

# DE-SERIES FAST POWER MOSFET™

## AN INTRODUCTION

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### Abstract

*The DE-SERIES Fast Power™ MOSFETs are unique high power devices designed as a circuit element from the ground up for high speed, high frequency, high power applications. This technical note describes the patented technology utilized to achieve and optimize the electrical, thermal and mechanical performance of the DE-SERIES devices.*

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## Introduction

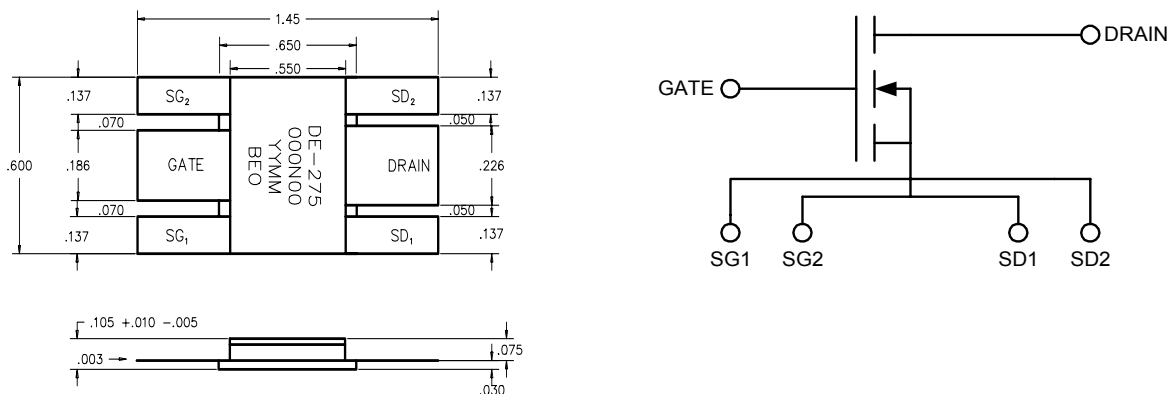
From its inception, power MOS has held great promise because of its potential speed. In fact, the particle transit time, drain to source, in any cell of the silicon die is theoretically on the order of 200ps. However conventional power MOSFET packages are poorly suited to high speed, high frequency applications.

It is interesting to note that the TO-3, a common high power package, was designed in the 1950s and mimics the octal pin and bolt pattern of a vacuum tube socket. The plastic TO-220 and TO-247 packages followed, providing some improvements, and more recent packages like the TO-254 and large block configurations have appeared. However, the topology and materials of these large high power packages are highly inductive, their thermal performance poor, and their mounting configuration at variance with low impedance circuit layout.

Even Radio Frequency (RF) type packages, when used with large power MOSFET die, suffer from similar problems. In short, die packaging has been addressed as a mechanical tooling convenience more than a circuit element. And in the interim, die chemistry and topology have been altered to stabilize operation because of these shortcomings.

The DE-SERIES Fast Power™ MOSFETs illustrated in Figure 1 are a new class of unique high power devices designed as a circuit element from the ground up for high speed, high frequency, high power applications. DEI's Fast Power™ technology features low insertion inductance ( $\approx 1.5\text{nH}$ ), and a low profile low cost plastic package, with a  $R_{\theta JC}$  as low as  $0.10^\circ\text{C/W}$ , which provides exceptional switching speeds and power handling capabilities.

