MICROWAVE MODULE PACKAGING

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ABSTRACT

The demonstration of a <$50 package for GaAs MMIC microwave module applications has not been achieved yet. This paper outlines the requirements for microwave packaging and describes three low-cost metal-package solutions: (1) brazed construction, (2) metal injection molded construction, and (3) pressure infiltration casting.

INTRODUCTION

The availability of high performance and affordable GaAs MMICs will make possible the realization of the <$500 T/R module function (in large quantities) within the next several years. The DARPA-sponsored MIMIC Program has had significant impact on chip cost reduction. Automated manufacturing techniques have also been sufficiently developed to enable module production at the rate of thousands per month. However, the demonstration of low cost (<$50) packaging has not been achieved yet. Achievement of this objective requires close cooperation among the system or component designers and manufacturers of packages.

REQUIREMENTS

The low cost of MMIC chips is being demonstrated in many foundries, but packaging remains a major cost and performance driver for MMIC assemblies. A cost effective packaging approach is necessary to meet both current and projected system requirements. The MMIC packaging design concept must evolve concurrently with the solutions to other system problems such as cooling, structural design, power and signal distribution, weight management, assembly and test processes, reliability, maintainability, electrical performance and system interconnections.

The design requirements for the packaging of GaAs MMICs are more demanding than those typically encountered for digital or low frequency analog applications. The microwave package must be affordable and:

- House and protect the electronic circuitry and be hermetic,
- Support shock, vibration, and temperature cycling,
- Minimize the DC/RF losses in the feedthroughs,
- Provide for controlled RF impedance at the feedthroughs,
- Minimize the thermal resistance from device to heat sink.

These seemingly innocuous requirements have a far greater impact on the package design and the integration of components into an affordable assembly than one might expect. For example, materials that match the coefficient of thermal expansion (CTE) of the GaAs MMIC and ceramic alumina substrates must be used. Precious few materials exist that simultaneously fulfill the requirement of high thermal conductivity and matched CTE - fewer still that are affordable.

A key application for GaAs MMIC devices is a transmit/receive module for a multi-thousand element phased array radar system. The FET channel temperature must be minimized because it is a first-order determinant of the T/R module failure rate. Materials with a high thermal conductivity (>150 W/m°C) must be utilized and transistor channel temperatures less than 120°C are desirable. However, a thermal conductivity value higher than approximately 150 W/m°K generally has a diminishing advantage for reducing the peak temperature. GaAs itself is a poor thermal conductor and a large percentage of the temperature rise from heat sink to device channel occurs across the thickness of the GaAs substrate. Figure 1 illustrates the result of a thermal analysis.

The effect of materials, processes, and enclosure characteristics on microwave signal transmission is by far the most important factor that separates microwave packaging from other packaging arenas. Interconnections among the numerous GaAs MMICs within a module must be accommodated, and microwave connection to the external environment must be handled efficiently and reliably without forming an I/O bottleneck.

Packages must be compatible with automated assembly and test processes in manufacturing (Figure 2) if the true low-cost potential of the batch-processed MMIC is to be realized. Materials must be fully characterized and process-capable before this can occur, and product development must usually proceed as a partnership between the system/microwave component user and the package manufacturer.

Tight mechanical tolerancing is typically required in microwave package design for several reasons. Small, tightly toleranced dimensions are necessary to minimize the accumulation of phase differences and to accommodate the small sizes of MMIC components. A snug fit of the lid is required for a hermetic seal using either a seam-weld joint or laser sealing. Smooth surface finish and package flatness is required for both direct die attachment of GaAs MMIC chips and maximum cold plate contact. The high cost of maintaining tight tolerances results from yield loss during the manufacturing process or from additional finishing operations such as grinding, lapping, or honing after the primary machining operation. Higher initial tooling costs will also result from tight tolerancing.

Package hermeticity is required to ensure the long-term reliability of critical GaAs MMIC circuit functions with exposed active devices, resistive films, and thin-film capacitors. Protection against possible exposure to moisture and ionic contaminants is a prerequisite in achieving high reliability to support the low life-cycle cost. Hermetic coaxial connectors and multi-pin headers can be one of the major cost drivers associated with microwave packaging.

