MANUFACTURE OF LOW-LOSS MICROWAVE CIRCUITS USING HMIC TECHNOLOGY

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Abstract

HMIC is a low cost, batch processed, surface mountable, microwave manufacturing technology that provides hybrid-type flexibility with monolithic-type passive component repeatability and precision. Recent results on power amplifier circuits have shown high power-added efficiencies with reduced size and is paving the way for low cost, high performance circuits for wireless communication markets.

Introduction

The Heterolithic Microwave Integrated Circuit (HMIC) technology, developed at M/A-COM, combines the properties of silicon and glass to create low-loss circuits for RF, microwave, and millimeter wave applications[1-3]. The monolithic nature of this technology allows the use of automated batch processing and testing at the wafer level thus providing cost and performance benefits over conventional chip-and-wire microwave manufacturing techniques. On the other hand, HMIC also offers the flexibility of integrating external active devices wherever the technological or economic factors prohibit a completely monolithic structure.

The basic HMIC chip consists of silicon pedestals embedded in a glass medium. Si device-based monolithic circuits, compared to GaAs FET-based circuits, have the potential for higher power dissipation, lower loss, lower distortion, and lower cost. The fabrication and performance of Si monolithic devices in HMIC such as PIN diodes, Schottky diodes, and bipolar transistors, has been discussed elsewhere [1-3]. Hence, this article will focus on wholly passive HMIC circuits where external devices and IC's are mounted on the silicon pedestals.

Fig. 1 shows the cross-section of a typical passive HMIC chip indicating the various circuit elements. The Si pedestals provide rf ground and also electrical connection for the surface mount configuration. The high thermal conductivity of Si results in efficient heat removal for devices and IC's mounted on the pedestals and thus provides a high power handling capability to HMIC. The glass provides electrical isolation, mechanical support, low dielectric constant (4.1) and low loss tangent (0.002 @ 10GHz). Thin film, batch processes are used to fabricate spiral inductors, interdigitated and MIM capacitors, and resistors on the glass at low cost, high performance, and good reliability. The result is a unique manufacturing technology suitable for a broad range of microwave circuits.

Two examples of passive HMIC circuits are discussed in this article. One is a 900 MHz power amplifier

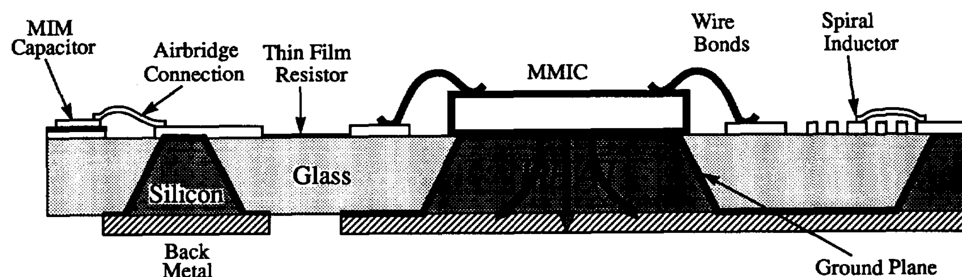

Fig.1: Cross-section of Passive HMIC

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amplifier circuit for cellular applications with a power-added efficiency of 60% and a significantly reduced size compared to any other commercial product. The other is a miniature, low-cost, 6-18 GHz bias network.

HMIC Glass

The most commonly used substrate materials in the microwave industry are alumina, beryllium oxide (BeO), quartz, and GaAs. However, glass was found to be the most appropriate material for the level of integration targeted for HMIC. Table 1 compares some properties of these materials [4].

Material	Dielectric Constant	Loss Tangent	Expansion Coefficient (ppm/C)
HMIC Glass	4.1	0.002	3.2
Alumina	9.4	0.001	6.6
Beryllium Oxide	6.8	0.002	6.8
Quartz	3.9	0.0002	0.55
GaAs	12.9		6.9

Table 1: Properties of microwave substrate materials

The low loss tangent of glass allows the fabrication of high-Q passive elements. The low dielectric constant of the glass results in lower parasitic coupling between circuit elements. It also allows the use of relatively thin glass layers to support a broad range of characteristic impedences. Fig. 2 shows the normal design range associated with two different glass thickness. The circuit designer now has the flexibility of high impedence lines without the high conductor loss associated with thin structures.

The thermal expansion match of glass with Si (=2.6 ppm/°C) is important for mechanical stability of the HMIC wafer and results in a considerable manufacturing advantage for HMIC. Si wafers are readily available at low cost, high purity, and excellent surface finish and flatness. The HMIC substrate can be handled just like a standard Si wafer thus allowing the use of automated cassette-to-cassette, semiconductor processing equipment.

