Evolution Of A High Power RF Part: The ARF450

Packaging is the key to thermal performance of power semiconductors

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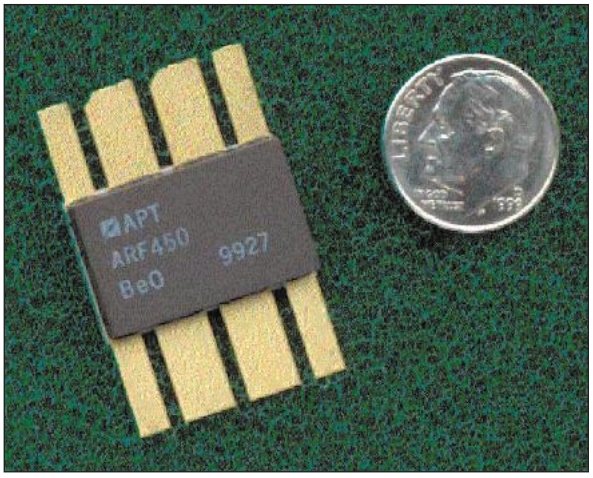
Advanced Power Technology Inc. (APT) started building its MOS IV switchmode power MOSFETs in 1987. Soon after the introduction of its 104 and 105 size die, several customers who used these switchmode devices in power supplies for RF amplifiers informed the company that the parts worked as RF amplifiers at the lower ISM frequencies between 2 and 27 MHz. Not only did they perform well, they were considerably cheaper than the 50 volt RF MOSFETs they replaced and they were able to operate at 150 volts or even 300 volts. The higher operating voltage permitted easier output matching.

At about this time, Motorola sampled a new part called the MRF156. It was an MRF150 die in a common source TO-247 plastic package. At the time, APT used the same assembly contractor as Motorola and when APT decided to build an RF-specific part, it was natural to build on that idea and use the similar configuration — even more so when Motorola decided not to introduce their part. The first parts were made with APT's standard MOS IV switchmode die.



▲ **Development of the ARF450 required a complete re-analysis of thermal design.**

RF-specific die geometry was introduced in 1997, greatly increasing the frequency range of the product line all the way to 100 MHz.

Last year the author wrote an application note that described a 300 watt, 80 MHz amplifier using a push-pull pair of ARF449A/B, using a

Property	Units	AlN	Al2O3	BeO	Si	Cu	Al	Cu15W	Alloy42	Kovar	Sn63Pb solder	Au80Sn solder	Pb92.5 Sn5Ag
Thermal conductivity	W/mK	180	36	260	125	388	238	185	17	17	50.9	57.3	29.5
Resistivity	% AICS	-	-	-	-	100	66	40	5	40.5	14		
CTE	ppm/C	4.6	7.0	8.47	4	16.8	23.4	7.1	5.3	5.9	25	15.9	
Density	g/cc	3.3	3.89	2.85	2.4	8.89	2.7	16.2	8.42	8.42	8.36	14.5	11.2
Bending strength	Mpa	410	360	230							46.2		
Hardness (Knoop)	Gpa	11.8	14.1	9.8									
Young's Modulus	Gpa	331	372	345		120	70	274	131	131	31		

▲ **Table 1. Physical properties of common package materials.**

125 volt supply voltage. The response to the article was very good but quite a few potential customers wanted to generate 2 to 5 kW. While the price of the ARF449 was reasonable, the part itself was too small. The cost and complexity of combining 8 or 16 of the basic amplifiers was not appealing. APT already makes multi-die custom assemblies for several customers who use them in multi-kilowatt ISM RF sources. It appeared that there was a market for a much larger standard RF part.

Customer requirements

If you produce a multi-kilowatt RF source for the competitive plasma generator and CO_2 laser driver markets, the number of parts and the efficiency are critical parameters. The market wants everything smaller, faster and cheaper. Water cooling is usually available. Operating frequencies are in the ISM bands between 13.56 and 81.36 MHz. Power density, W/in^3, becomes a differentiating factor.

