LOW COST, HIGH DENSITY, POWER PACKAGING FOR SPACE SYSTEMS

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ABSTRACT
The planned dramatic increase in satellites will require visionary design to reduce semiconductor cost, weight, and size without compromising reliability. Current designs typically use TO-254 type devices (through hole) for high power and surface mount devices (SMD) for low power. This paper will review new low cost hermetic power SMD packages used for Rectifier, Schottky, TVS, and MOSFET which can replace the TO-254 types. There are some concerns with thermal dissipation and coefficient of thermal expansion (CTE) mismatch when using high power SMD on printed circuit boards (PCB).

DISCUSSION ON SMD
The individual power components are not necessarily the main cost drivers on Space Systems. High costs are mostly attributed to excess weight. In Geosynchronous Orbit (GEO) the penalty is estimated at $40,000.00 per Kg. High costs are also caused by labor intensive assembly, wiring, hand soldering, and high piece part count. Standard industry power packages require complex installation, hardware, glue, conformal coating compounds, and heatsinks.

Through-hole technology is plagued with reliability problems such as cracked seals, damaged leads, and higher junction temperatures. Glass or ceramic seals are prone to break during lead bend or insertion into the PCB. Each component requires mounting hardware and the packages are heavy and occupy critical space.

From a performance point of view, the round leads of through-hole packages have high inductance and resistance. Additionally, the small lead sizes do not allow connection to larger gauge or odd sized wires in the next assembly.

The trend in the Aerospace Industry is to convert from through-hole to SMD packages. However, the high power DO-4 (see Figure 1), DO-5, and TO-3 are instead being replaced by TO-254 type.
The DO-4 package is still used in Space designs, however it is heavy and has several quality concerns. (Note that all discrete packages depicted in CAD form are shown actual size for comparison.) The TO-254 (see Figure 2) is lighter weight than the DO-4 and has the advantage of an internal isolated substrate. However, the TO-254 is not truly SMD since it must be attached with hardware and can only be used on a surface mount PCB if the leads are bent and flattened. The TO-254 has fragile glass-to-metal or ceramic-to-metal eyelets, high weight, high cost, and difficulties in circuit level assembly. It is also not convenient to use mixed technology (through hole and SMD) in the same circuit.

Space system manufacturers, who have historically been conservative, are using SMD to reduce critical size and weight. For low power applications under 10 amps average, there is a myriad of hermetic surface mount active components available in flatpack, MELF, and CLCC. For high power applications over 10 amps the selection of hermetic SMD is limited. Several low cost, high density, surface mount hermetically sealed power packages have been developed to replace the TO-254. The goal of high power SMD is to make the package as small as possible to accommodate the largest die. The discrete high power semiconductor industry has designed various sizes and shapes of die (hexagonal, round, square, rectangle) and different metallization schemes (solderable gold or tri-metal, metallurgically bondable gold or silver, wire-bondable aluminum, etc.) Optimal space utilization and efficiency is achieved by using a square die in a square package. This is critical because there is a direct correlation between large die area and lower power dissipation and lower thermal resistance. It is desirable to use simple materials (eliminate exotic alloys) to lower costs, and to eliminate fragile or CTE mismatched processes which are prone to reliability problems. Some examples of these packages are the Slugger™, the ThinKey™, and the CoolPack™.

With these SMD packages, weight and size are significantly reduced, up to a factor of 10X. No mounting hardware is required, labor cost is low, and they can be tape and reeled or waffle packed for high volume pick-and-place. Other advantages include no glass or ceramic seals to break, no lead bends or insertions into PCB, and the flat leads have lower inductance and resistance. The thermal resistance of the SMD package is lower than through hole packages due to the thin metal (thermally conductive) contact beneath the semiconductor die.

Figure 3 gives a comparison of power through-hole versus power SMD. The values in Figure 3 are based on using about the same die size. It can be seen that the weight is reduced up to a factor of 10X while significant reduction in thermal resistance and overall size are achieved.

