ADVANCED POWER TECHNOLOGY®

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APPLICATION NOTE

CUTTING-EDGE MOUNT DOWN METHODS BOOST POWER SEMICONDUCTOR PERFORMANCE

Cutting-Edge Mount Down Methods Boost Power Semiconductor Performance and Cut System Costs

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ABSTRACT

For a power semiconductor, optimum thermal management depends crucially on the method chosen to attach it to its heat sink -- screw, solder, spring or clamp, as well as on the medium chosen to minimize interface thermal resistance. This paper will evaluate the performance of TO-264 and new T-MAX™ plastic packaged MOSFETs in a variety of mount down situations, both galvanically isolated and electrically hot. Traditional interface materials such as mica, elastomers and thermal grease will be compared against state-of-the-art "phase change" products, where interface voids are effectively filled as the material melts and flows at temperatures from 43-51°C. It will be shown that pressure mounting, with force applied centrally over the semiconductor chip, yields significantly lower junction temperatures than with conventional offset single screw attachment.

INTRODUCTION

The semiconductor industry constantly strives to improve the performance and convenience of its power product offerings. Today, choice is no longer limited to difficult-to-mount TO-3, TO-220, or TO-218 packages, these styles having largely given way to isolated mounting hole TO-220s, TO-247s and TO-264s. The motivating force here has been to eliminate the chore of isolating mounting screws, and to increase the surface area available for chip mount down. "Cold" screws cost less to install, while bigger chips increase output power. Fully isolated versions of these packages are also produced, by over-molding the normally bare copper mounting tabs with a thin layer of plastic.

The industry has also realized that the presence of a mounting hole drastically curtails the surface area available for chip placement. As a result, various "screw-less" housings have started to appear where the full footprint area is available for chip placement. Device mount down is accomplished by soldering the device down onto a suitable substrate, or by pressing it against the surface of a heat exchanger with a centrally located spring clip. When the package is soldered down, it is known as a "surface mount device" (SMD), representative products being the well-established D-PAK, D^2-PAK, and D^3-PAK. While exclusively pressure mounted packages are still limited,, some very high performance products do exist, the most advanced available today being the new TO-247 footprint T-MAX™ from Advanced Power Technology. This TO-247 outline device will accept chips as large as those accommodated in the larger TO-264 package, yielding the same low $R_{DS(ON)}$ and power handling capability, but with the smaller footprint.

While these innovations provide more "watts per square inch", it is also important that the equipment designer optimize device mount down for maximum cost effectiveness. This paper will evaluate the performance of well established interface media like thermal grease, mica and loaded elastomers, as well as that of state-of-the-art "phase change" materials, where interface voids are effectively filled as the material melts and flows at temperatures from 43-51°C. Comparisons will be made between case-to-sink thermal resistance of screw mounted and clip mounted products with like chip sizes, in both isolated and non-isolated situations, to highlight the vastly improved thermal transfer made possible by the centrally applied mounting force of a spring clip or clamp.

TEST SET UP

Figure 1 illustrates the water-cooled heat exchanger used to conduct the tests. It consists of a 1/2" thick aluminum plate, with an embedded 3/8" diameter water pipe zigzagging under its 12" by 8" surface. The DUTs (devices under test) are installed directly over the water channel for lowest sink-to-ambient thermal impedance, measured at about 0.12 K/W after a 10sec 150W power pulse. Heat sink temperature is monitored by 0.01" diameter wire type K thermocouples, installed in holes bored 0.05" from and parallel to the mounting surface, terminating under the DUTs as shown. Case temperature is measured by similar thermocouples, installed in holes bored 45° up, to penetrate the sink surface at the DUT footprint center points.

DUT attachment is by either a purpose-designed spring clip secured with a single 3mm machine screw, by a 6-32 machine screw directly through the hole in the package, or by the special calibrated "C" clamp shown. Since the recommended maximum clamping force for a TO-264 or T-MAX™ package is 30kg force, the jig depicted in Figure 2 is used to establish this force in the "C" clamp. With a known torque applied, the clamp grips a spacer block of the same thickness as the heat sink web plus DUT. The winch is then tensioned until the trapped sheet of film is just released. Release force, indicated by the spring balance, is set to 30kg by varying the torque applied to the clamp. For the setup shown, the required torque is 5dNm, and this value is used for all thermal measurements with the "C" clamp. The spring clip option is a custom part designed by BARCO Belgium for mounting TO-247 devices in their range of professional projection systems. Its nominal applied force is 5kg, representing the low end of acceptable mounting pressure for the types of DUT under test. It was used deliberately for that reason, to provide comparison with mounting at the higher force level exerted by the "C" clamp. The third mounting option, a 6-32 screw with a 5/16" diameter under-head washer, was torqued to 7dNm (6in-lb), the suggested limit for this size machine screw.