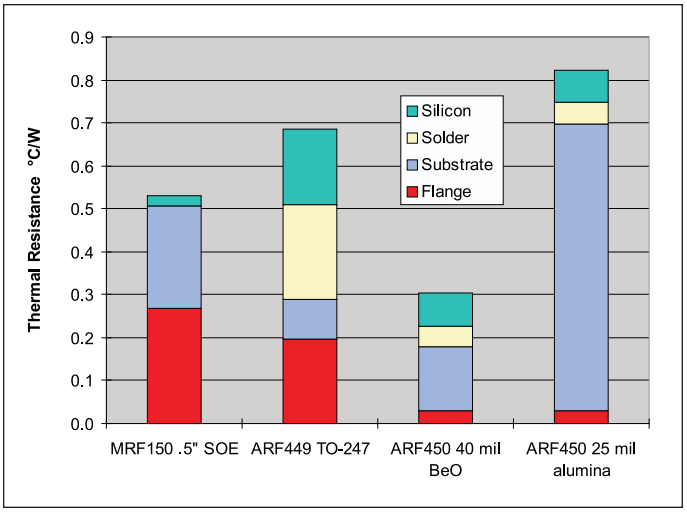
Looking at the parts available to RF suppliers, Motorola has various 50 volt devices including the huge MRF154. With 1350 watts dissipation (P_d), it is at the height of power, but it is very expensive, even in dollars per watt. The next level down are the push-pull "Gemini" parts like the MRF151G. ST, Philips, Polyfet, and Semelab offer parts with comparable 50 volts. All are fairly expensive because they are rated at 500 watts P_d up to 175 MHz. They were designed primarily for the communications market. DEI offers single parts up to 375 watts P_d and has established a different packaging format, a rectangular ceramic package without a mounting flange. The cost is moderate but the frequency range is less than 30 MHz because of the switchmode die used, but the parts operate up to 300 volts.

Defining the product configuration

The objective for APT's new RF part, simply stated, was to build the most powerful high frequency part in the smallest possible package for the smallest price. Thus, there were several design choices to investigate.

APT's hottest part, the ARF449, uses a 40,400 mil^2 MOS V process die. It runs up to 100 MHz in a common source TO-247 plastic package with 165 watts P_d. The high power ISM market seems to be looking for something well over the 500 watt mark and expects around 10 watts per dollar in production quantities. The 100 MHz frequency response of our existing die should be adequate but the power dissipation needs to be much higher than that provided in a plastic TO-247.

The highest gain at the highest frequency is produced by the smallest die. Small die and high power are not compatible. A larger die means more inter-electrode capacitance, lower frequency response, and very low RF input impedance. How about using two die in push-pull like the MRF151G or Philips BLF278? That would not only double the power dissipation but would also raise



▲ **Figure 1. Comparison of thermal stacks.**

the available gain by reducing the stray inductance between the two sources. It would also raise the input and output impedance. For those who want to run single ended, the two sides could be placed parallel to one another. Thus the decision was made to make the P_d twice the original.

The power dissipation of a device is defined under specific (and admittedly unrealizable and impractical) conditions: case at 25° C, the junction temperature at maximum. In plastic parts, the maximum junction temperature, T_{jmax}, is limited to 150° C by the plastic molding compound. In a metal or ceramic package, the limit is usually 200° C, determined by the silicon. Going from a molded plastic package to a ceramic and metal package nets a 40 percent increase in dissipation rating. The second decision was made — the new package would be ceramic and metal.

Increasing P_d any further would have to be done by mechanical means. The most obvious method is die thinning. The raw silicon wafer needs to be thick enough to withstand automatic handling through the fabrication process without damage. Our wafer thickness is 23 mils. Reducing this by mechanical and/or chemical lapping after fabrication improves the over-all thermal conductivity considerably. Most RF die are thinned in a separate process after fabrication. Some LDMOS parts are regularly thinned to one mil.

After thinning, the back side of the wafer must be re-implanted and the back metalization for the drain connection needs to be re-applied. This required us to do some process development work in the fab. The back metal is Ti-Ni-Ag.

The passivation layer on the top side of the wafer is quite thick in order to cover the sides of the trenches. When the wafers were thinned below 10 mils, the unrelieved stress between the nitride passivation layer and the silicon wafer caused the wafers to curl up like pota-

to chips. Inventing a new top side planarization process to reduce the required thickness of the passivation layer would take too much time. Ten mils was chosen as the limit for now.

Packaging

The package size was determined by the area of the two 40,400 mil^2 die plus the additional area needed to attach leads and secure the lid. The TO-247 footprint was a good target for the overall size of 0.5 in^2. A suitable thick-walled alumina ceramic lid was chosen from a vendor's open tooling list and the substrate size was then adjusted to fit the lid.

