits the peak voltage, it also slows down the effective switching speed. In so doing, it absorbs energy during the whole of the switching period, not just at the end of it, as does a voltage clamp. A snubber is therefore less efficient than a true voltage clamping device.

Note that the highest voltage transient occurs when switching the highest level of current. The waveform of the voltage across the HEXFET should be checked with a high-speed oscilloscope at the full load condition to ensure that switching voltage transients are within safe limits.

Do Not Exceed the Peak Current Rating

All HEXFETs have a specified maximum peak current rating. This is conservatively set at a level that guarantees long-term reliability, and it should not be exceeded.

It is often overlooked that peak transient currents can be obtained in a practical circuit that are well in excess of the expected normal oper-

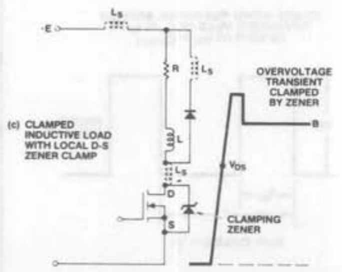


Figure 5. Overvoltage Transient at Switch-Off Clamped by Local Drain-Source Zener

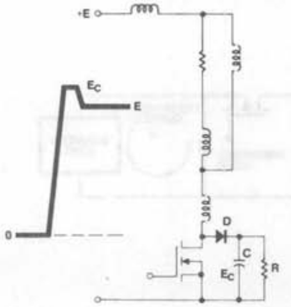


Figure 6. Overvoltage Transient at Switch-Off Limited by Local Diode-Capacitor-Resistor Clamp

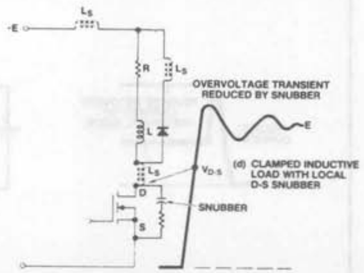


Figure 7. Overvoltage Transient at Switch-Off Limited by Local Capacitor-Resistor Snubber

ating current, unless proper precautions are taken. Heating, lighting and motor loads, for example, consume high in-rush currents if not properly controlled. A technique that ensures that the peak current does not exceed the capability of the HEXFET is to use a current sensing control that switches OFF the HEXFET whenever the current instantaneously reaches a preset limit.

Unexpectedly high transient current can also be obtained as a result of rectifier reverse recovery, when a HEXFET is switched ON rapidly into a conducting rectifier. This is illustrated in Figure 8. The solution is to use a faster rectifier, or to slow down the switching of the HEXFET to limit the peak reverse recovery current of the rectifier.

Do Not Operate at an RMS Current In Excess of the Rating

All HEXFETs have a maximum continuous direct current rating, I_D. The internal bonding wires, bonding pads, and source metallization of the HEXFET are designed to carry this rated current continuously. The total continuous RMS current handled by the HEXFET should not exceed the I_D rating. This means that in a switching application, for example, if the peak current is I_{PK}, and the duty cycle is D, as illustrated in Figure 9, then the maximum permissible value of I_{PK} is $I_D/\sqrt{D}$, so long as this value is less than the $I_{D(max)}$ rating.

Stay Within the Thermal Limits

The power HEXFET, being a power device, is thermally limited. It must be mounted on a heatsink that is adequate to keep the junction temperature within the rated $T_{J(max)}$ (150° C) under the "worst case" condition of maximum power dissipation and maximum ambient temperature.

It must be remembered that in a switching application, the total power is due to the conduction loss and the switching loss. Switching time and hence switching losses are essentially independent of temperature, but the conduction losses increase with increasing temperature, because $R_{D(on)}$ increases with temperature. This must be taken into account when sizing the heatsink. The required thermal resistance of the heatsink can be calculated as follows:

The transistor conduction power, P_T, is given approximately by:

$$P_T = I^2_T\, R_{D(on)}\, [1 + 0.007\, (\Delta T_{JA} + T_A - 25)]$$

where I_T = RMS value of "transistor current"

$R_{D(on)}$ = ON resistance at 25° C

T_A = ambient temperature - °C

ΔT_{JA} = temperature rise, junction-to-ambient

The term within the brackets [ ] accounts for the typical 0.7% increase in $R_{D(on)}$ per degree C temperature rise above 25° C. The data sheet can be consulted for a more accurate value of temperature coefficient for any specific device.