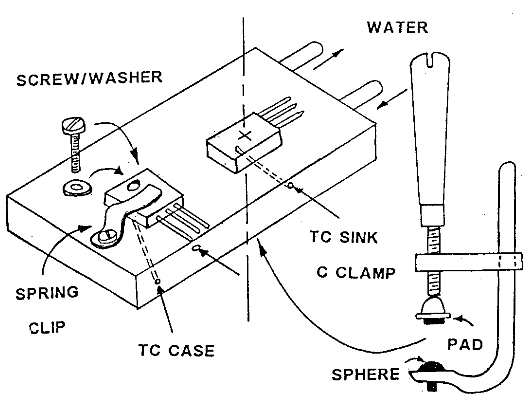

Figure 1 - Water-cooled Test Fixture

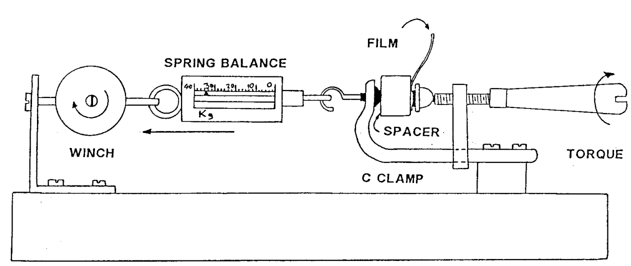

Figure 2 - Mounting Clamp Calibration

TEST PROCEDURE

The goal of the tests was to measure peak junction temperature in the various DUTs, as a function of mounting method and case to sink interface. As long as the heating power and final ambient are constant, with the DUTs all positioned for identical sink-to-water thermal resistance, peak junction temperature is directly proportional to interface thermal resistance. T_J max then becomes a figure of merit for the whole mounting system, including both attachment and interface material. Thermal resistance, junction-to-case or junction-to-sink, is simply calculated from T_J, T_{CASE} and T_{SINK}. Interface thermal resistance is the difference between the two.

Heat input is provided by a 35VDC/5A regulated power supply, adjusted such that DUT drain voltage measured at its terminals is 30V or 20V, depending on the nature of the test being run. Heating current and time duration are always 5A and 10 seconds, the time interval being chosen so that at its conclusion the DUT is operating in a steady state DC thermal mode, and not accumulating additional heat. Both these parameters are programmed into the APT designed thermal impedance tester used to measure junction temperature.

In this gear, a precision current source establishes a 10mA calibration current in the DUT body diode, as long as this device is not conducting heating current. Positive drain voltage is removed from the DUT during its inactive period, so that the 10mA can flow unhampered, by a MOSFET switch in series with the DUT. This switch is turned on and off along with the DUT by the 10sec long input pulse. In that the body diode forward voltage drop, V_{SD}, is directly proportional to junction temperature, its value decreasing by about 2.6 mV for each degree C increase in T_J, measurement of V_{SD} permits accurate assessment of T_J. A few microseconds after the heating pulse ends, a sample-and-hold circuit measures V_{SD} during an interval of 20µs, this data being recorded on a VOM. Junction temperature is then read off from an oven established calibration curve of V_{SD} versus T_J.

In the tester, heating current amplitude is programmed by applying an appropriate voltage to the "I_D set" input, the calibration factor being 1V per amp of heating current. This voltage is used to modulate V_{GS} of the DUT, with current feedback to maintain I_D at the programmed level.

TEST RESULTS

1. APT5010LVR TO-264 package mounted with Thermalcote II silicone-free thermal compound.

i) 6-32 screw:

$R_{\theta JC}$ = f (T_C=45°C, V_{SD}=0.428V)
T_J at V_{SD} = 0.428V = 62°C, giving
$R_{\theta JC}$ = (T_J - T_C)/P_D=17/150=0.11K/W

$R_{\theta JS}$ = f(T_S=33°C, T_C=62°C), giving
$R_{\theta JS}$ =(T_J - T_C)/P_D = 29/150 = 0.19K/W
$R_{\theta CS}$ = (0.19 - 0.11) = 0.08K/W

ii) Spring clip.