Systems that utilize GaAs MMIC components generally require high transmitted power output, high efficiency, high reliability, and low system noise. Operational frequencies may be encountered typically anywhere between 1 and 20 GHz. The key module packaging requirements that are driven by these system level requirements are summarized as follows:

Housing Density	3-8 gms/cm^3
Thermal Conductivity	>150 W/m°C
Cavity Leak Rate	<5 x 10^{-8} atm-cc/sec
Thermal Expansion	6-7 PPM/°C
Flatness	<±0.1 percent
Surface Finis	<20 μin. RMS
Dimensional Tolerance	±0.003 in.
Cost	<$50 per TX/RX function

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MULTI-PIECE ASSEMBLED PACKAGES

Microwave packaging approaches that were utilized in the past have included a number of technologies. Early MMIC packaging approaches reflected usage of small quantities of modules. Although low cost was an important future goal, demonstration of acceptable electrical performance was the far more important design driver. The mainstay of early 1980 design included the high-temperature co-fired ceramic alumina corral brazed to a copper-tungsten base. The requirement for high thermal conductivity was met because the base material for this module housing (measuring 0.8 in. by 0.6 in.) is a copper-tungsten material, formed using powdered metallurgy, with a thermal conductivity of >200 W/m°C. The CTE is very closely matched to GaAs and the ceramic alumina. However, the assembly of the ceramic corral to the copper-tungsten base was performed using a high-temperature (850°C copper-silver) braze. Over these tremendous temperature excursions the minor CTE differences in the package materials resulted in high numbers of stress-fractures in the ceramic. This resulted in yields low enough to deprive the design and the technology of being used in subsequent development. Figure 3 shows the constituents of this construction.

The brazed package assembly shown in Figure 4 represents a similar attempt to address the problems of hermeticity, thermal management, CTE-match, solderability, and acceptable microwave electrical performance. A metal enclosure 2.0 in. long by 0.9 in. wide by 0.25 in. high was formed by welding together two CTE-matched materials: copper-tungsten and Kovar (an iron-nickel-cobalt alloy). The resultant package succeeded in meeting the electrical performance, hermeticity, and thermal goals. This package design allowed T/R modules to be inserted directly into the array face that contained both the cold-plate and the antenna elements. Modules were easily insertable and replaceable, and assembly of the MMICs and substrates could be accomplished using automated assembly technology. The two-piece base plate conducted heat efficiently away from the heat-dissipating areas of the modules toward the cold plate structure. Coaxial connectors were used for the microwave connections and a 15-pin DC header was used to introduce high-current bias and control signal distribution to the module. But the design had shortcomings: the costly machining and welding processes precluded the extension of this housing design to volume production, and the package was far too heavy at 34 grams for practical application in an airborne array.

The packaging approaches shown in Figure 5 are much more producible. They utilize a composite copper-molybdenum flange that is soldered to an iron-nickel alloy sidewall with ceramic feedthroughs. The concept of a ceramic feedthrough captured in a two-piece metal housing (1) reduces the expensive machining operations and simplifies the housing assembly process, (2) allows for automated assembly and test processes to be used, and (3) reduces the overall module volume. The ceramic feedthroughs enable RF and DC connections to be made in a single-connection medium and ease the integration difficulty experienced at the next higher assembly - the array level.

This multi-component assembly approach to housing design shows great potential for meeting cost and performance goals for many applications, but it may not be optimum for applications such as spaceborne surveillance or communications where extremely lightweight components are required. The two-piece housing with ceramic feedthroughs measures 1.6 in. x 0.5 in. x 0.125 in. and weighs approximately 12 grams.

SINGLE-PIECE MOLDED PACKAGES

Packaging techniques that make use of net-shape forming methods are uniquely compatible with the low-cost and performance objectives and are amenable to the economies of scale necessary to demonstrate this objective. Two distinctly different net-shape forming technologies appear to be viable alternatives for producing MMIC enclosures: metal-injection molding and pressure infiltration casting.

The use of metal-injection molding in fabricating precision microwave housings has been demonstrated for use with copper-tungsten materials. The process of metal injection molding mixes fine metal powders and binders into a feedstock that is then injection-molded to shape. The molded housing shape is then treated to remove the polymer binders and sintered at high temperature to fuse the part to a solid composite structure. As a result of the high temperature (<1000°C) processes, significant shrinkage of the molded part will occur.

The primary advantage of metal injection molding is that low cost potential for volume production can be envisioned for precision structures. The housings illustrated in Figure 6 were built using the injection molded process with copper-tungsten. MMIC modules that were assembled using these housings were compliant with the requirements for hermeticity, thermal management, electrical performance, and compatibility with automated assembly. Although the injection molding process has been demonstrated with high density copper-tungsten and is being developed for medium density copper-molybdenum composites, lightweight materials for use with this process are not yet compatible.

