I. Introduction

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Alone, an MMIC die sawed from a GaAs wafer is extremely fragile and must be protected from mechanical damage and hostile environments. In addition, it is electrically and thermally isolated and thus requires interfaces to electrical sources, other components, and thermal sinks. The broad technology focused on providing these functions is called packaging. Because of the many functions it must fulfill, packaging of MMICs, as with all ICs, is a technically challenging and critical step in the production of the product. The package provides mechanical support and protection, thermal heat sinks or paths to dissipate the heat generated by the IC, and electrical contact pads for both the RF and dc bias leads.

For microwave and millimeter-wave circuits, the package design must also provide electromagnetic shielding from the outside environment and between MMICs within a multichip package. Specific applications impose other unique design constraints. For phased-array antennas, the MMIC package should be smaller than a half of a wavelength to permit the proper antenna element spacing. Thus, very small packages such as the 20- to 40-GHz ceramic package shown in Figure 9-1 are required. Alternatively, the package may be designed with antenna elements on the package surface or inside the package; radiation from the latter must be through one of the package surfaces. For example, Figure 9-2 shows a 30-GHz, multichip package that contains four MMIC phase shifters, a power divider, control circuits, and four radiating elements protruding out of the package walls. For wireless applications, the package must be inexpensive and of low weight to be useful in a hand-held transmitter/receiver. Even optical interfaces may be required in packages designed to house microwave optical modulators or optically controlled MMICs. Each application and each MMIC or MMIC chip set represents new challenges and design constraints for the package designer.

Besides the electrical, thermal, size, and cost constraints imposed on the package design, the reliability of the package itself must be considered since the package must have a lifetime greater than or equal to the MMICs it is protecting from hostile conditions. In addition, the package design, materials, and fabrication must not degrade the MMICs performance or reliability. Unfortunately, it is common for the MMIC characteristics to change and new failure mechanisms to develop as a result of MMIC packaging, this due to the presence of the lid, sidewalls, coupling between components, mechanical stresses, and chemical interactions between materials. Therefore, since the reliability of the packaged part is the end user’s ultimate concern, the user must consider the total packaged MMIC assembly in the reliability specifications. It is not sufficient to assume reliability of a packaged MMIC because the MMIC and the package have individually passed acceptance tests or have been qualified previously.

This chapter will first discuss the functions of the package in detail, then introduce different types of microwave packages and the advantages and disadvantages of each, and, finally, present reliability issues of several packages or packaging technologies. Within the context of this guide, this chapter should be used to gain understanding of the reliability issues; a more in-depth investigation with the aid of the reference lists is left to the reader.

Figure 9-1. 20- to 40-GHz ceramic MMIC package. (Fabricated by Hughes Aircraft Company under contract to NASA Lewis Research Center.)

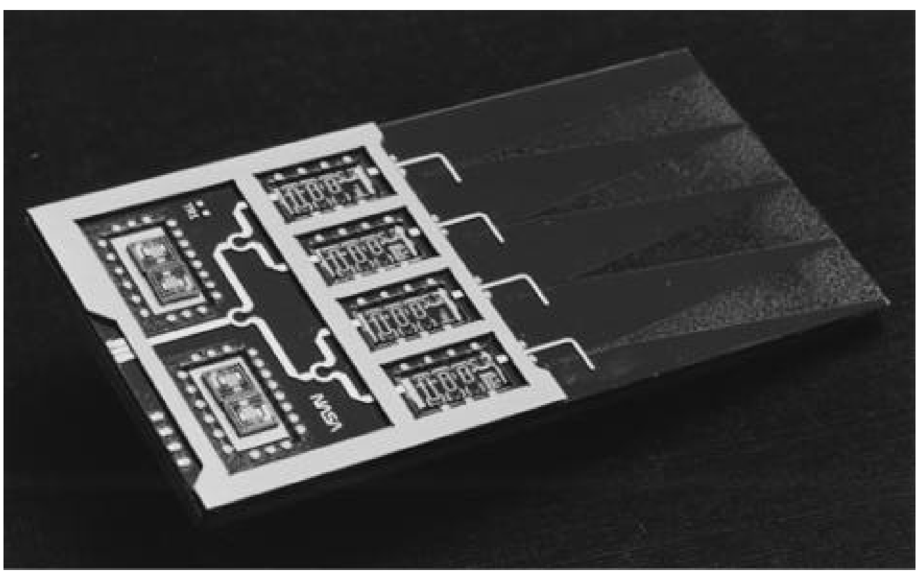

Figure 9-2. Prototype of a four-element antenna package with MMIC phase shifters, power divider, and control circuits. (Fabricated under SBIR Contract NAS3-25870 for NASA Lewis Research Center.)