$R_{\theta JS}$ = (subscripts dropped) = f(33°C, 0.434V) giving T_J = 60°C, $R_{\theta JS}$ = 0.18K/W and $R_{\theta CS}$ = 0.09K/W

iii) Clamp

$R_{\theta JS}$ = f(34°C, 0.445V), giving T_J = 56°C, $R_{\theta JS}$ = 0.15K/W & $R_{\theta CS}$ = 0.04K/W

Observations: The Barco clip mount, with its centrally applied mounting force, is not much better thermally than a 6-32 single-sided screw mount. The 30kg clamp, on the other hand, has notably better performance. A possible explanation here is that the low pressure Barco clip is not totally effective with a "hard" insulating media-free interface, the high force exerted by the clamp being required to "squash" the joint together.

2. APT5010B2VR T-MAX™ mounted with Thermalcote II thermal compound.

i) Clamp

$R_{\theta JC}$ = f(42°C, 0.433V)
giving T_J = 58°C & $R_{\theta JC}$ = 0.11K/W
$R_{\theta JS}$ = f(35°C, 0.433V)
giving $R_{\theta JS}$ = 0.15K/W & $R_{\theta CS}$ = 0.04K/W

Observations: The results here show that a T-MAX™ package is virtually identical in performance to a like-chipped TO-264, when mounted in the same (clamped) manner. Junction-to-case thermal resistance is the same very low value for both devices, measured clamped for the T-MAX™, but screw mounted for the TO-264. Thermal resistance, junction-to-case, is of course, independent of mounting method.

Bergquist HIFLOW™ grease replacement material.

Bergquist HIFLOW™ is a new "phase change" material designed specifically to replace grease as a thermal interface. It is a filled polymer that may be applied either to a heat sink or directly to the mounting tab of the semiconductor itself. At even low mounting pressures, the material changes from a solid and flows at approximately 43°C, thereby assuring total wet-out of the interface. Thixotropic characteristics of the material prevent it from flowing out of the interface. The result is a thermal interface comparable to grease, without the mess, contamination and difficult handling. In order to verify the performance of this product with APT MOSFETs, the HIFLOW™ applicator fixture of Figure 3 was fabricated. In this fixture, a DUT is inserted tab-side up in the machined groove, this groove being exactly the depth of the device package. A stop is also affixed in the groove, to prevent the device moving when the spatula is scraped across the tab. The fixture, with device inside, is heated to about 75°C in an oven, along with a small quantity of HIFLOW™in a small vial. A few drops of hot liquid HIFLOW™ are then applied to the DUT tab, and squeegeed across with the spatula. The rectangular cutout in the stencil corresponds to the copper tab area of the DUT, while stencil thickness is the 0.004" recommended by Bergquist for best performance. Once applied, the material is quite dry to the touch.

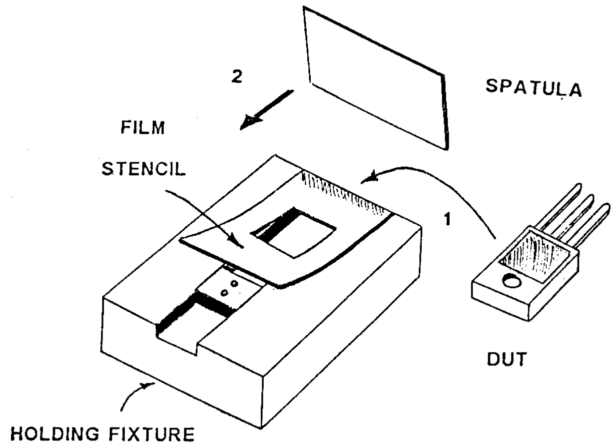

Figure 3 - HIFLOW™ Deposition Fixture

3. APT5010LVR on HIFLOW™

i) 6-32 Screw

$R_{\theta JS}$ = f(33°C, 0.426V)
T_J at 0.426V = 63°C
giving $R_{\theta JS}$ = 0.20K/W and $R_{\theta CS}$ = .09K/W

ii) Spring clip

$R_{\theta JS}$ = f(34°C, 0.423V)
T_J at 0.423V = 64°C
giving $R_{\theta JS}$ = 0.2K/W and
$R_{\theta CS}$ = 0.09K/W

iii) Clamp

$R_{\theta JS}$ = f(33°C, 0.422V)
giving $R_{\theta CS}$ = 0.09K/W

Observations: As suggested by Bergquist, HIFLOW™ seems to function well at relatively low mounting pressures, in that measured values of T_J and $R_{\theta CS}$ are virtually independent of mount down. Interface thermals are of the same order as those obtained with thermal grease at low pressure, but not as good as those obtained with grease at high pressure.