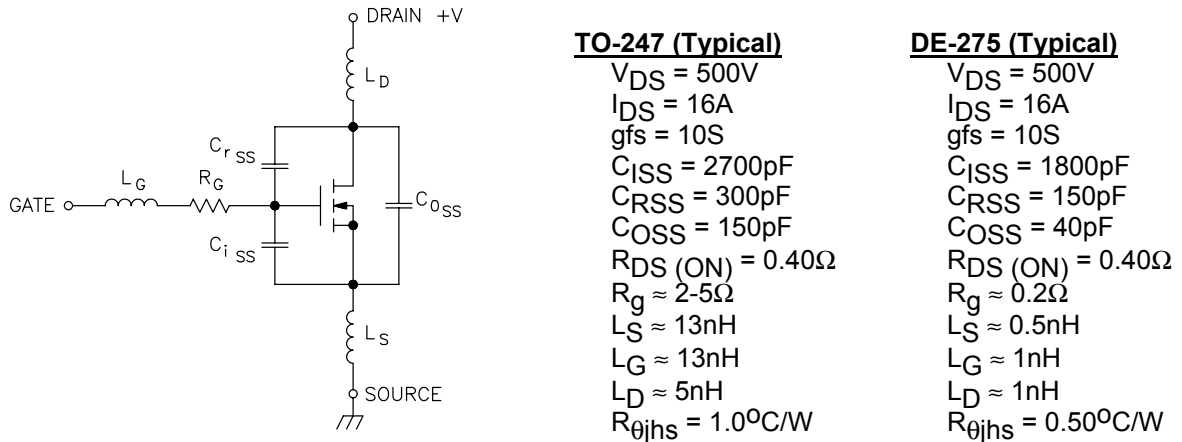
The DE-SERIES, available in 5 power ranges ( DE-150, DE-275, DE-275X2, DE-375 and the DE-475 ) offer 10 times the speed and 3 times the power dissipation, with 1/2 the volume, 1/3 the weight and greatly reduced die stress, of comparable conventional power MOSFET devices. This article describes the patented technology utilized to achieve and optimize the electrical, thermal and mechanical performance of the DE-SERIES.



**FIGURE 1 DE-SERIES Fast Power MOSFET™**

## Standard Packaging

In order to more clearly understand the necessity for the mechanical topology of the DE-SERIES, it is useful to first look at some of the negative feedback terms in power MOSFETs.



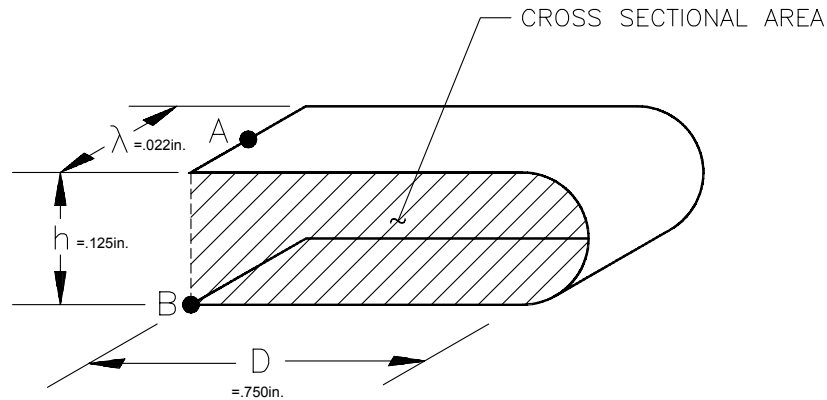
**Figure 2 MOSFET Circuit Model**

Figure 2 illustrates the circuit model for a conventional MOSFET. The same analysis applies to bipolar devices. The effect of the  $L_D$  term is on the output circuit and is often of little consequence. There are several parasitic elements that inhibit high-speed operation. At turn-on, if we apply a step voltage function to the external gate terminal, with  $T_r = 0$  and  $Z_o = 0$ , the parasitic elements  $L_G$ ,  $R_G$  and  $L_S$  isolate in time the capacitance of the internal gate structure of the power MOSFET such that the rate of voltage rise on the gate structure is limited to the quarter wave time of this network ( $T_r = 1/4F$ ), thus slowing the turn-on of the device. Furthermore, this  $L_G$ ,  $L_S$ ,  $R_G$ ,  $C_{ISS}$ ,  $C_{RSS}$  network forms a resonant tank circuit which can oscillate and cause spurious operation of the MOSFET. This resonance will limit the maximum useful frequency of the device.

When the device turns on, there are additional parasitic elements that further inhibit high-speed operation. As current rises in the drain circuit, the voltage developed across  $L_S$  provides a negative feedback term, which further limits the turn on speed. In conjunction with the  $L_S$  term, as current rises in the drain circuit, the voltage fall at the drain is coupled to the gate circuit via  $C_{RSS}$  (the Miller effect), providing additional negative feedback to the gate.

It is clear that a new packaging concept, a new paradigm, is necessary to address and, as much as practical, eliminate these parasitic inductive elements. To explore this further, let us look at the mechanical nature of these inductive terms.

## Inductance in Three Dimensional Space



**Figure 3 One Turn Inductor**

Recalling the previous discussion on the effects of stray inductance, it is useful to examine just how big, physically, a 26nH inductor is. This lets us see, in a dynamic way, the need for extreme care in package and die design as well as circuit layout.