<table>
<thead>
<tr>
<th>Package Type</th>
<th>Weight (grams)</th>
<th>ROJC (C/W)</th>
<th>Volume * (cubic inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DO-4</td>
<td>10</td>
<td>1.5</td>
<td>0.250</td>
</tr>
<tr>
<td>TO-254</td>
<td>9</td>
<td>1.5</td>
<td>0.125</td>
</tr>
<tr>
<td>CoolPack1</td>
<td>1.5</td>
<td>0.3</td>
<td>0.050</td>
</tr>
<tr>
<td>ThinKey1</td>
<td>1.0</td>
<td>0.3</td>
<td>0.020</td>
</tr>
<tr>
<td>Slugger1</td>
<td>0.9</td>
<td>0.5</td>
<td>0.012</td>
</tr>
</tbody>
</table>

* Includes heatsink, isolation hardware, and/or PCB.

Though these packages solve many problems, there are issues which must be addressed when utilizing large SMD devices. One concern is that there is no standardization of power SMD (except the DO-217). Since high power SMD is relatively new and has not reached the high volumes of through-hole packages, there are few
package manufacturers offering these as standard (off-the-shelf). Therefore, each semiconductor manufacturer may have their own size of package with different materials and construction processes. Inspection of SMD package types which have all the connections on the bottom side is difficult after PCB attach, and there exists the possibility of trapped flux or solder balls. Large SMD packages are not always available on tape and reel for automated PCB assembly. Additionally, specialized equipment and expertise is required for power SMD installation and soldering to the PCB.

One issue with using high power SMD on a circuit board is the most frequently asked question: “How do you get the heat out?” System manufacturers typically use low thermal dissipation materials such as G10, FR4, or similar polyimide type PCB. Some power SMD packages are rated at hundreds of watts when properly heatsunk, however they can only dissipate about 2W when mounted on a polyimide type PCB without special thermal vias.

A serious reliability problem is the CTE mismatch of the SMD (typically 4.5 - 7 ppm/°C) to the PCB (typically 20-40 ppm/°C). For SMD with contacts (footprints) greater than 0.250” square, there is a high possibility that the solder joint between the SMD and the PCB will fail during extensive power or temperature cycling.

Figure 4. The Slugger™1 and Slugger™2 SMD packages for high power Rectifiers and TVS.

The Slugger™ (see Figure 4) is designed for round or hexagonal die such as high power Rectifiers and Transient Voltage Suppressors (TVS). The Slugger™ accommodates up to a 0.225” diameter die which can be rated up to about 70 amps, depending on the voltage. The package technology has a patent pending design which puts the die in compression allowing the maximum surge capability of the die. The technology uses a ceramic frame and metal discs with eutectic die attach. A higher profile version, the Slugger™2, allows stacking of up to four (4) die in TVS applications allowing greater surge suppression power and higher voltages.

The ultra-low profile Slugger™1 (0.090” maximum) provides external dielectric protection over 600 volts at sea level (this design is only limited due to arcing from the top to bottom pad across the ceramic) and up to 250 volts at any altitude. The higher profile Slugger™2 (though not as desirable for high current DC applications due to its higher thermal resistance) provides external dielectric protection up to 700 volts at any altitude. For applications requiring higher voltages, conformal coating can be applied over the device after mounting on the PCB. Conformal coatings from manufacturers such as Furane and Conap have dielectric protection rated at 1,000 volts per 0.001” thick coating.

The Slugger™ is capable of surviving extensive thermal shock from liquid nitrogen (-197°C) to hot oil (+150°C), and survives all applicable environmental qualification tests (i.e.: Group B, C, and E testing per MIL-PRF-19500 or LAT testing per ESA5000). An advantage to users is that the package footprint is round and less than 0.250” in diameter. This means that the Slugger™ can be safely used on polyimide PCB since the CTE mismatch is offset by the small size and round shape (minimizes stress). The Slugger™ also employs built-in stress relief through the copper alloy top strap.

Figure 5. The ThinKey™ SMD package for high power Rectifiers and Schottkys.

The ThinKey™ (see Figure 5) package is designed for square die such as high power Rectifiers and Schottkys. The package is available in at least three (3) sizes from 25 amp die size to 150A die size. The ThinKey™ utilizes the largest standard production Schottky
die available, which is 0.306” square. The ThinKey™ utilizes the same construction techniques as the Slugger™, therefore the environmental reliability and qualification are the same. The only consideration which is unique for the ThinKey™ (compared to the Slugger™) is that the larger sizes may not be compatible with pure polyimide boards due to the CTE mismatch and large stress potential. This can be offset by using lower CTE thermal vias, or lower CTE board materials such as Kevlar or ceramic.