Glass is an amorphous material and so it can be polished to a fine surface finish. Hence, it can readily support thin-film deposition and fine-line photolithographic processes used in the fabrication of inductors, capacitors, and resistors.

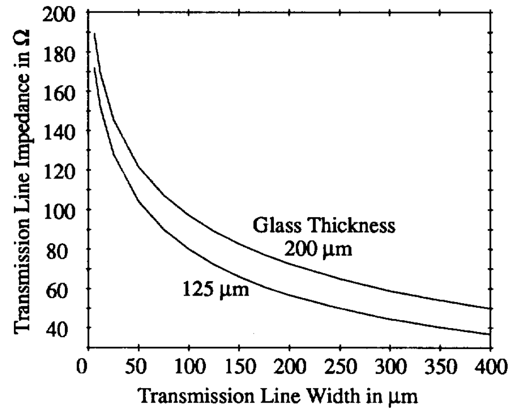

Fig.2: HMIC transmission line impedence vs.line width.

While individual characteristics of HMIC mentioned above may hold true for the other microwave media as well, HMIC combines all these advantages in a highly manufacturable process for low cost, high performance microwave circuits.

HMIC Process

The HMIC process starts with a (100)-oriented Si wafer, arsenic doped to <0.003 Ω.cm resistivity. Epitaxy and ion implantation processes are used to fabricate active junctions depending on the type of devices desired. However, for wholly passive HMIC circuits no epitaxial layers are grown and no doping profiles are created. Si pedestals are defined using a wet anisotropic etch which results in side walls parallel to (111) planes. Predictable and reproducible geometries are fabricated by this process with the final pedestal height in the range of 125 to 250 µm.

A high conductivity silver ground plane is deposited on the bottom of the etched Si and on the pedestals. This is followed by a glassing step which fills in the trenches between pedestals with the low-loss glass. After the glassing step, the glass is at least 50 µm thicker than the depth of the Si pedestals. The wafers now undergo grinding and polishing operations to expose the top of the Si pedestals. This results in the planar substrate shown in Fig.1.

The planar HMIC wafer with its smooth surface finish allows for fine-line lithography. The standard metallization scheme comprises a titanium layer for adhesion, a platinum layer as diffusion barrier, and a substantially thicker gold layer as conductor. It is used in

the fabrication of inductors, capacitors, transmission lines, and air-bridges. A critical capability is the definition of thick metal lines with lift-off techniques which enables the use of difficult-to-etch metals such as gold and platinum with aspect ratios exceeding 1:1. The thick metal capability allows the fabrication of high-Q inductors and capacitors.

Spiral inductors of 1-100 nH have been fabricated with very high Q values (for example, Q of 35 for a 3.5nH inductor at 1GHz). Interdigitated capacitors are used for values less than 0.1 pF while MIM capacitors are used for values in the range 0.1-100 pF. Silicon nitride is used as the dielectric for the MIM capacitors with a capacitance per unit area of 0.21×10^{-3} pF/μm^2. MIMs are routinely fabricated with V_b > 100V. Thin film resistors are fabricated using NiCr metallization with a sheet resistance value of 35 Ω/□.

The completed HMIC circuit is encapsulated with silicon nitride and a polyimide scratch protection layer which are patterned to access bond pads and Si pedestals for mounting devices or IC's. The 6000Å thick silicon nitride is an effective diffusion barrier against moisture. The polyimide layer has a dielectric constant of 3.5 and loss tangent of 0.002 (from manufacturer's data at 1KHz) and does not cause any significant performance degradation for most HMIC circuits. All the air-bridge crossovers get completely encapsulated in the polyimide and so the HMIC circuits can reliably withstand handling during subsequent assembly and packaging.

For surface mount chips, the silicon pedestals bring electrical connection from top of the chip to the backside. Thick gold hard bumps or Pb-Sn solder bumps are fabricated on the backside of the silicon pedestals to facilitate surface mount assembly.

Examples

The following two examples of passive HMIC circuits will illustrate the capability of HMIC technology.

Power Amplifier

In mobile communications, DC power is limited and so the DC-RF efficiency is a critical system parameter. A 900 MHz, high efficiency, power amplifier circuit was developed using the low loss passive component capability of HMIC. A GaAs driver FET and a high efficiency GaAs power FET (both manufactured at M/A-COM) were mounted on Si pedestals on the HMIC substrate. The input, interstage, and output matching networks containing high-Q inductors, capacitors, and resistors were fabricated on the low loss glass of the HMIC substrate.