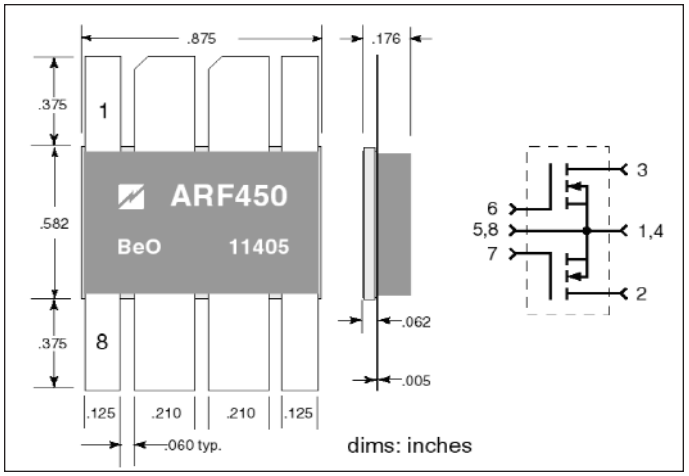
The possible combinations of base and mounting flange materials were evaluated using a model for the thermal stack that ignored any spreading of heat from the top of the die all the way to the base of the package. This very simplistic model underestimates the performance, but it still provides for true relative comparisons. The predictions of thermal performance it produced are very conservative. Unlike a fancy finite element thermal modeling program, it was simple, cheap, and readily implemented on a spreadsheet.

The die attach method is another area for making tradeoffs. Most of APT's switchmode die are attached with high temperature tin-lead solder. This is necessary because relatively thick die are being attached to a copper header. The difference in the coefficient of thermal expansion (CTE) between these materials requires a soft material like Pb-Sn solder. RF die are usually eutectically bonded with Au-Si solder which is very hard. The substrate needs to have a fairly close CTE match to silicon. With a large thick die, this will not be acceptable for the rigors of thermal cycling. The thermal performance penalty of the thick solder layer is clearly evident in Figure 1.

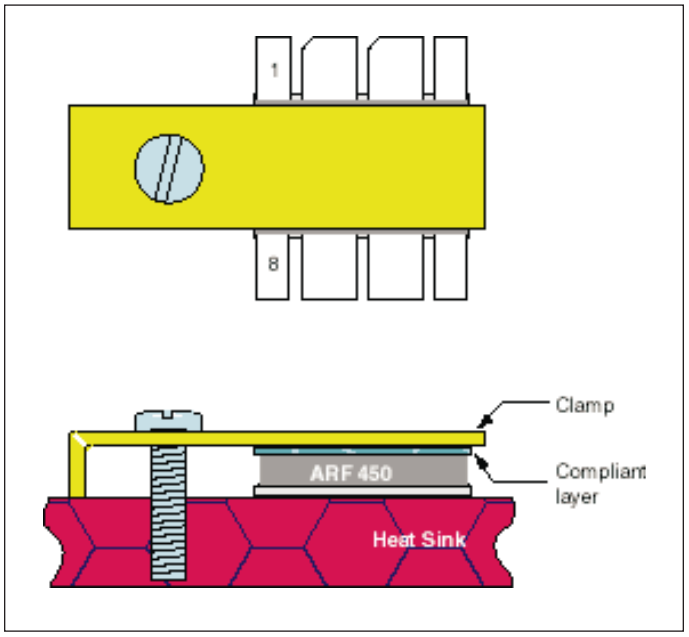
To Flange or not to flange

In an earlier career designing TV broadcast transmitters, the author had some experience with MRF150 devices in the standard 0.5 in. SOE package. In order to improve the thermal performance of the devices, APT changed to a type without the flange — just the ceramic. The improvement was amazing. Not only were the parts easier to mount, they had more power capability, and they were cheaper, too. DEI of Ft. Collins, CO, has offered rectangular flangeless packages for quite a while so the concept is not new. The reason it was addressed in the design of APT's new part was that in pricing copper-tungsten flange material and modeling the effect of its extra 80 mils in the thermal stack, it became apparent that the flange itself was an impediment. The cost of the flange would almost double the cost of the package and would reduce the available P_d by more than 30 percent.