The one turn inductor shown in Figure 3 is equivalent to one turn of 0.022 inch wide conductor ( $\lambda$ ) wound on a 0.125 inch diameter ( $h$ ). With distance ( $D$ ) equal to 0.750 inches, the inductance of this one turn coil is given by equation 11:

$$E1. \quad L \approx \left[ \frac{K\mu_0\mu_r N^2 A}{\lambda} \right]$$

Where:

$L$  = inductance in Henrys

$K$  = a dimensionless constant, form factor correction (10.) ( $K=.2$ )

$\mu_0$  = the permeability of free space, ( $\mu_0 = 4\pi E-7 \text{ H/M}$ )

$\mu_r$  = the relative permeability ( $\mu_r = 1$ )

$N$  = the number of turns ( $N = 1$ )

$A$  = the cross sectional area of the coil ( $A = 5.81E-5M^2$ )

$\lambda$  = width of the conductor ( $\lambda = 5.5E-4M$ )

Inserting values as described for Figure 5 in equation 11, we get:

$$E2. \quad L \approx \frac{.2 \left[ \left( 12.5E-7 \frac{H}{M} \right) \cdot \left( 5.81E-5 \frac{H}{M} \right) \right]}{5.5E-4M} = 26nH$$

This is the inductance for the mechanical loop of Figure 3 and is equal to the  $L_G + L_S$  loop inductance for the MOSFET of Figure 2. Given the small size of the loop, it would appear that any attempt to reduce its inductance would prove futile. However the reduction of the inductance, as shown earlier, can provide exceptional improvement in performance and is therefore worth the effort.

Recalling equation 1, we can simplify this equation so that we can get a feel for what parameters are driving the inductance.

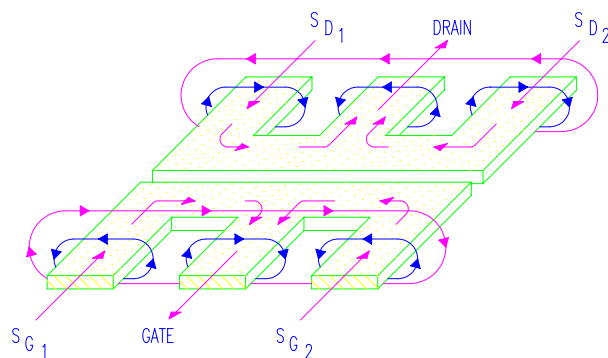
Let:  $\mu_0$ ,  $N$  and  $\mu_r = 1$ , then:

$$E3. \quad L \propto \frac{A}{\lambda}$$

From equation 3 we see that we must minimize the cross sectional area  $A$  (Area Minimization) (Figure 3) and maximize the width  $\lambda$  (Multiple Distributed Paths). If we reduce  $A$  by 10 or increase  $\lambda$  by 10, the inductance would be reduced to 2.6 nH. However there are practical limits that will limit how far we can push these parameters. This means that we must invoke additional physics to drive the inductive term even lower.

If we recall that the inductive term is actually derived from the energy stored in the magnetic field, and if we can reduce or eliminate the energy stored in the magnetic field ( $B$ ), then the inductive term will be reduced accordingly. We can do this by coupling magnetic field vectors of equal magnitude  $180^\circ$  out of phase to yield a resultant of  $\approx 0$ . This is the patented technique we call EM-Symmetry. In fact, EM-Symmetry by necessity invokes Area Minimization ( $A$ ) and Multiple Distributed Paths ( $\lambda$ ), which are subsets of the complete process.

### Electrical Advantages



**Figure 4 Coplanar DE-Series Structure**

### **EM-Symmetry**

DEI developed EM-Symmetry, shown in Figure 4, to address the need for a true low inductance, high speed, and high power device. The package design is best described as a distributed coplanar transmission line.