A. Functions of Microwave Packages

Summarized in a single statement, the package serves to integrate all of the components required for a system application in a manner that minimizes size, cost, mass, and complexity, provide electrical and thermal interfaces between the components and the system, and ensure the reliability of the individual components and the overall package. The following subsections present the four main functions of the package: mechanical support and protection, protection from the environment, power and signal distribution, and thermal stabilization.

1. Mechanical Support and Protection

With the reduction of the MMIC substrate thickness to 25 to 100 μm to facilitate heat dissipation and lower via-hole inductance and 0.1-μm feature sizes, the requirement to support and protect the MMIC from thermal and mechanical shock, vibration, high acceleration, particles, and other physical damage during the storage, launch, and operation of the parts in space becomes critical. The mechanical stress endured depends on the mission or application. For example, landing a spacecraft on a planet's surface creates greater mechanical shock than experienced by a communication satellite. There is also a difference between space and terrestrial applications: In space, particulates are suspended and can damage the MMIC if they impact or land on electrically sensitive areas.

In a typical MMIC package, the three components shown in Figure 9-3 are integrated to protect the MMIC. A carrier or the package base supports the MMIC, the ring (or sidewalls) encloses all of the components in the package, and a lid seals the top. The base or carrier may be the most critical part of the package, because it is the only part in contact with the MMIC. The base or carrier may be designed with raised areas and wells to accommodate the MMIC, other ICs, signal distribution networks, and chip capacitors and resistors, but the most important decision made in the design of the base is the choice of materials. The coefficient of thermal expansion (CTE) of the carrier should be equal to or slightly greater than the CTE of GaAs for reliability, since thermal shock or thermal cycling may cause die cracking and delamination if the materials are unmatched or if the GaAs is subject to tensile stress. Other important parameters are thermal resistance of the carrier, the material's electrical properties, and its chemical properties, or resistance to corrosion. Typical materials used for the base of MMIC packages are metal alloys such as CuMo and CuW, metal composites such as Kovar™ and Silvar™, ceramics such as alumina and low-temperature cofired ceramic (LTCC), and glass, quartz, and diamond. If the base provides only mechanical support and thermal dissipation, metal and metal composites are preferred because of their high thermal and electrical conductivities and low manufacturing costs. However, if the base is also used as a substrate for electrical transmission lines, electrically insulating materials are required. Also, the method used to attach the MMIC die to the carrier will have a major effect on reliability; this subject is covered separately in Sections 9-II and 9-III.

Once the MMIC is supported on a carrier, the other components have been added, and the wire bonds or other electrical connections are made, the assembly must be protected from scratches, particulates, and other physical damage. This is accomplished either by adding walls and a cover to the base or by encapsulating the assembly in plastic or other material. Since the electrical connections to the package are usually made through the walls, the walls are typically made from glass or ceramic. Although the CTE