4. APT5010B2VR on HIFLOW™

i) Barco clip

R_θ = f(39°C, 0.408V)
T_J at 0.408V = 64°C
giving $R_{\theta JS}$ = 0.17K/W and
$R_{\theta CS}$ = 0.06K/W

ii) Clamped at 30 kg

Same results as above;
$R_{\theta JS}$ = 0.17K/W and $R_{\theta CS}$ = 0.06K/W

Observations: Better results for apparent interface thermals than the TO-264 package, but junction temperatures were nearly the same in both cases. This probably indicates a non-uniform interface for the APT5010B2VR, but with very good thermal contact near the thermocouple position.

Metafix pre-greased mica.

This is a modernized version of the traditional mounting system employed for decades, when galvanic isolation between device and heat sink is mandatory. It is tested here as a benchmark, against which will be compared the more exotic interface materials. The pre-greased mica used is die-cut to the proper size for TO-247/264 packages, and is delivered sandwiched between protective sheets in roll form. While it is generally accepted that mica performs very well as an interface material, it is difficult to apply and is messy when greased.

5. APT5010LVR on mica

i) 6-32 screw mount

$R_{\theta JS}$ = f (27°C, 0.226V)
T_J at 0.226V = 141°C
giving $R_{\theta JS}$ = 0.76K/W and
$R_{\theta CS}$ = 0.65K/W

ii) Barco clip

$R\theta_{JS}$ = f(28°C, 0.241V)
T_J at 0.241V = 135°C
giving $R\theta_{JS}$ = 135°C and
$R\theta_{CS}$ = 0.71K/W

iii) Clamp at 30kg

$R_{\theta JS}$ = f(30°C, 0.253V)
T_J at 0.253V = 130°C
giving $R_{\theta JS}$ = 0.67K/W and
$R_{\theta CS}$ = 0.56K/W

Observations: Here, the beneficial effects of central force application are quite apparent, with T_J operating at 11°C lower with 30kg clamping than with screw mounting.

6. APT5010B2VR on mica

i) Barco clip, 100W input (100W used initially to reduce T_J below 150° during SILPAD tests)

$R_{\theta JS}$ = f(26°C, 0.272V)
T_J at 0.272V = 120°C
giving $R_{\theta JS}$ = 0.94K/W and
$R_{\theta CS}$ = 0.83K/W

ii) Clamp, 100W input

$R_{\theta JS}$ = f(26°C, 0.298V)
T_J at 0.298V = 109°C
giving $R_{\theta JS}$ = 0.83K/W and
$R_{\theta CS}$ = 0.72K/W

Observations: Again, the benefit of centrally applied force is unmistakable.

Silpad® 1500 film.

This thermally conductive insulator is designed to be clean, grease free and flexible. The combination of a tough fiberglass carrier material with silicone rubber creates a versatile material for minimizing interface thermal resistance, with sufficient dielectric strength to withstand high voltage. Because silicone rubber exhibits cold flow, which excludes air from the interface as it conforms to the mating surfaces, the need for thermal grease is eliminated. In that this material, with its rough surface texture, will show a 15-20% decrease in thermal resistance over a 24-hour period, the values measured in the tests may err on the high side since the measurements were not repeated later.

7. APT5010LVR on Silpad®

i) 6-32 Screw

$R_{\theta JS}$ = f(23°C, 0.13V)
T_J at 0.13V = 178°C
giving $R_{\theta JS}$ = 1.03K/W and
$R_{\theta CS}$ = 0.92K/W

Because T_J > 150°C, its max allowable value, the test circuit was reprogrammed to input 100W, instead of 150W, by reducing the DUT drain voltage to 20VDC.

i) 6-32 screw, at 100W

$R_{\theta JS}$ = f(18°C, 0.287V)
T_J at 0.287V = 117°C
giving $R_{\theta JS}$ = 0.99K/W and
$R_{\theta CS}$ = 0.88K/W

ii) Spring clip, at 100W

$R_{\theta JS}$ = f(20°C, 0.293V)
T_J at 0.293V = 115°C
giving $R_{\theta JS}$ = 0.95K/W and
$R_{\theta CS}$ = 0.84K/W

iii) Clamp, at 100W

$R_{\theta JS}$ = f(21°C, 0.321V)
T_J = 104°C
$R_{\theta JS}$ = 0.83K/W and
$R_{\theta CS}$ = 0.72K/W

Observations: With a soft material like Silpad, when side-located screw mount down is employed, the material flows in the high pressure region around the screw position, the opposite end of the DUT tilts up from the sink, and good thermal contact over much of the mounting area is lost. This phenomenon is reflected in the wide 13°C (11%) temperature difference between screw and clamp mounting.