The switching energy depends upon the voltage and current being switched and the type of load. The total switching loss, P_S, is the total switching energy, e_T, multiplied by the operating frequency, f. e_T is the sum of the energies due to the individual switchings that take place in each fundamental operating cycle.

$$P_S = e_T \cdot f$$

The total power dissipation is the sum of the conduction power, P_T, and the switching power, P_S.

$$\begin{aligned} P &= P_T + P_S \\ &= I^2_T\, R_{D(on)}\, [1 + 0.007\, (\Delta T_{JA} + T_A - 25)] + P_S \end{aligned}$$

Since:

$$\Delta T_{JA} = PR_{JA}$$

where:

R_{JA} = junction-to-ambient thermal resistance

The required value of R_{JA} for a given value of ΔT_{JA} is given by:

$$R_{JA} = \frac{\Delta T_{JA}}{I^2_T R_{D(on)}[1+0.007(\Delta T_{JA}+T_A-25)]+P_S}$$

The junction-to-ambient thermal resistance, R_{JA}, is made up of the internal junction-to-case thermal resistance, R_{JC}, plus the case-to-heatsink thermal resistance, R_{CS}, plus the sink-to-ambient thermal resistance, R_{SA}. The first two terms are fixed for the device, and the required thermal resistance of the heatsink, R_{S-A}, for a given junction temperature rise ΔT_{J-A}, can be calculated from:

$$R_{S-A} = R_{J-A} - (R_{JC} + R_{C-S})$$

Pay Attention to Circuit Layout

Stray inductance in the circuit can cause overvoltage transients, slowing down of the switching speed, unexpected unbalance of current between parallel connected devices, and unwanted oscillations.

In order to minimize these effects, stray circuit inductance must be minimized. This is done by keeping conduction paths as short as possible, by minimizing the area of current loops, by using twisted pairs of leads, and

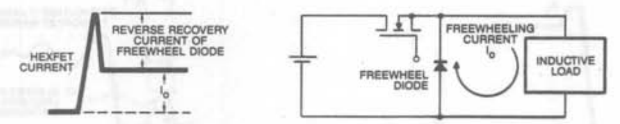


Figure 8. Switching on the HEXFET into a Conducting Rectifier Can Result in High Peak Current, due to Reverse Recovery of Rectifier.

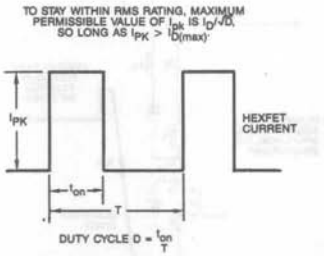


Figure 9. To Stay Within I_D RMS Rating, Maximum Permissible Value of I_{PK} is $I_D/\sqrt{D}$, so long as $I_{PK} \leqslant I_{D(max)}$.

by using ground plane construction. Local decoupling capacitors alleviate the affects of any residual circuit inductance, once these measures have been taken.

Circuit layout should be kept as symmetrical as possible in order to maintain balanced currents in parallel connected HEXFETs. The gates of parallel connected devices should be decoupled by small ferrite beads placed over the gate connections, or by individual resistors in series with each gate. These measures prevent parasitic oscillations.

Be Careful When Using the Integral Body-Drain Diode

The HEXFET's integral body-drain diode exhibits minority carrier reverse recovery. Reverse recovery presents a potential problem when switching any rectifier off; the slower the rectifier, the greater the problem. The HEXFET's rectifier is relatively fast — not as fast as the fastest discrete rectifiers available, but considerably faster than comparably related conventional general purpose rectifiers. By comparison with the HEXFET itself, on the other hand, the switching speed of the integral reverse rectifier is quite slow. The switching speed of a circuit which utilizes the body-drain diode of the HEXFET may therefore be limited by the rectifier. Whether this will be so depends upon the circuit and the operating conditions.

The most common applications of the HEXFET in which the switching speed, and hence frequency, will potentially be limited by the rectifier, are DC to DC choppers, and inverters for regulated power supplies, electric motor controllers, and so on, in which "multiple" voltage pulses are used. Fortunately, these applications generally do not require ultra-fast switching, and hence they can tolerate the reverse recovery characteristic of the rectifier.

Regardless of the overall circuit configuration, or the particular application, the "local" circuit operating situation that is troublesome occurs when the freewheeling current from an inductive load is commutated from the integral rectifier of one HEXFET to the transistor of an "opposite" HEXFET, the two devices forming a tandem series connected pair across a low impedance voltage source, as shown in Figure 10. This "local" circuit configuration occurs in most chopper and inverter schemes.

If the incoming HEXFET switches ON too rapidly, the peak reverse recovery current of the integral body-drain diode of the opposite HEXFET will rise too rapidly, the peak reverse recovery current rating will be exceeded, and the device may possibly be destroyed.