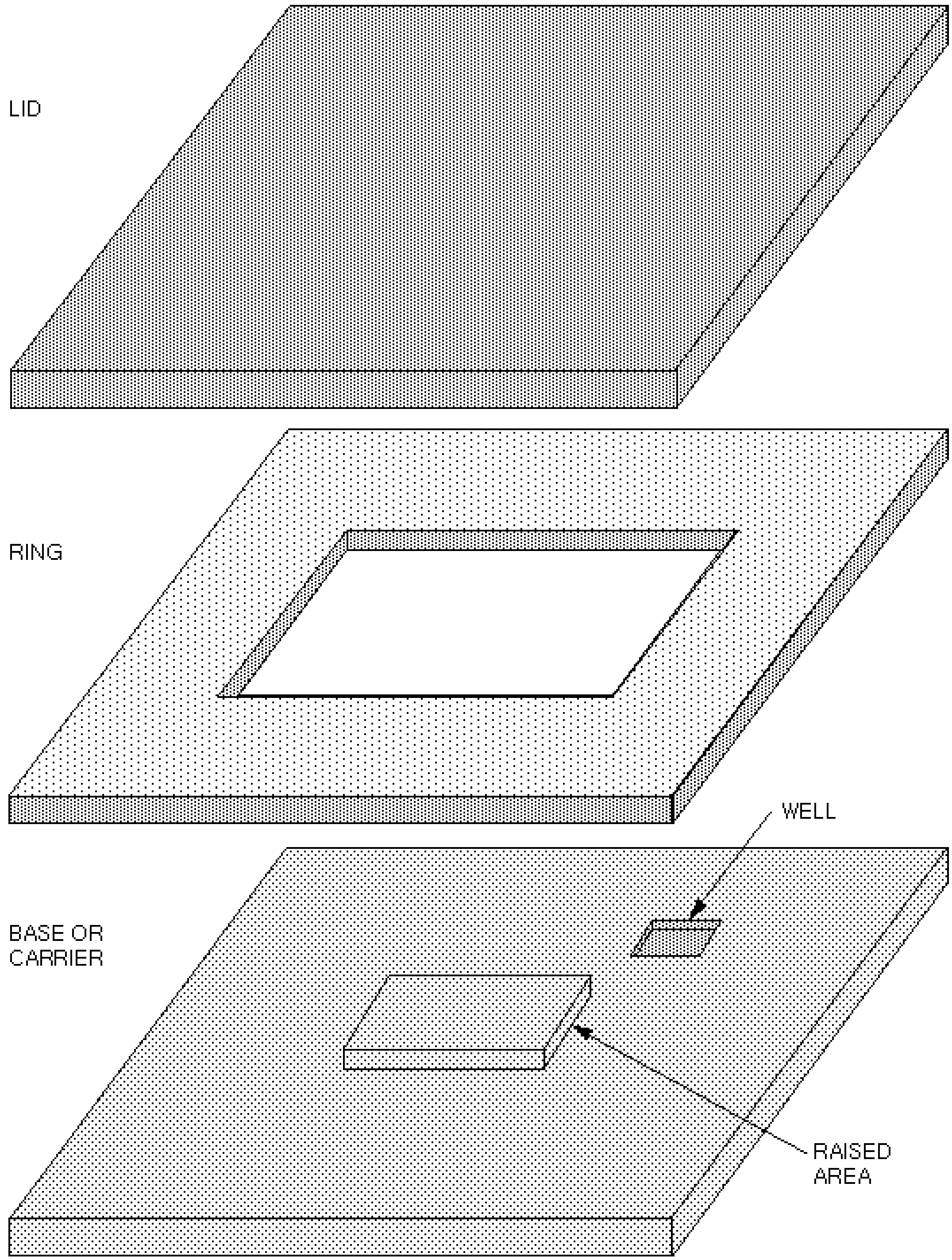

Figure 9-3. MMIC package.

of the walls and lid does not have to match the CTE of GaAs since they are not in contact, it should match the CTE of the carrier or base to which they are connected.

2. Protection From Environment

Many elements in the environment can cause corrosion or physical damage to the metal lines of the MMIC and other components in the package. Although there is no moisture in space, moisture remains a concern for MMIC space applications since it may be introduced into the package during fabrication and before sealing. The susceptibility of the MMIC to moisture damage is dependent on the materials used in its manufacture. For example, Al transmission lines and gate fingers can corrode quickly in the presence of moisture, whereas Au lines degrade slowly, if at all, in moisture. Also, junctions of dissimilar metals can corrode in the presence of moisture. Moisture is readily absorbed by some materials used in the MMIC fabrication, die attachment, or within the package; this absorption causes swelling, stress, and possibly delamination.

To minimize these failure mechanisms, MMIC packages for high reliability applications are normally hermetic with the base, sidewalls, and lid constructed from materials that are good barriers to liquids and gases and do not trap gasses that are later released. In addition, the bonds used in fabricating the package are compatible with hermetic package construction.

