THERMALLY ENHANCED PLASTIC PACKAGES USING DIAMOND FOR MICROWAVE APPLICATIONS

Marc Gomes-Casseres, Philip M. Fabis*

Sanders, A Lockheed Martin Co., Nashua, NH
*Norton Diamond Film, Saint-Gobain Norton Industrial Ceramics Corp., Northboro, MA

ABSTRACT

The superior material properties of CVD diamond combined with the economics of plastic provide an improved thermal management solution for microwave packages. The thermomechanical issues of attaching Gallium Arsenide devices to diamond have been investigated. Results indicate that a 43% decrease in maximum junction temperature and a 10^6 increase in mean time between failure has been achieved. In addition, an insertion loss of <1.5 dB and a VSWR of 1.5:1 was achieved for a 1 inch long 50 Ω coplanar transmission line up to 20 GHz.

I. INTRODUCTION

The superior material properties of diamond allow the use of totally new system architectures to handle the critical thermal management issues associated with high performance electronic systems. Norton Diamond Film's NorCool™ † package combines the superior thermal properties of Chemical Vapor Deposited Diamond (CVDD) with the low cost of plastic packages. The NorCool™ package replaces the die paddle of a typical copper leadframe with a diamond substrate. This diamond substrate is physically attached to all the leads thereby providing a dramatic improvement in thermal performance. The material properties of diamond allow all the leads to be thermally connected to the substrate yet electrically isolated from each other. Figure 1 compares the traditional leadframe to the NorCool™ leadframe. Figure 2 illustrates a plastic package with the integrated diamond substrate.

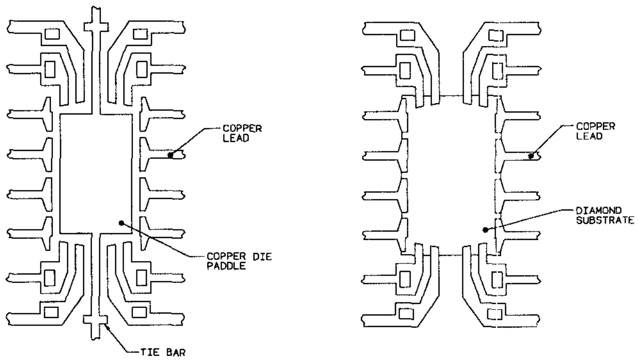

Figure 1. Traditional vs. NorCool™ Leadframes

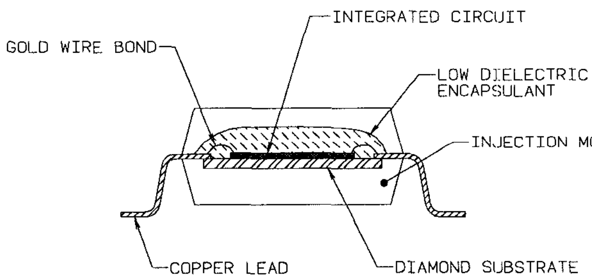

Figure 2. NorCool™ Package with an Integrated Diamond Substrate

† NorCool™ is a trademark of Norton Diamond Film

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The continued demand to reduce cost and improve performance has led to an increased use of Gallium Arsenide (GaAs) Monolithic Microwave Integrated Circuits (MMICs) in injection molded plastic packages for commercial microwave applications. Unfortunately, typical plastic packages are limited to devices that dissipate a maximum of 1-2 Watts which often necessitates the use of more expensive ceramic packages. Integrating a diamond substrate into a plastic package increases the thermal dissipation capability of the package to 15 W at half the cost of a typical ceramic package. High power GaAs MMICs can now take advantage of low cost plastic packages. Table 1 outlines the mechanical and electrical properties of diamond and other common materials.

Material	Thermal Conductivity [W/mK]	Resistivity [Ω-cm]	Dielectric Constant	Loss Tangent
CVDD	1000-1500	$>10^{13}$	5.6	<.002
Cu	393	1.7×10^{-6}	--	--
BeO	240	2×10^{14}	6.8	1×10^{-4}
AlN	170-190	10^{14}	8.6	.001 - .0001

Table 1. Mechanical and Electrical Properties

The main drawback of attaching GaAs MMICs to diamond substrates is the Coefficient of Thermal Expansion (CTE) mismatch; the CTE's of GaAs and diamond are 5.7×10^{-6} ppm/°C and 1.4×10^{-6} ppm/°C respectively. The CTE mismatch may cause unusually high stresses and strains between the dissimilar materials thereby affecting the reliability of the electronic packages. Numerous avenues exist to accommodate these thermally-induced strains, and hence stresses, in these 'macro-composite' structures[1,2]. However, the challenge is to collectively satisfy the thermal, mechanical, electrical, and economical package specifications with minimal design compromise. The process and methods to overcome this challenge are presented in this paper.