One of APT's customers uses a large package on a mounting flange the same as that used in the MRF154



▲ **Figure 2. ARF 450 package dimensions and connections.**



▲ **Figure 3. Mounting the ARF450 package.**

"HOG" package. His experience with it has not been pleasant. If the coefficient of thermal expansion (CTE) of the flange is not matched closely with the CTE of the heatsink, the differential forces can warp the flange causing it to bend enough to degrade its thermal contact with the heatsink. The flange material is determined by a requirement to match the CTE of the substrate. Unless a CTE match is also made with the heatsink, the larger the area of package, the bigger the problem.

Most RF power parts have mounting flanges of one sort or another. The paradigm is for an RF part to have holes in the flange to screw it down on the heat sink. At the risk of being unconventional, APT decided to eliminate the flange along with its cost and negative effect on the available P_d. In marketing terms, the flangeless

package would become a "differentiating attribute."

High power flangeless packages avoid header warping problems because the mount permits the mating surfaces at the thermal junction to float relative to each other. A thin film of thermal grease is all that is needed to ensure proper heat transfer. The interface actually will improve over time as the two surfaces wear into each other. The clamping force required is no different from that for a conventional flanged package. The package dimensions are shown in FIgure 2 and a typical installation is illustrated in Figure 3.

Material science

Once the decision to eliminate the flange was made, the next decision involved the substrate material. Without a flange to protect the substrate, APT decided that the back side of the substrate would need a metal covering. The substrate is a very hard material and it is pressed onto a heatsink with considerable force. It requires some compliance to contend with grit and surface irregularities. Fired Mo-Mn metalization was not thick enough nor durable enough so the alternative was to use direct bonded copper, DBC. This would appear as a smooth, gold-plated back surface on the package. It appealed to the senses and met the physical requirements. DBC is rugged, withstands thermal cycling well and would provide firm anchoring for brazing the leadframe on the top side. DBC with flying leads was considered was soon discarded as a possibility because of its high cost.

With or without a flange, connecting the sources through to the back side of the substrate was also considered. The idea was abandoned after investigating the techniques available, the effects on reliability and the cost. An eight lead configuration with a source lead on each corner was chosen. The leadframe was originally made from 102 copper, but upon evaluation it was not stiff enough to support the internal bridge used for lead bonding to the source. After looking at the electrical and mechanical requirements, Alloy 42 was chosen. This is a Ni-Fe alloy similar to Kovar. Gold plating greatly reduces the losses associated with Ni-Fe at RF.

At this point, the cover, leadframe, package size and metalization had been decided upon. The remaining decision was which ceramic material to use for the substrate. It would be based on a combination of performance and economic issues. The goal was to make a part with the highest possible power dissipation using just two die. After looking over the choices for substrate materials, alumina, aluminum nitride (AlN), and beryllium oxide, it was clear that some trading was needed to achieve the goal.

As shown in Table 1, all three ceramic materials have about the same strength, hardness and density. The major differences are thermal conductivity and cost. Their costs are approximately proportional to their thermal conductivity. Other factors being equal, the selling price of an RF part is generally a function of the power dissipation.

To make the decision on which substrate material to use, we compared the three types of ceramic substrates including some cost and thickness options on each. We determined an assembly and testing cost. The thermal stack calculation described earlier provided the power dissipation. A spread sheet then used the power dissipation based on the thermal property of the substrate to predict gross margin when the selling price was expressed in dollars per watt of power dissipation.

As an example, the P_d of a part using a 25 mil thick alumina substrate has about a third of the P_d of the part built using 40 mil BeO, but was less than half the cost. The values in Figure 4 are calculated per die to permit comparison with single die parts. It clearly shows the effects of die thinning, solder selection, and flange removal. The decision to use BeO was based on its ability to provide a part with 1000 watts of power dissipation.

The R_{Qjc} for each die is 0.35 ° C/W. The projected selling price will be around $100 at quantities of 10,000.

Conclusion

The objective was achieved. The development was an exercise in process engineering, materials science, and value engineering. The ARF450 will probably change the way we generate high RF power below 100 MHz. Application circuits are being designed by several people and will hopefully be published before the end of the year. They include a broadband HF linear amplifier and a Class E amplifier for 27.12 MHz ISM use. Sample quantities are available now.

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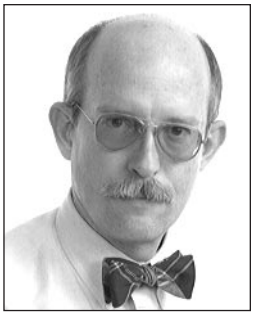

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