A recently discovered failure mechanism in GaAs MMICs produces a sudden change in transistor current when the MMIC is operated in a hydrogen-rich atmosphere. Unfortunately, hydrogen is easily trapped and released by many materials, and within a hermetic package, the hydrogen concentration can be high. This new failure mechanism is not well understood, but of enough importance to be discussed separately in Section 9-VII.

3. Power and Signal Distribution

Because the package is the primary interface between the MMIC and the system, it must provide the transfer of dc power and RF signals between the two. In addition, the package must distribute the dc and RF power to the components inside the package. The drive to reduce costs and system size by integrating more MMICs and other components into a single package increases the electrical distribution problems since the number of interconnects and transmission lines within the package increases. Furthermore, the current carried by the dc lines increases because more power is required, but the bias voltage cannot be raised because of system constraints. The dc power is usually fed into the package along metal lines that pass through the package walls, called feedthroughs, and it is then routed between different circuits along metal lines that may have vertical interconnects through via holes. These features may be seen in Figures 9-1 and 9-2.

RF signals can also be introduced into the package along metal lines passing through the package walls, or they may be electromagnetically coupled into the package through apertures in the package walls. Ideally, RF energy is coupled between the system and the MMIC without any loss in power, but in practice, this is not possible since perfect conductors and insulators are not available. In addition, power may be lost to radiation, by reflection from components that are not impedance matched, or from discontinuities in the transmission lines. Reflections also create standing waves since reflected signals add constructively and destructively at different points along the line. The final connection between the MMIC and the dc and RF lines is usually made with wire bonds, although flip-chip die attachment, discussed in Section 9-III, and multilayer interconnects using thin dielectric layers over the MMIC with via-hole interconnects are gaining acceptance. Wire bonds add significant inductance to the transmission line and therefore limit high frequency operation and change the matching impedance. Therefore, short, flat, ribbon bonds are preferred when they are compatible with the application.

Within the package, undesired coupling between different parts of the circuit results in energy transfer from one line to another. Typically, coupling is stronger between adjacent transmission lines with discontinuities, but severe radiation from a discontinuity may travel across the substrate and couple to nonadjacent transmission lines. Examples of circuit elements especially prone to radiation, and therefore coupling, are wire bonds with large loops, open-circuit microstrip stubs, and apertures in ground planes. Coupling can be reduced by partitioning the package into smaller areas with metal walls or via-hole fences. Unfortunately for the package designer, models and design rules for packages and microwave components placed in packages are not available. Microstrip, coplanar waveguide, and stripline are usually used for the microwave transmission lines within the package and for the feedthroughs, but the presence of sidewalls, cover plates, and adjacent lines changes the line characteristics from their normal, open characteristics and complicates the design. Therefore, the perfection of package design usually requires more complex electromagnetic simulators and several iterations. Further discussion of problems resulting from electromagnetic effects is presented in Section 9-VI.

4. Thermal Stabilization

It was shown in Chapter 4 that the reliability of GaAs devices is inversely proportional to the junction temperature of the devices. For small signal circuits, the temperature of the device junction does not increase substantially during operation, and thermal dissipation from the MMIC is not a problem. However, with the push to increase the power from amplifiers, coupled with their poor efficiency, and the increased level of integration within a package, the temperature rise in the device junctions can be substantial and cause the device to operate in an unsafe region. Therefore, thermal dissipation requirements for power amplifiers, other large signal circuits, and highly integrated packages can place severe design constraints on the package design.

The junction temperature of an isolated device can be determined by

$$T_j = Q * R_t + T_{case}$$

where Q is the heat generated by the junction and is dependent on the output power of the device and its efficiency, R_t is the thermal resistance between the junction and the case, and T_{case} is the temperature of the case. Normally, the package designer has no control over Q and the case temperature, and therefore, it is the thermal resistance of the package that must be minimized. Figure 9-4 is a schematic representation of the thermal circuit for a typical package, where it is assumed that the package base is in contact with a heat sink or case. It is seen that there are three thermal resistances that must be minimized: the resistance through the GaAs substrate, the resistance through the die-attach material, and the resistance through the carrier or package base. Furthermore, the thermal resistance of each is dependent on the thermal resistivity and the thickness of the material. A package base made of metal or metal composites has very low thermal resistance and therefore does not add substantially to the total resistance, but electrically insulating materials used for bases, with the exception of diamond, have less thermal conductance than metal. To maintain high thermal dissipation through these materials, metal-filled via holes are routinely used under the MMICs to provide a thermal path to the heat sink. Although thermal resistance is a consideration in the choice of the die-