In a coplanar line the ground tracks lie on either side of the signal track. This topology provides several benefits. The distribution of the  $E$  and  $B$  fields are symmetric and uniform, the currents flow in sheets, and the voltage gradient changes are smooth and continuous. Referring to Figure 4, the conductors and die are shown as one element. In the DE-SERIES devices they form a coplanar transmission line. As illustrated,  $S_{G1}$  and  $S_{G2}$  are the ground tracks for the Gate signal while  $S_{D1}$  and  $S_{D2}$  are the power ground tracks used for the Drain signal. By circuit topology we insure that:

E4.  $I_G = I_{SG1} + I_{SG2}$  and  $I_{SG1} \approx I_{SG2}$  so that  $B_{IGS1} + B_{IGS2} \Rightarrow 0$

Furthermore:

E5.  $I_D = I_{SD1} + I_{SD2}$  and  $I_{SD1} \approx I_{SD2}$  so that  $B_{IDS1} + B_{IDS2} \Rightarrow 0$

This symmetry (E4 and E5) provides cancellation of magnetic field vectors in the far field, effectively reducing the insertion inductance. To enhance switching speed further, the source lead inductance negative feedback term  $L_S di/dt$  found in all conventional devices has been eliminated by integrating a differential Kelvin lead with EM-Symmetry of the input leads. Thus, the gate drive reference plane floats on the  $L_S di/dt$  term, and therefore the drain source currents flowing in  $S_{D1}$  and  $S_{D2}$  are prevented by topology from flowing in  $S_{G1}$  and  $S_{G2}$ .

Some manufacturers have invoked a Kelvin lead with no reduction in insertion inductance. This can have serious effects on device stability and reliability.

### Die Topology

The DE-SERIES die, shown in Figure 5, are manufactured with epitaxial material to more precisely control material properties. They are also designed with "small" horizontal and vertical structures and "small" cell size so that particle transit times are consistent with the desired operating frequency. These die employ multiple gate and source pads consistent with the coplaner package design of the DE-SERIES. The die also has a metal gate structure that provides an extraordinarily low value of  $R_G$ .

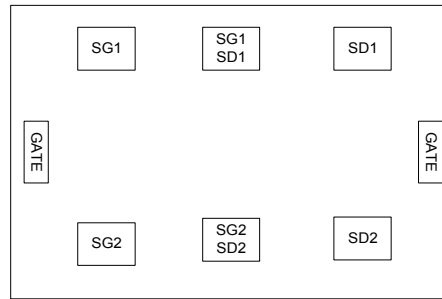


Figure 5 DE-SERIES Die Topology

## Electrical Performance

The DE-Series represent the highest level of performance of any high voltage high power MOSFET available today.

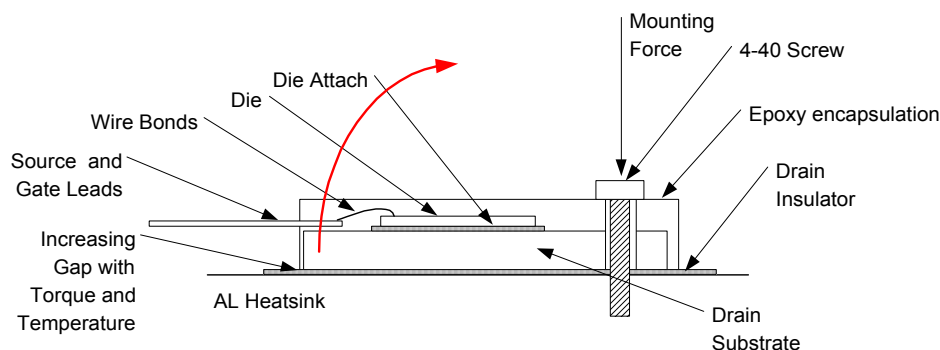
1.  $V_{ds}=100V$  to  $1000V$
2.  $T_{ON} \leq 2ns$
3.  $T_{ON DLY} \leq 3ns$
4.  $T_{OFF} \leq 2ns$
5.  $T_{OFF DLY} \leq 3ns$
6.  $F_{MAX} \geq 100MHz$
7.  $I_{DS CONT} \geq 44A$
8.  $I_{DS MAX} \geq 6X I_{DS CONT}$  in pulse mode
9.  $P_{DIS MAX} \geq 1500W$

This level of performance is now limited only by the parasitic elements  $C_{OSS}$ ,  $C_{RSS}$ ,  $C_{ISS}$ , and the capability of the gate drive. Therefore DEI has developed and continues to develop an extensive array of high performance gate driver designs.

There is a further electrical advantage of the DE-SERIES that falls out of this mechanical topology. The case (drain) to ground capacitance is approximately 10pF, compared to 100pF for a TO-247 isolated from the heat sink with a 2 mil thick kapton insulator. In high frequency, high power applications, this large capacitance can cause large ground currents and EMI problems. Furthermore, it appears directly across the drain and contributes to  $C_{OSS}$  losses.