Pressure infiltration casting is also an alternative net-shape forming process for precision microwave housings that utilizes low density composite materials such as silicon carbide particulates in an aluminum metal matrix (SiC_p/Al). This process uses powdered silicon carbide particles that are mixed with polymers into a slurry. The slurry is injected into a mold to create a preform. The preform is then infiltrated with molten metal (aluminum) under pressure and temperature. The housing is formed when pressurized inert gas forces the liquid aluminum into the preform of reinforcement material. The pressure infiltration system is unlike other net-shape formation processes in that almost any reinforcement material or matrix metal is possible, because the production of components occurs within a pressure/temperature vessel.

The pressure infiltration process has several advantages for the product design of microwave housings: (1) a high volume-fraction loading of silicon carbide can be utilized in an aluminum matrix. This implies that the CTE of a lightweight housing can be made to approach the desirable 6 PPM/°C goal; (2) net-shape formation of complex septums, shapes, corners, etc is possible; (3) thin-wall, low-strength (low-cost) molds can be used in the process; (4) lightweight aluminum structures are possible.

Materials and processes for lightweight packaging are a desirable but not exclusive requirement when considering a packaging technology for most applications. The lightweight silicon carbide-loaded aluminum housings shown in Figure 7 were built using the pressure infiltration process. This material is considered more desirable than either the copper-molybdenum or the copper-tungsten material system because the density of the copper-based materials is so high. Table 1 illustrates the comparative differences between these materials.

LOW-COST OBJECTIVE

Among system designers the key module packaging issue is to produce a packaged T/R function for less than $50 in quantities of 50,000 or more. The total cost of the package must include the piece part and attendant fabrication costs. The package cost includes not only the cost of fabricating the housing shell, but also the cost of the interconnections (ceramic feedthroughs, coaxial connectors, DC connectors), lids, solder preforms, molds, and assembly steps, such as brazing, plating, post-process machining, inspection, and sealing.

The cost of interconnections will depend upon the specific implementation but an upper limit of $12 is supported by present technology. Similarly, preform and lid costs of $3 can be achieved. Package assembly is projected to be under $15. This cost breakdown in shown in Table 2. Thus, a $30 cost for assembly of any packaging shell approach appears to be achievable with existing technology. Consequently, manufacturing the shell for less than $20 becomes the primary challenge.

With our present understanding of the process deficiencies the three most promising design approaches are the following: (1) brazed sidewall-to-base housing assembly with brazed ceramic feedthroughs; (2) metal injection molded one-piece housing with brazed ceramic feedthroughs and/or coax connectors; (3) Metal infiltrated one-piece housing with brazed ceramic feedthroughs and/or coax connectors. The major advantage of molded and cast housings is the ability to produce complex shapes in single pieces. These approaches require minimal, if any, post-process machining. The cost of the metal injection molded shell is projected to be $5, while the cost of metal infiltrated housings is projected at $20. The cost of the preform is included within this $20. The brazed ring and base assembly are considered to be the lowest risk approach for less complex housings and the cost is projected at $15 per shell.

CONCLUSION

Packages and packaging technologies that are compatible with the requirements of microwave electronic systems are becoming a reality. Housing costs that are less than $50 for large quantities can be achieved. The system designer should be able to select an interconnect approach without incurring significant cost penalties. If minimum weight is not an essential requirement, a 10 percent-20 percent cost savings appears to be possible.

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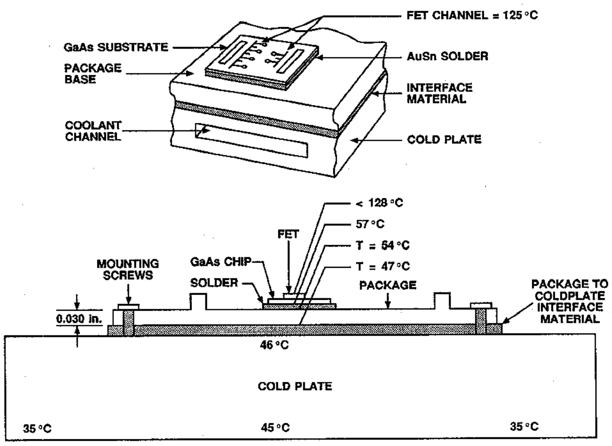

Figure 1. The results of a thermal analysis for CW dissipation in a MMIC amplifier module housing with a 175 W/m°C thermal conductivity indicate that 75 percent of the temperature rise in the system occurs across the thickness of the GaAs substrate.