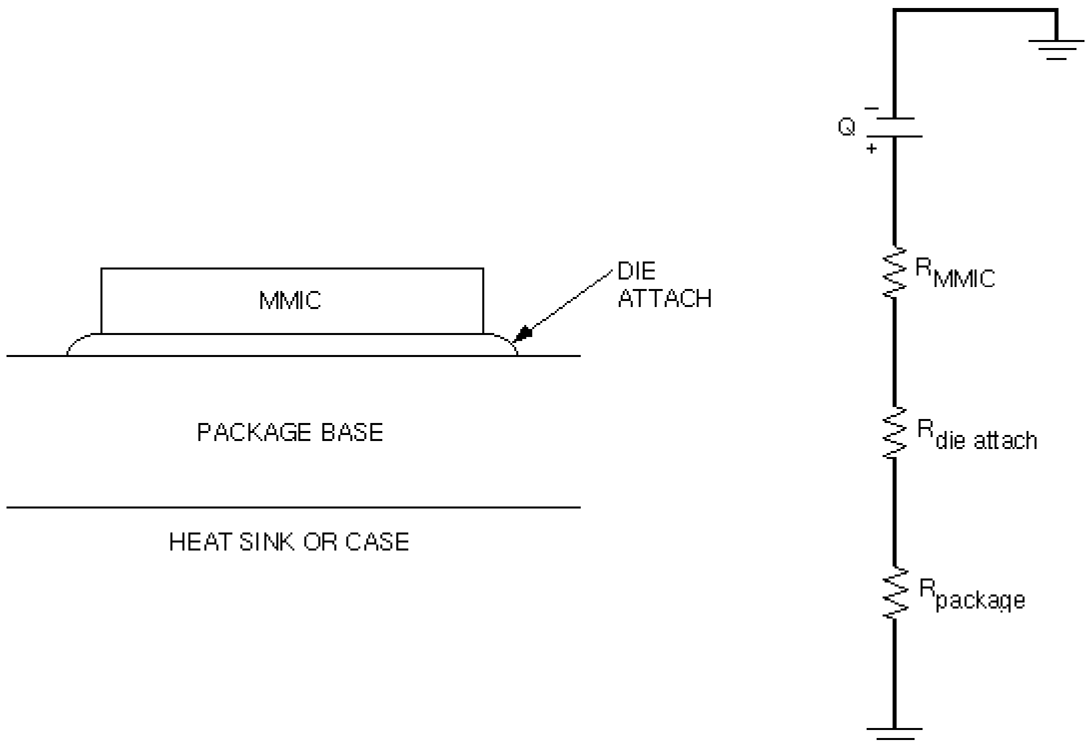

Figure 9-4. Cross section of MMIC attached to a package and its equivalent thermal circuit.

attach material, adhesion and bond strength are even more important. To minimize the thermal resistance through the die-attach material, the material must be thin, there can be no voids, and the two surfaces to be bonded should be smooth. Ideally, the thermal resistance of the GaAs determines the total thermal resistance. To minimize R_{MMIC}, substrate thicknesses have been reduced from a standard of 100 μm to 25 μm.

B. Types of Microwave Packages

As discussed earlier in this section, each application or MMIC usually requires a new package design to optimize the performance of the circuit or to meet the needs of the system. The packages shown in Figures 9-1 and 9-2 clearly illustrate the differences in the size, construction, and features that microwave packages may have, but it is possible to loosely group packages into several categories. Four of these categories—all metal packages, ceramic packages such as those shown in Figures 9-1 and 9-2, plastic packages, and thin-film multilayer packages—are presented below.

1. Metal Packages

The metal packages shown in Figures 9-5 and 9-6 are often used for microwave multichip modules, passive circuits such as filters and power dividers, and hybrid circuits because they provide excellent thermal dissipation, excellent electromagnetic shielding, and they can have a large internal volume while still maintaining mechanical reliability.