The peak reverse recovery current of the rectifier can be reduced by slowing down the rate of change of current during the commutation process. The rate of change of current can be controlled by purposefully slowing down the rate of rise of the gate driving pulse. Using this technique, the peak current can be reduced to almost any desired extent, at the expense of prolonging the high dissipation switching period. The oscillograms in Figure 11 illustrate the effect. By slowing the total switch-ON time from 300ns to 1.8μs, the peak current of the IRF330 has been decreased from 20A to 10A. The energy dissipation associated with the "unrestrained" switch-ON in Figure 11(a) is 0.9mJ, whereas it is 2.7mJ for the controlled switch-ON of Figure 11(b). Note, however, that the average switching losses at a switching frequency of, say 5kHz, are quite manageable — 4.5W and 13.5W for Figures 11(a) and 11(b), respectively.

Note also that it is not necessary to slow the switching-OFF of the HEXFET, hence the energy dissipation at switch-OFF will be relatively small by comparison with that at switch-ON. For operation at frequencies up to a few kHz, where ultra-fast switching is not mandatory, slowing the applied gate drive signal to reduce the peak reverse recovery current of the "opposite" rectifier offers a good practical solution.

Be On Your Guard When Comparing Current Ratings

The user can be forgiven if he assumes that the continuous drain current rating, I_D, that appears on the data sheet represents the current at which the device can actually be operated continuously in a practical system. To be sure, that's what it should represent; unfortunately it often does not.

Most manufacturers assign a "continuous" current rating to the device which in practical terms cannot be used, because the resulting conduction power dissipation would be so large as to require a heatsink with an impractically low thermal resistance, and/or an impractically low ambient operating temperature.

Table 1 is an illustration of the present lack of standardization of current ratings amongst different MOSFET manufacturers. The devices with higher ON-resistance are seen to have generally higher current ratings assigned to them than the lower ON-resistance parts — a tra-

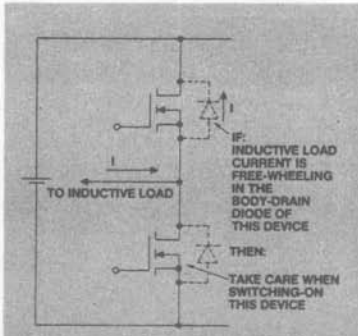
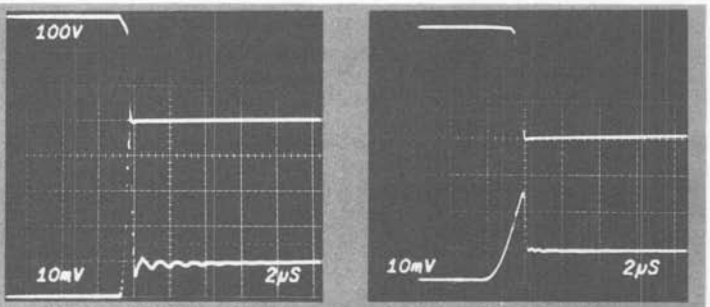


Figure 10. Local Circuit Configuration and Operating Condition Requiring Special Care When Using the HEXFET's Integral Body-Drain Diode.



(a) $I_{(max)}$ = 20A, di/dt = 50A/μs. Switching time = 300 nsec.

(b) $I_{(max)}$ 20A, di/dt = 50A/μs. Switching time 1.8μs.

Figure 11. Oscillograms of IRF330 Switching into Reverse Rectifier of Another IRF330 with Freewheeling Current of 4A.
Top Trace: Voltage 100V/div.
Bottom Trace: Current 4A/div.
Time Scale: 2μs/div.

vesty of the "correct" situation that would, and should, exist if all types of given chip size and junction-to-case thermal resistance were rated on the basis of a given power dissipation.

The best advice to the user is to compare different types *on the basis of ON-resistance*, and not of I_D rating. Fortunately, all manufacturers specify $R_{D(on)}$ at 25° C, and this provides a common basis for comparison. This parameter, taken in conjunction with the junction-case thermal resistance (which, unfortunately, not all manufacturers specify), is a much better indication of the HEXFET's true current handling capability.

Table 1. Comparison of Different Manufacturers' Practices for Assigning Current Ratings (All Parts are Rated 400V)

Device Type	$R_{D(on)}$ Ohms	I_D Amps	$R\theta J{=}C$ °C/W	$T_{C(max)}$ Calculated Applicable to I_D °C
IRF330	1.0	4	1.67	90
MTP565	1.5	5	1.67	25
HPWR6504	1.0	5	1.39	80
VN4001A	1.5	8	?	<25 ?
VN0340B1	1.5	8	?	<25 ?

Conclusions

Power HEXFETs have many advantages. When properly applied they yield an overall system design that frequently has fewer components, is lighter and more compact, and has better performance than can be obtained with other types of devices.

In common with all power semiconductors, power HEXFETs do have their own little technical subtleties. If these subtleties are properly understood, the potential pitfalls can be easily overcome, at minimal cost — and potentially great reward. ☐