II. EVALUATION PLAN

NorCool™ packages were assembled using metallic and polymeric attach media in both chip and wire, and flip chip configurations. Two different compliant metallizations were evaluated (Ti/Pt/Au and Cr/Cu/Ni/Au) to minimize the CTE mismatch between GaAs and diamond. Several solders were evaluated for optimal die attach to diamond. These solders included AuSn, PbSnAg, and InPbAg (Indium #2). Gold bumps were used in the flip chip assemblies.

The GaAs MMIC on diamond assemblies underwent 500 temperature cycles (-50 to +125 °C) to eliminate those die attach materials that did not provide adequate CTE relief and resulted in die cracking. Die shear testing was also performed. Finally, non-destructive (micro-radiography, 100 MHz ultrasonics) and destructive (optical and electron metallography) evaluations were performed on as-attached and temperature cycled assemblies to determine if voids were apparent in the die attach media.

Thermal and mechanical stress models were created using finite element analyses and compared to the actual data obtained from the MMIC on diamond assemblies. A comparison of junction temperatures using solder versus epoxy die attach and flip chip versus the traditional chip and wire assembly was also performed.

An additional experiment was conducted with diamond substrates to determine the effects of surface finish and metallization thickness on RF performance. Several test pieces of 50 Ω coplanar transmission lines metallized on various grades of diamond were evaluated.

III. RESULTS

The thermal analyses indicated that the plastic package with the diamond substrate reduced the maximum junction temperature by 163 °C (43%) for a 2.5 W GaAs MMIC when compared to the same MMIC in a traditional plastic package. Figures 3 and 4 show the differences in the heat contours of the traditional versus the NorCool™ package. As these figures suggest, the diamond integrated package allows the heat to be directly routed out of the plastic package via all the leads. Table 2 summarizes the results of the thermal analyses.

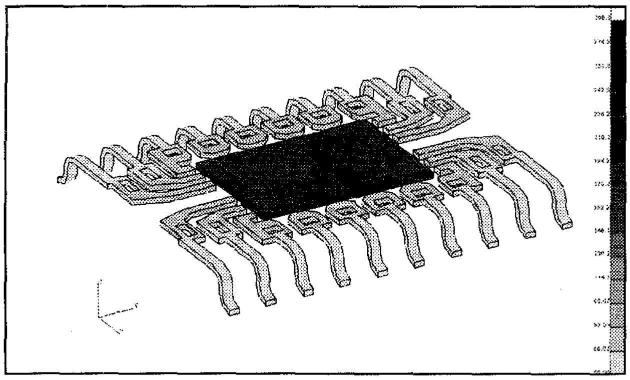

Figure 3. Traditional Plastic Package with Copper Leadframe

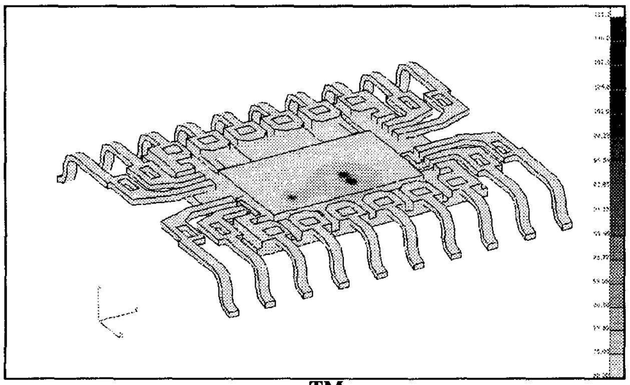

Figure 4. NorCool™ Package with an Integrated Diamond Substrate

Packaging Configurations	Maximum Junction Temperatures
Traditional Plastic Package w/ Cu Leadframe	290 °C
Plastic Packages with Diamond Leadframe:	
Chip & Wire Assembled with Solder	127 °C
Chip & Wire Assembled with Epoxy	157 °C
Flip Chip with Gold Bumps	141 °C
Flip Chip with Polymer Bumps	219 °C

Table 2. Summary of Thermal Results

The reduction in maximum junction temperature has a direct effect on package reliability. As shown in Figure 5, a 10^6 hour increase in the mean time between failure can be achieved when using the NorCool™ package versus the traditional plastic package.