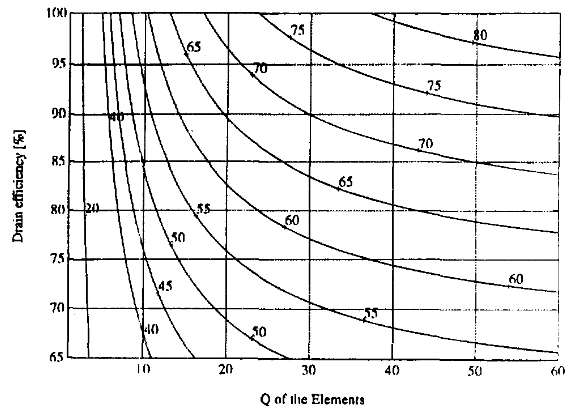

Fig.3: Efficiency contours for the power amplifier

The significance of this capability is illustrated in Fig. 3 which shows efficiency contours for the power amplifier as a function of FET drain efficiency and Q (at 900 MHz) of a 3.5 nH inductor used in the output match. Assuming a FET drain efficiency of 75%, an improvement in Q from 10 to 35 will result in an efficiency improvement from 45% to 60%.

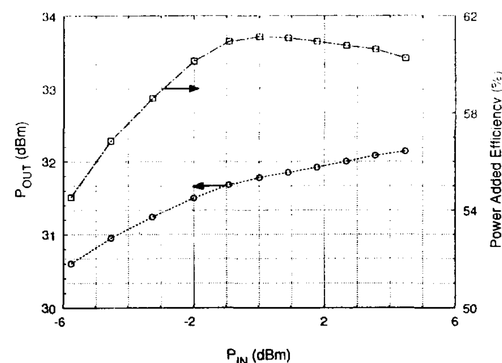

Fig.4: Measured output power and efficiency data for the power amplifier

Fig. 4 shows measured data for the power amplifier at 31.8dB output power and 61% efficiency for operation with a 5V supply. The overall amplifier size was less than 18 mm^2 which was a substantial reduction in size from any other comparable, commercially-available product. This state-of-the-art performance in the small size was possible because of the high-Q lumped circuit elements and the hybrid-type flexibility of integrating the driver and power FETs on the same HMIC substrate.

Bias Network

The HMIC process was used to fabricate a miniature, low-cost chip for injecting DC bias into rf circuits, for operation at 6-18 GHz. As shown in Fig. 5, the circuit is simply made up of a spiral inductor, DC-block capacitor, and ground via. The advantages are reduced component count, fewer bond wires, and reduced size (0.67 mm^2).

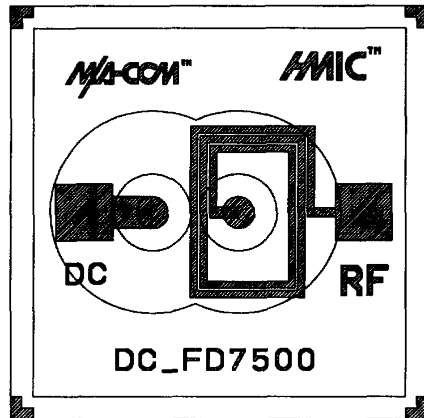

Fig.5: Layout of the 6-18GHz bias network chip

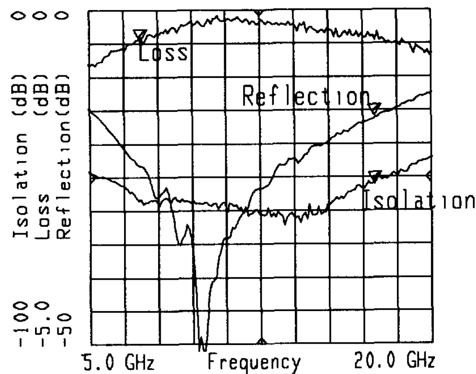

Fig.6: Typical measured performance of the 6-18GHz bias network chip

Measurements in shunt with a 50Ω transmission line showed <0.4dB insertion loss, >15dB input return loss, and >50dB isolation, as shown in Fig. 6.

Summary

The Heterolithic Microwave Integrated Circuit (HMIC) technology, developed at M/A-COM, is a low cost, high performance, flexible manufacturing technology for microwave circuits. It combines the advantages of the power handling capability of Si, low-loss property of glass, automated batch processing and testing, and a hybrid-type flexibility of integrating various devices and ICs.

Two examples of the HMIC technology have been presented: a 900MHz power amplifier circuit with 60% power-added efficiency, and a miniature, low cost, 6-18GHz bias network chip. Developments in progress in HMIC are multilevel metallization with polymer dielectrics, flip-chip bonding of devices to HMIC, and optoelectronic circuits.

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