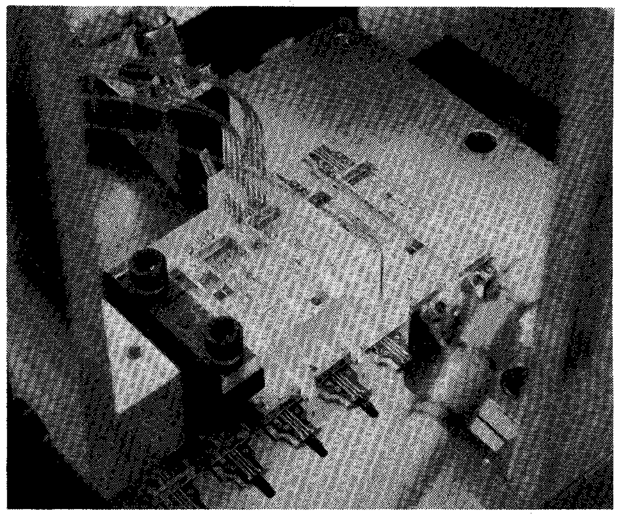

Figure 2. Package design should be compatible with automated assembly and test in a common carrier fixture if low-cost design objectives are to be met.

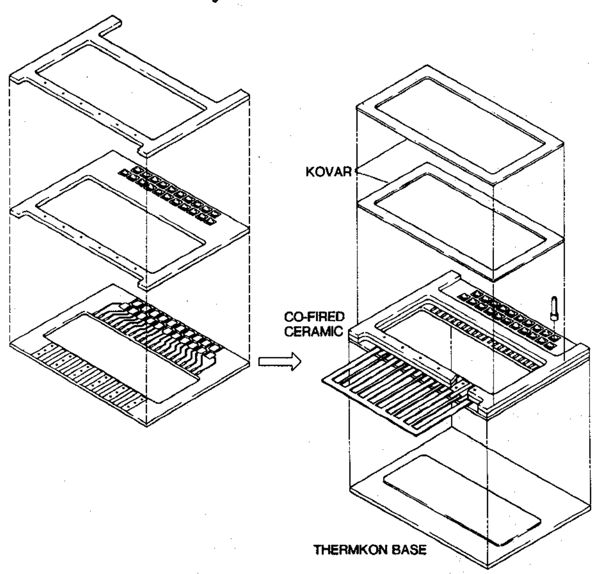

Figure 3. Fabrication of a ceramic-walled MMIC package requires lamination, firing, and brazing at processing temperatures ranging from 700°C through 1500°C.

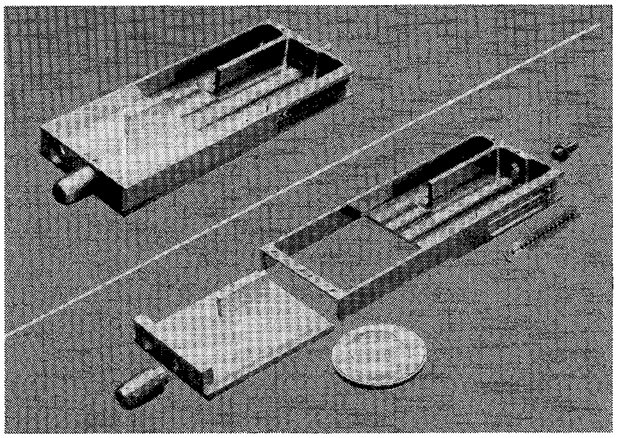

Figure 4. This hermetic MMIC module was fabricated by brazing two machined, CTE-matched materials (Kovar and copper-tungsten) together. RF and DC connectors were then soldered into place.

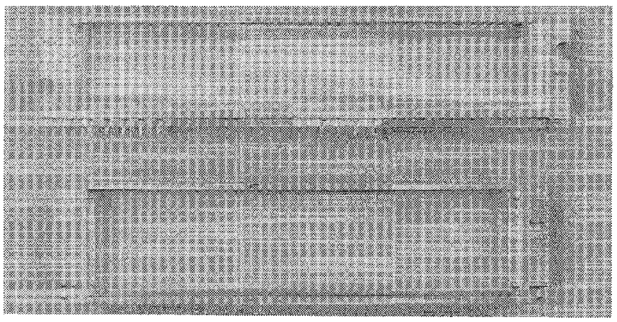

Figure 5. This low-profile, hermetic MMIC package is compatible with automated assembly and test methods. An iron-nickel alloy is brazed to a copper-molybdenum base plate to capture ceramic feedthroughs.