The package can use either an integrated base and sidewalls with a lid, as the two shown in Figures 9-5 and 9-6, or it can have a separate base, sidewalls, and lid. Inside the

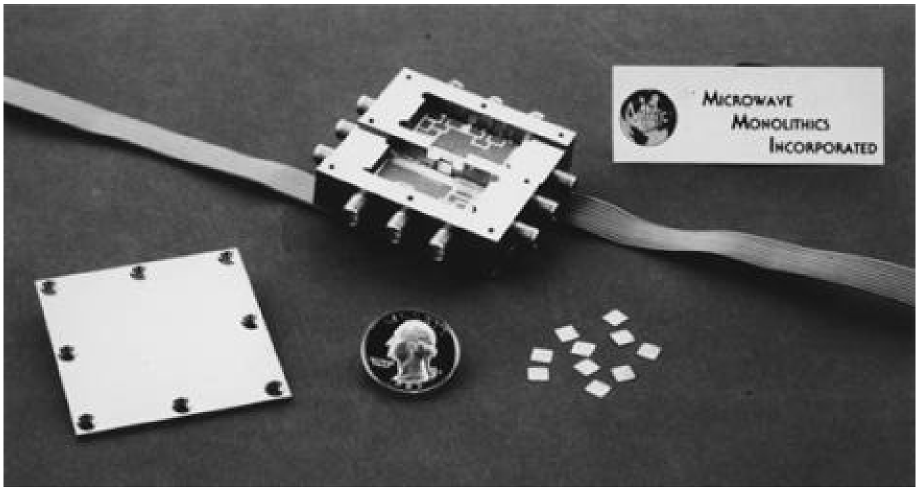

Figure 9-5. GaAs MMIC switch matrix in a metal package. (Fabricated under contract to NASA Lewis Research Center.)

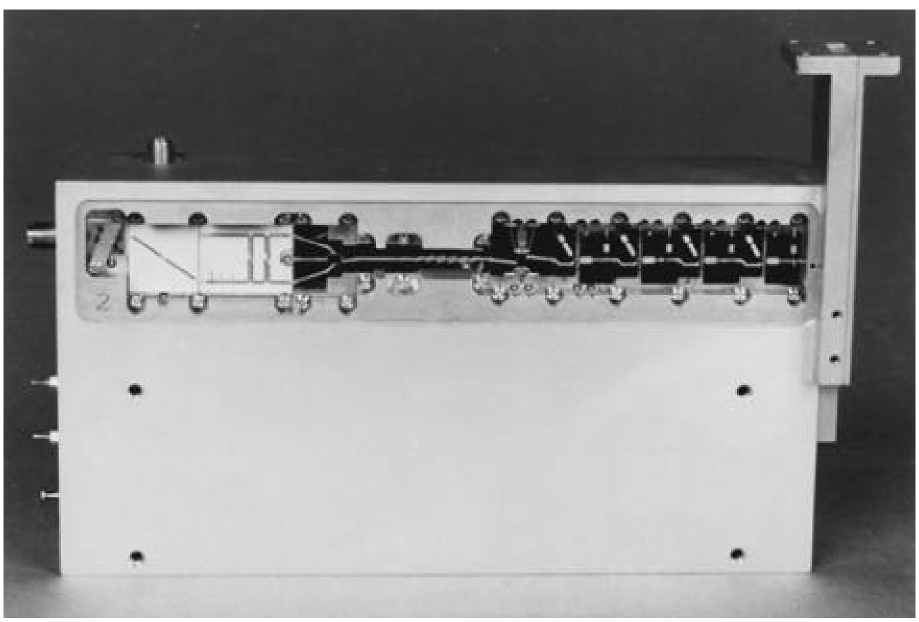

Figure 9-6. 20-GHz receiver in a metal package. (Fabricated by Harris Corporation under contract to NASA Lewis Research Center.)

package, metal partition walls are often added to decrease coupling between MMICs and to eliminate waveguide resonance in the package. Waveguide resonance occurs when the package becomes equal to $\lambda/2$ in any direction. The partition walls also act as ribs to strengthen the package. Lastly, ceramic substrates or chip carriers are required for use with the MMICs and feedthroughs.