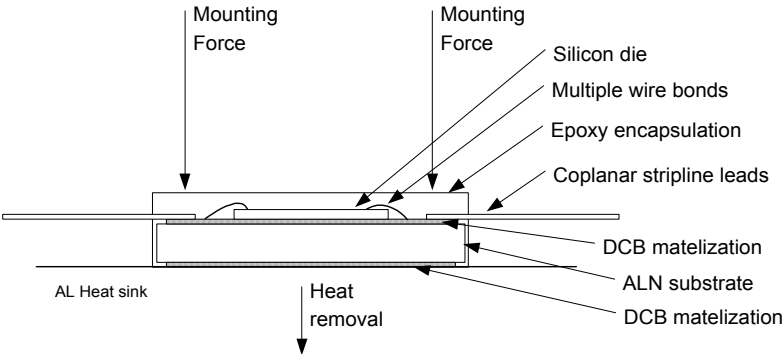
## Thermal and Mechanical Advantages

The drain substrate, usually copper in typical devices, is by default a very electrically active node. This requires an electrical insulator and therefore loss of thermal performance. The mismatch in Thermal Coefficient of Expansion (TCE) between the die and this substrate is large, often requiring buffering materials that further degrade the thermal performance. Furthermore, the mounting screw attaches the package to the heat sink at one point. The heatsink and the drain substrate are usually very different materials. When operated in a high power dissipation mode, the package will warp as shown in Figure 6 by the red arrow. This causes a loss of thermal contact, hence loss of power handling capability and an increase in mechanical die stress.



**Figure 6 TO-247 Cross-Sectioned View**

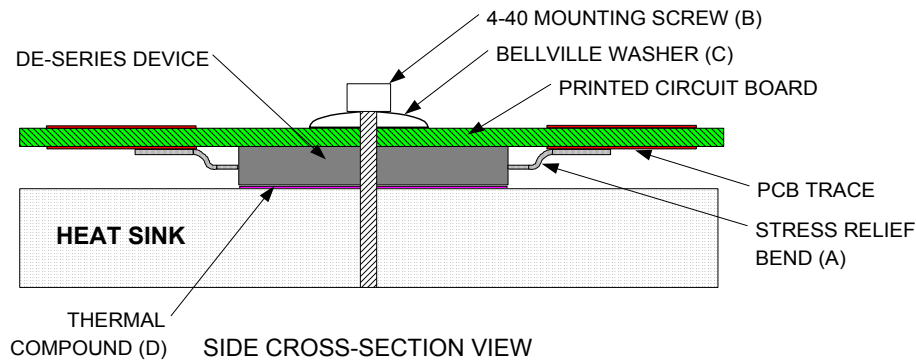
For high power applications, the DE-SERIES incorporates several design features to provide excellent thermal dissipation and high power handling capability while offering a less cumbersome mounting technique than the conventional devices we have described. The first of these is illustrated in Figure 7.



**Figure 7 DE-SERIES Cross-Sectioned View**

Here we see a cross-sectioned view of a DE-SERIES device and the thermal path from die surface to the heat sink. By minimizing layer thickness, selecting materials with low thermal impedance and with a TCE near silicon, a multi-layer configuration is assembled that not only provides low thermal impedance and low die stress but also allows for electrically isolated elements, gate, drain and source. This configuration and selection of materials provide the DE-SERIES devices with exceptional thermal resistance, ( $R_{\theta jc}$ ) as low as  $0.10^{\circ} C/W$ .



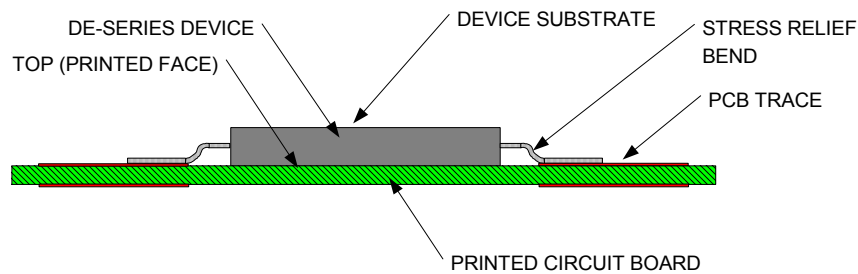


**FIGURE 8 High Power Mounting**

In order to maintain a low thermal impedance, the package design must be capable of maintaining intimate contact between the heat extraction surface of the package and the heat sink, and at the same time allow the device to expand in X (width of heat sink), Y (length of heat sink), and Z (normal to heat sinking surface). Figure 8 illustrates how this is accomplished with the DE-SERIES.