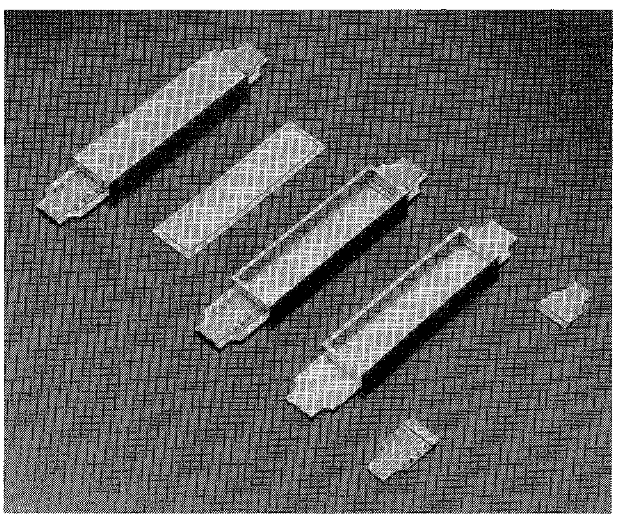

Figure 6. MMIC packages produced using metal injection molding of copper-tungsten. Ceramic feedthroughs are brazed into position through the openings left in the housing endwalls.

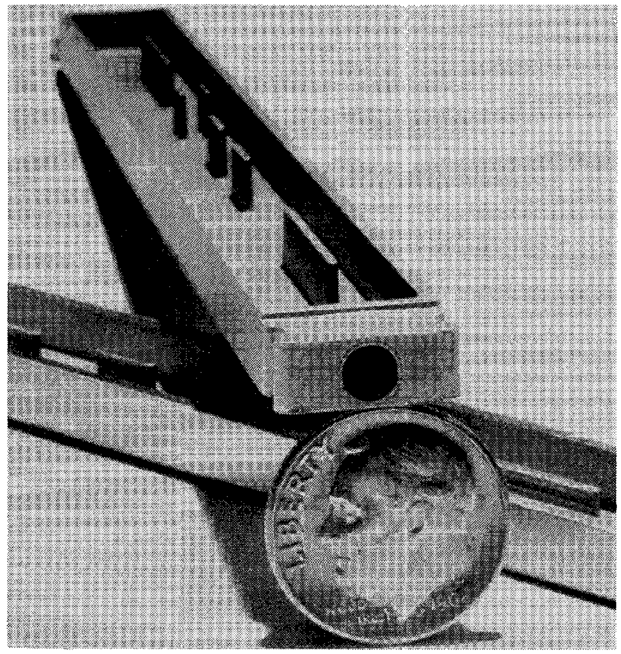

Figure 7. Pressure infiltration casting allows for the net-shape formation of intricate features and is compatible with numerous materials systems. The lightweight unit shown here is fabricated using SiC_p/Al that has a density of 2.9 gms/cm^3.

TABLE 1. PROPERTIES OF COMPOSITE MATERIALS

Material Name	Thermal Cond (W/m°C) (@25°C)	CTE (PPM/°C)	Density (gm/cm^3)	Comments
SiC_p/Al (40% v/o)	130	12.1	2.9	DWA
SiC_p/Al (55% v/o)	200	8.8	3.0	DWA
SiC_p/Al (65% v/o)	190	6.5	3.0	P-Cast
SiC_p/Al (35% v/o)	160	8.5	3.0	Lanxide NX5201
Al/AlN (50% v/o)	147	11.5	3.3	Lanxide NX5101
CuW (10/90)	209	6.0	17.0	Sumitomo
CuW (10/90)	157	5.7	17.2	CMW
CuW (15/85)	184	6.5	16.4	Sumitomo
CuW (20/80)	180	7.6	15.6	CMW
CuMo (20/80)	145	6.5	9.9	CMW
CuMo (15/85)	135	6.0	9.9	CMW
CuMo (15/85)	184	6.6	9.9	Sumitomo
Cu-Mo-Cu (20/60/20%)	247	6.6	9.7	C-T-A, Clad Mtl

TABLE 2. SINGLE PACKAGE COST PROJECTIONS 50,000 QUANTITY

	Cost
• Housing Shell	
- Metal Injection Molded	$5
- Brazed Sidewall & Base	$15
- Pressure Infiltration Casting	$20
• Other Pieces	
- Connectors	$12
- Lid	$1
- Solder Preform	$2
• Assembly	
- Brazing	$4
- Post-Process Machining	$1
- Plating	$4
- Inspection	$3
- Sealing	$3