The ThinKey™ utilizes high temperature (>320°C) solder, therefore it will not reflow when assembled onto the PCB. An additional circuit advantage is that the ThinKey™ with a Schottky die (typically used as an output rectifier) can be used without the top strap where the transformer wires are soldered directly to the top of the package. This allows reduced PCB area and lower stray capacitance and inductance.

**Figure 6. The CoolPack™1 SMD package for high power MOSFETs and IGBTs or dual Rectifiers and Schottkys.**

The CoolPack™ (see Figure 6) package is designed for high power MOSFETs and IGBTs or dual Rectifiers and Schottkys. The CoolPack™ is available in at least three (3) sizes as three (3) terminal and five (5) terminal packages. The CoolPack™ is primarily designed for aluminum top die which are wire bonded with aluminum wire, whereas the Slugger™ and the ThinKey™ are designed for solderable die. The CoolPack™ has all the electrical connections on the bottom of the package and is relatively large, therefore it should not be attached onto a polyimide board.

The CoolPack™ series accommodates MOSFET or IGBT die sizes from #5 to #10 including the protection rectifier(s) die in the same package. The package technology has a patented ceramic frame design which reduces weight, provides additional dielectric protection, and increases mechanical strength. The frame also employs “arches” in the ceramic for ease of cleaning and visual inspection (it is difficult to inspect for solder bridging underneath an SMD package when all terminations are against the PCB).

The CoolPack™ package has been qualified to Group B,C, and E testing per MIL-PRF-19500 and has been tested beyond these requirements for thermal shock, 1,000 cycles from liquid nitrogen (-197°C) to hot oil (+150°C). The minimum spacing between the CoolPack™ metal contacts is 0.040”, therefore the dielectric protection is over 1200 volts at sea level and over 400 volts at any altitude.

An in-circuit advantage of the CoolPack™ is that it can be used for applications where the MOSFET and protection Rectifiers (such as Schottky or Synchronous rectifiers) must be enclosed in one package. This reduces the PCB footprint and significantly reduces costs and parasitic inductance and capacitance. Since the package has multiple terminations, it can be used for dual Rectifiers (centertap configuration), or for paralleling common drain or common cathode type configurations.

**DISCUSSION ON HPM**

The high power SMD packages reviewed herein offer many benefits, however the concerns remain about how to dissipate their potential power and how to eliminate the CTE mismatch. The best solution to both the thermal dissipation and CTE mismatch problems is the Hermetic Power Module (HPM). The Hermetic Power Module consists of high power SMD packages mounted on an isolated substrate(s) and a metal base which are closely matched CTE materials.

These materials are also simple, low cost, and light weight. The HPM allows optimum thermal management via correct placement of heat generating components. The overall cost of the circuit is reduced because there is one device as opposed to several different SMDs, each with their own specification. The reliability is
increased substantially since there are no glass or ceramic seals to bend or break.

HPMs are designed for the highest reliability applications such as Satellites, Military Systems, and Commercial Aircraft. These Hermetic Power Modules are rated for -55°C to +150°C. The high temperature is limited only by the rating of the MOSFET die. The low temperature is limited only by the rating of the direct bond copper substrate (rectifier versions and/or versions with special substrates are available with ratings of -80°C to +200°C).

HPMs can be made to fit the exact application, eliminating the problem of “putting a square peg in a round hole”. There are many possible shapes and configurations which can be tailored to the specific application. The HPM is generally a custom device, however standard materials are used to reduce cost and development time.

A general comparison is given in Figure 7, which illustrates the overall performance of a circuit utilizing four (4) 20 amp Schottky rectifiers in parallel with through hole versus HPM technology. It is apparent that there is a significant savings in weight and size while reducing thermal resistance.

<table>
<thead>
<tr>
<th>Package Type</th>
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<th>Volume (cubic inches)</th>
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<td>DO-4</td>
<td>70</td>
<td>0.375</td>
<td>1.00</td>
</tr>
<tr>
<td>TO-254</td>
<td>55</td>
<td>0.375</td>
<td>0.70</td>
</tr>
<tr>
<td>HPM</td>
<td>25</td>
<td>0.150</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Note: weight, thermal, and volume are for total circuit including hardware and heatsinks.