The selection of the proper metal is critical. CuW/ 10–90, Silvar™ (a Ni–Fe alloy), CuMo/ 15–85, and CuW/ 15–85 have good thermal conductivity and a slightly higher CTE than GaAs, which makes them good choices. Kovar™, a Fe–Ni–Co alloy commonly used for sidewalls and lids, is not recommended for the base since its CTE is slightly less than the CTE of GaAs. All of the above materials, in addition to Alloy-46, may be used for the sidewalls and lid. Cu, Ag, or Au plating of the packages is commonly done.

Before final assembly, a bake may be performed to drive out any trapped gas or moisture. This reduces the onset of the hydrogen-related failures. During assembly, the highest curing epoxies or solders should be used first and the processing temperature should decrease until the final lid seal is done at the lowest temperature to avoid later steps damaging earlier steps. Au–Sn is a commonly used solder that works well when the two materials to be bonded have similar CTEs. Au–Sn solder joints of materials with a large CTE mismatch are susceptible to fatigue failures after temperature cycling, and Au–Sn intermetallics may form that have unfavorable mechanical properties. Welding using lasers to locally heat the joint between the two parts without raising the temperature of the entire part is a commonly used alternative to solders. Regardless of the seal technology, no voids or misalignments should be tolerated since they may cause the package to fail hermetic tests.

Feedthroughs or dc and RF interconnects can be coax-to-microstrip launchers, rectangular waveguide-to-microstrip transitions, and planar ceramic lines. These are illustrated in Figures 9-5, 9-6, and 9-1, respectively. Significant reflections can result within the package at the connections between the feedthroughs and the transmission lines, and undesired modes can be launched on the transmission lines. Some of these issues are discussed in Section 9-VI.

2. Ceramic Packages

Ceramic packages have several features that make them especially useful for MMICs: low mass, reduced waveguide box resonance, mass-production compatibility and therefore low cost, they can be made hermetic, and can more easily integrate signal distribution lines and feedthroughs. As illustrated in Figures 9-1 and 9-2, they can be machined to perform many different functions, and, by incorporating multiple layers of ceramics and interconnect lines, the interconnect line loss and parasitic effects are reduced. Multilayer ceramic packages also allow reduced size and cost of the total microwave system by integrating multiple MMICs and other components into a single, hermetic package. These multilayer packages offer significant size and mass reduction over metal-walled packages. Most of that advantage is derived from the close spacing of MMICs that is possible in ceramic packages and the use of three dimensions instead of two for interconnect lines.

The most widely used ceramics for MMIC packages belong to the class known as "low temperature cofired ceramics" (LTCC). These materials are based on Pb-B-Si-O glass with alumina fillers. The material properties, including the dielectric constant and loss tangent, are dependent on the ceramic composition; generally, the relative dielectric constant is in the range of 6 to 9.9 and the loss tangent is acceptable for microwave applications. Other material properties that must be considered are the CTE, the processing temperature of the ceramics, the processing temperature of the metals used for interconnect lines, and interactions between the various materials.

LTCC packages are constructed from individual pieces of ceramic in the "green" or unfired state. These materials are thin, pliable films. During a typical process, the films are stretched across a frame in a way similar to that used by an artist to stretch a canvas across a frame. On each layer, metal lines are deposited using thick-film processing (usually screen printing), and via holes for interlayer interconnects are drilled or punched. If larger holes or cutouts are required in the layer to form wells for MMICs, they are also drilled, usually by a laser. After all of the layers have been fabricated, the unfired pieces are stacked and aligned using registration holes and laminated together. Finally, the part is fired at a high temperature of 800 to 1000°C. The MMICs and other components are then epoxied into place, and wire bonds are made the same as those used for metal packages.

Several problems that can affect the reliability of the MMIC arise from the fabrication procedure. First, the green-state ceramic shrinks during the firing step. The amount of shrinkage is dependent on the number and position of via holes and wells cut into each layer. Therefore, different layers may shrink more than others creating stress in the final package. Second, because ceramic-to-metal adhesion is not as strong as ceramic-to-ceramic adhesion, sufficient ceramic surface area must be available to assure a good bond between layers. This eliminates the possibility of continuous ground planes for power distribution and shielding. Instead, metal grids are used for these purposes. For microwave transmission lines, the ground planes are reduced by design to three times the strip width; this reduction increases the conductor loss of the lines. Third, the choice of metal lines is limited by the processing temperature and ceramic properties. To eliminate warping, the shrinkage rate of the metal and ceramic must be matched. Also, the metal must not react chemically with the ceramic during the firing process. The metals most frequently used for LTCC packages are Ag, AgPd, Au, and AuPt. Ag migration has been reported to occur at high temperatures, high humidity, and along faults in the ceramic. The microwave design issues that arise from ceramic packages are covered in depth in Section 9-VI.