8. APT5010B2VR on Silpad®

i. Spring Clip, at 100W

$R_{\theta JS}$ = f(25°C, 0.230V)
T_J at 0.230V = 138°C
$R_{\theta JS}$ = 1.13K/W and
$R_{\theta CS}$ = 1.02K/W

ii) Clamp, at 100W

$R_{\theta JS}$ = f(26°C, 0.263V)
T_J at 0.263V = 127°C
giving $R_{\theta JS}$ = 1.01K/W and
$R_{\theta CS}$ = 0.9K/W

Observations: In this case it appears that the 5kg mounting force applied by the Barco clip was insufficient to ensure adequate compression of the rough surfaced silicone loaded fiberglass. Why this phenomenon did not appear under similar circumstances with the TO-264 package is unclear. The $R\theta_{CS}$ value calculated for the 30kg clamping force is also inexplicably high.

Orcus "Crayotherm" thermal transfer pads.

These pads bear the same relationship to grease coated mica as Bergquist HIFLOW does to plain thermal grease. Crayotherm is a similar "change of state" thermal material that is used to coat both sides of an electrically insulating polyimide film, either 0.002" or 0.003" thick. At 51°C, these coatings change state from a solid to a liquid and flow into all the microscopic voids between the semiconductor and heat sink. When the electrical circuit is no longer under power, the change of state coating returns to the solid state. In this condition it is, of course, dry to the touch.

9. APT5010LVR on 0.003" Crayotherm

i) 6-32 screw at 100W

$R_{\theta JS}$ = f(20°C, 0.321V)
T_J at 0.321V = 102°C
giving $R_{\theta JS}$ = 0.82K/W and
$R_{\theta CS}$ = 0.71K/W

ii) Spring Clip

$R_{\theta JS}$ = f(21°C, 0.336V)
T_J at 0.336V = 98°C
giving $R_{\theta JS}$ = 0.77K/W and
$R_{\theta CS}$ = 0.66K/W

iii) Clamp

$R_{\theta JS}$ = f(23°C, 0.360V)
T_J at 0.36V = 89°C
giving $R_{\theta JS}$ = 0.66K/W and
$R_{\theta CS}$ = 0.55K/W

Observations; These are the best values of interface thermal resistance to be achieved so far with an isolated mount down. As for the Silpad material, however, a substantial improvement is realized by substituting center mounting for side mounting, thereby eliminating the "tilt" syndrome. The material does seem to be sensitive to mounting pressure, in that results at 30kg are significantly better than at 5kg.

10. APT5010B2VR on 0.0003" Crayotherm

i) Spring clip

$R_{\theta JS}$ = f(28°C, 0.328V)
T_J at 0.328V = 98°C
giving $R_{\theta JS}$ = 0.7K/W and
$R_{\theta CS}$ = 0.59K/W

ii) Clamp

$R_{\theta JS}$ = f(28°C, 0.340V)
T_J at 0.34V = 93°C
giving $R_{\theta JS}$ = 0.65K/W and
$R_{\theta CS}$ = 0.54K/W

Observations: The Orcus material seems to give very consistent results between the two packages. Again, the recorded values of interface thermal resistance are outstandingly low for a galvanically isolated system that does not resort to costly BeO or AlN ceramic interfaces.

CONCLUSIONS

It has been clearly demonstrated that the thermal performance of APT's new T-MAX™ pressure mounted package, with its TO-247 compatible footprint, is equal in every respect to that of the much larger TO-264, when both are equipped with the same chips and the TO-264 is pressure mounted like its sibling. When a TO-264 is conventionally screw mounted, its thermal performance is inferior to that of the T-MAX™. The fundamental reason for this is the package "tilting" that occurs when a laterally situated mounting screw compresses the interface material near the end of the package. This canting action leads to reduced contact pressure under much of the device, with consequent poor thermal transfer.

Assessment of the diverse interface products tested indicates that most improvements, compared to the products available 20 years ago, owe more to ease-of-use than to fundamental advances in heat transfer technology. Nonetheless, there is no doubt that the new "phase change" materials do perform admirably, as well as being very user friendly. Orcus Crayotherm in particular, exhibits the lowest thermal resistance of any isolating medium tested, although this may be due in part to its remarkable thinness.

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