- (A) The leads are bent up and soldered to the bottom side of the PCB. This allows the device to be removed from the heat sink with the PCB, simplifying assembly procedures. The leads of the DE-SERIES are made of 99.9% pure copper with the grain structure aligned in the direction of the lead length, producing an extremely soft lead. This, along with the stress relief bend, provides excellent lead compliance and offers low stress to the package seals.
- (B) Two screws pass through the PCB on either side of the device, and place it in compression this provides X and Y compliance.
- (C) Belleville washers may be used to provide vertical compliance and maintain an even pressure on the device. This allows vertical Z expansion with no loss of contact.
- (D) The DE-SERIES package design virtually floats on the thermal compound. This allows the device to maintain excellent thermal contact with the heat sink, yet expand in X, Y and Z while minimizing the mechanical stress.

This package design and mounting configuration give the DE-SERIES a significant increase in power handling capability over conventional devices while also providing for isolated elements.



SIDE CROSS-SECTION VIEW

**Figure 9 Low Power Mounting**

For low average power applications, the device may be mounted on the component side in traditional surface mount style as shown in Figure 9. (Low power is defined as that power level which will not exceed the free air dissipation rating of the device.) The MOSFET is mounted on the component side of the PCB, with the top (printed face) of the device flat against the PCB.

### **Quality and Reliability**

DEI / IXYS are committed to setting a new standard for excellence in power semiconductors. Reflecting our dedication to industry leadership in the manufacture of medium to high power devices, reliability has assumed a primary position in raw material selection, design, and process technology. Reliability utilizes information derived from applied research, engineering design, analysis of field applications and accelerated stress testing and integrates this knowledge to optimize device design and manufacturing processes. All areas that impact reliability have received considerable attention in order to achieve our goal to be the #1 reliability supplier of power semiconductor products.

We believe DEI / IXYS products should be the most reliable components in your system. We have committed significant resources to continuously improve and optimize our device design, wafer fab processes, assembly processes and test capabilities. As a result of this investment, DEI / IXYS has realized a dramatic improvement in reliability performance on all standardized tests throughout the product line. Excellence in product reliability is “built-in”, not tested-in. Moreover, it requires a total systems approach, involving all parties: from design to raw materials to manufacturing. In addition to qualifying new products released to the market, life and environmental tests are periodically performed on standard products to maintain feedback on assembly and fabrication performance to assure product reliability.

To that end the following tests are performed: High Temperature Reverse Bias (HTRB), High Temperature Gate Bias (HTGB), Temperature Cycle Humidity Test and Power Cycling. More information is available on the DEI / IXYS web sites ([www.directedenergy.com](http://www.directedenergy.com) and [www.ixys.com](http://www.ixys.com)).

## Conclusion

The DE-SERIES devices provide a combination of unparalleled speed, power and frequency. The specific advantages are reviewed below.

### **Key Advantages of the DE-SERIES**

1. **Switching Speed:**  $\leq$ HF RF MOSFET devices and  $\approx$ 5-10 times faster than conventional MOSFETs.
2. **Frequency:** Equal to many HF RF devices and at least 5-10 times higher than conventional MOSFETs.
3. **High gain:** Approximately 3 times higher than HF RF MOSFET devices.
4. **Power Dissipation:** Approximately twice that of HF RF MOSFET devices and over 3 times higher than conventional MOSFET devices.
5. **High Power Surface mount design:** This allows the device to be loaded on to the PCB with all the other components in a high or low power configuration, simplifying mechanical assembly of the system.
6. **Lowered Mechanical Stress:** The device floats on the thermal compound such that the mounting hardware will not induce further package stress.
7. **Low Inductance Packaging:** The DE-SERIES has the lowest insertion inductance of any equivalent power device.
8. **Economical High Power Mounting:** The mounting configuration does not require machining of the PCB or an expensive clamping mechanism.

The DE-SERIES employs the most electrically, mechanically and thermally advanced high-speed device design available today. The combination of silicon die and packaging make the DE-SERIES the device of choice for high power high-speed applications.

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