3. Thin-Film Multilayer Packages

The disadvantages of ceramic packages need to be addressed. First, wire bonds are required for the final connection to the MMIC along with all of the parasitics associated with them (assuming flip-chip technology is not used). Second, the space between lines to reduce coupling is relatively large .

Thin-film multilayer packages solve both of these problems. Within the broad subject of thin-film multilayer packages, two general technologies are used. One uses sheets of polyimide laminated together in a way similar to that used for the LTCC packages described above, except a final firing is not required. Each individual sheet is typically 25 μm and is processed separately using thin-film metal processing. The second technique also uses polyimide, but each layer is spun onto and baked on the carrier or substrate to form 1- to 20-μm-thick layers. In this method, via holes are either wet etched or reactive ion etched (RIE). The polyimide for both methods has a relative permittivity of 2.8 to 3.2. Since the permittivity is low and the layers are thin, the same characteristic impedance lines can be fabricated with less line-to-line coupling; therefore, closer spacing of lines is possible. In addition, the low permittivity results in low line capacitance and therefore faster circuits. The wire bonds can be eliminated by depositing the polyimide over the MMIC and using via holes to couple the RF signal, dc power lines, and the MMIC. These features of thin-film mutilayer packages are illustrated in Figure 9-7.

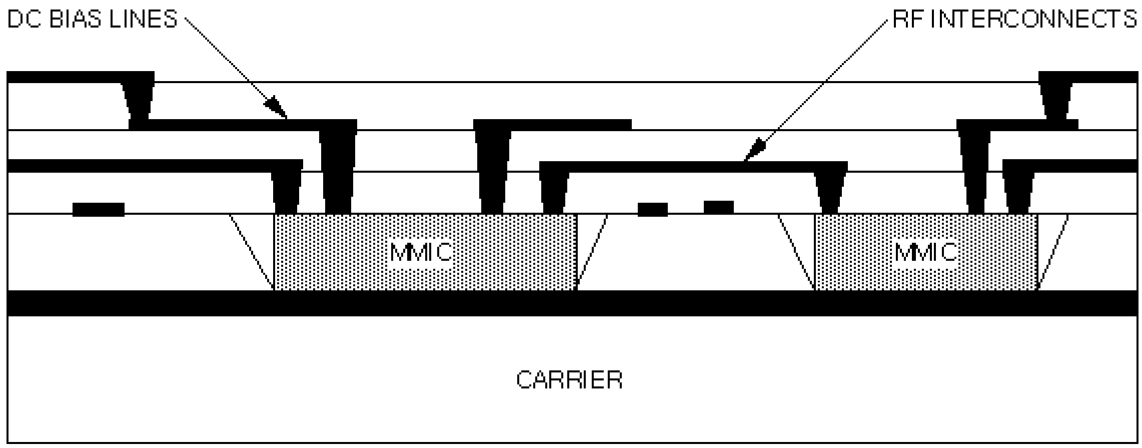

Figure 9-7. Schematic of thin-film multilayer package with integrated MMICs.

As with other technologies, there are problems with thin-film multilayer packages. The conductor loss per unit length can be as high as 10 dB/cm at 110 GHz, but because the line lengths are short, the loss is acceptable. Other problems relating to reliability are covered in depth in Section 9-IV.

4. Plastic Packages

Plastic packages have been widely used by the electronics industry for many years and for almost every application because of their low manufacturing cost. High-reliability applications are an exception because serious reliability questions have been raised. Plastic packages are not hermetic, and hermetic seals are required for high-reliability applications. The packages are also susceptible to cracking during temperature cycling in humid environments or where the plastic has absorbed moisture. The packaging of GaAs MMICs in plastic for space applications may gain acceptability if one of the proposed LEO or GEO satellite constellations for personal communications makes successful use of it. The reliability of plastic packages is presented in Section 9-V.

Additional Reading

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