In normal operation, the Schottky is reverse biased by the battery cell and basically does nothing. The charge diodes receive a positive bias from the battery cell but not enough to open them. In the event that a battery cell fails (open circuit), the battery current passes through the Schottky, thus bypassing the failed cell.

Figure 8 is a Battery Bypass Protection circuit using DO-5 for the Schottky and DO-4 for the diodes. A typical bypass circuit made with this through hole technology would weigh about 150g per cell. For a satellite having 32 cells this equates to 4.8Kg of hardware. At an estimated launch penalty of $40,000.00 per Kg for a GEO satellite, this would be a cost of $192,000.00.
Figure 9. MM136 Battery Bypass Protection HPM reduces GEO launch cost (about ½ scale).

Figure 9 is an example of a Battery Bypass Protection HPM, part number MM136. This HPM is an off-the-shelf device utilizing the standard Slugger™1 and ThinKey™3 packages. The MM136 weighs less than 25g including the hardware. In the above example with 32 cells, this would be a cost savings of $160,000.00 over through-hole technology.

In addition to hermetic power SMD, the HPM mechanical components consist of the base, substrate, and terminations. The following is a brief description of material and technology:

1. The base is the heatsink and mounting plate. Standard material is Al/SiC (Aluminum impregnated Silicon Carbide). Al/SiC is 3 times lighter than copper (2.7 g/cc vs. 9 g/cc). Al/SiC has the same thermal conductivity as aluminum (180W/mK), and is very closely matched to the SMD (7.2 ppm/°C). In the automotive industry, Al/SiC is a common material used in applications such as Honda engine cylinder walls and Lotus brake pads. An alternate material is a Copper/Molybdenum sandwich (Cu/Mo/Cu, 33/34/33) which is heavier than Al/SiC (Cu/Mo/Cu = 10 g/cc), but provides greater mechanical strength and higher thermal conductivity (260W/mK).

2. The substrate interconnects the SMD and terminations and electrically isolates the circuit from the base. Standard material is DBCu/Al₂O₃ (Direct Bond Copper on Alumina). The thermal conductivity of the sandwich is 200W/mK and the CTE (7 ppm/°C) matches the Al/SiC base. Alternate materials such as Beryllium Oxide (BeO) and Aluminum Nitride (AIN) are available with DBCu, however they are more expensive, not as reliable in temperature cycling, and have reduced bond strength.

3. The terminations connect the HPM to the next assembly circuit. Terminations are virtually unlimited, including solder turrets, male and female screws, plug-in, straps, and various wire sizes. Standard material is copper or copper alloy. Copper has low dc resistance and is ideal for high frequency applications because it reduces “skin effects”. For high current threaded terminals, Cold Rolled Steel (CRS) is used for higher torque capability (stronger threads).

The HPM is ideal for applications where reliability and performance are mandatory and where priority is given to low cost and weight. Popular electronic systems where HPMs are used are Spacecraft Battery Protection, Power Supply Switch or Distribution, and Motor Control.

Circuits for Spacecraft Battery Protection include Battery Bypass, Charge and Discharge (as discussed above), and Solar Array Shunt. These circuits work with the solar arrays or batteries to protect sensitive electronics by redirecting or shunting current during eclipse or battery failure. The advantages of HPM in these circuits are light weight, small footprint, custom shapes to fit cylindrical batteries, low voltage drop, and long term reliability.

Power Supplies include Boost or Buck Converters, Power Distribution Units, Radar Switching, Fire Control, and Synchronous Rectification. These circuits can switch up into the MHz range, requiring sophisticated component placement and heat sinking to prevent oscillations and thermal runaway. The HPM excels in these conditions due to low parasitic ac/dc losses and enhanced thermal management.

Movement of surfaces on a vehicle such as wings, flaps, booster nacelles, docking systems and fuel pumps are typically initiated by electric motors. Motor control circuits such as Three Phase or Single Phase Rectifier, IGBT, or MOSFET Bridges convert power directly from engines or rockets. There are severe variable spikes and fluctuations which can be absorbed by the HPM because of its rugged, matched CTE construction and low thermal resistance.
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