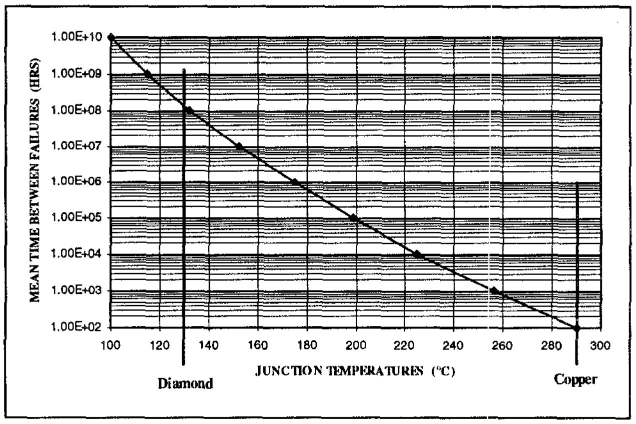

Figure 5. MTBF for Typical FET

Finite Element modeling revealed that reductions in stress concentrations and crack propagation in the GaAs MMICs could be realized using compliant metallizations. As shown in Figure 6, increasing the metallization thickness decreased the stresses in the GaAs. Specifically, Cr/Cu/Ni/Au decreased the stresses more in the GaAs when compared to Ti/Pt/Au. Although observed infrequently, transverse (through thickness) cracking of GaAs MMICs suggested that 'in-plane' thermal stresses were the dominant cause for failure.

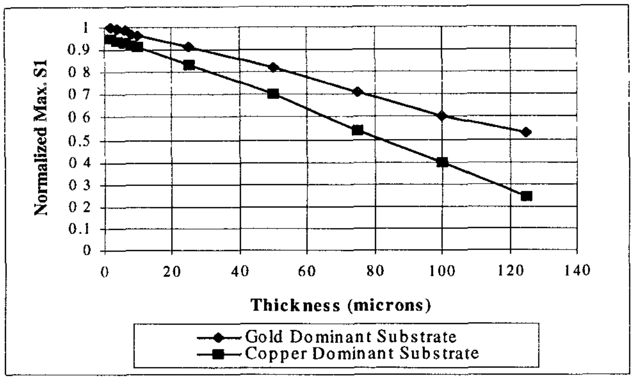

Figure 6. Stress Gradient in GaAs

Successful die attach was achieved following solder attachment to Cr/Cu/Ni/Au metallized diamond using Pb/Sn/Ag and Indium based solders. GaAs die-cracking failures were observed for only AuSn soldered assemblies following temperature cycling. Non-destructive and destructive tests of the GaAs to diamond attachment revealed that low void densities, small void sizes, and a low volume-fraction of intermetallics were associated with high joint shear-strength and high probability of GaAs survival. No die cracking was observed for flip chip attached MMICs to diamond using gold bumps.

As shown in Figure 7, good electrical results were achieved for the 50 Ω coplanar transmission lines metallized on diamond. The transmission lines were 1 inch long and metallized with Cr/Cu/Ni/Au at various thickness.

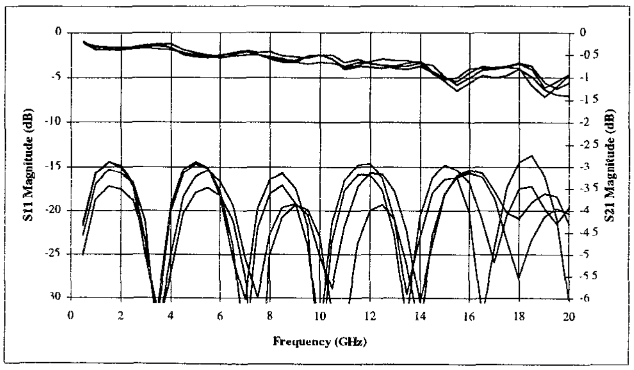

Figure 7. S11 and S21 Data on Diamond

IV. CONCLUSIONS

Integrating CVD diamond into plastic packages will now allow high power GaAs devices to be packaged in plastic rather than in traditional ceramic packages. This will, in turn, reduce the cost of military and commercial hardware and simultaneously improve the thermal efficiency, operating frequency, and reliability. Results indicate that a 43% decrease in maximum junction temperature and a 10^6 hour increase in MTBF has been achieved. In addition, reliable solder attach and flip chip attach has been achieved on diamond using Cr/Cu/Ni/Au as the compliant metallization layer. Finally, RF results were shown to be good up to at least 20 GHz.

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