NOVEL MICROMACHINED APPROACHES TO MMICs USING LOW-PARASITIC, HIGH-PERFORMANCE TRANSMISSION MEDIA AND ENVIRONMENTS

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1.0 INTRODUCTION

Micromachined high-frequency circuits with integrated packaging offer light weight and controllable parasitics, which makes them appropriate for hand-held communication systems and miniature intelligent millimeter-wave sensors where system requirements impose strict limits on electrical performance. Recent advances in semiconductor processing techniques allow for integration in all of the directions of the three-dimensional space. The capability to incorporate one more dimension, and a few more parameters, in the circuit design, leads to revolutionary shapes and integration schemes. These circuit topologies have reduced ohmic loss and are free parasitic radiation or parasitic cavity resonances without loosing their monolithic character. Integration capabilities are thereby extended and performance is optimized. The evolution of micromachined circuits and antennas for operation in microwave and millimeter-wave frequencies is still in its infancy. However, presented here is a description of recent accomplishments in this area, with emphasis on the effort performed at the University of Michigan. There are two techniques which have shown promise for use, and which extensively use micromachining to realize novel circuits. The first utilizes dielectric membranes to support transmission line and antenna configurations [1]-[2] and emphasizes optimization of circuit performance. The second technique introduces new concepts in packaging such as adaptive or conformal packaging and, in addition to improvement in performance, it emphasizes size/volume/cost reduction [3]. The merits of each approach, in relation to electrical performance, fabrication, and compatibility, will be presented, and the impact of the newborn technologies to the state of the art will be discussed.

2.0 MICROMACHINING APPROACHES

This section describes a variety of micromachining approaches which have been used in millimeter-wave circuit and antenna designs:

Dielectric Membrane Supported Circuits: The successful development of a membrane-supported transmission line, called microshield, was presented for the first time in the 1991 MTT-S International Microwave Symposium [1]. The microshield is only one of the possible membrane-supported geometries shown in Figure 1. All of these geometries are evolutions of conventional planar lines with one major difference; the substrate material underneath the lines has been removed and a membrane is utilized to support the conductors. Figure 1a shows a membrane coupled strip line, very closely resembling the conventional coupled strip line, which can provide very efficient antenna feeding networks. The second of the membrane geometries, Figure 1b, is the microshield line, very similar in shape with the conventional coplanar waveguide. This line has zero dispersion, limited parasitic radiation and the capability to suppress the excitation of the unwanted slot-line mode due to the presence of the folded ground which operates as a continuous air bridge. Figure 1c shows a membrane coaxial which resembles a rectangular coaxial, and is characterized by zero dielectric loss, zero dispersion, zero parasitic radiation while maintaining compatibility to planar monolithic geometries. Also, Figure 1d shows the geometry of a membrane microstrip which can be design to operate in a single mode TEM operation for frequencies as high as 300 GHz. This propagating structure is completely shielded and can provide passive circuit components with optimum performance. The membrane line as a transmission medium has created the basis of a new technology for circuit and antenna applications in the millimeter and sub-millimeter-wave regions. The success of membrane-supported circuits relies on the development of thin-film dielectric membranes or diaphragms with good electrical and mechanical properties. These thin-film layers are grown on Si or GaAs wafers, and are used to support the planar conducting strip lines. In view of the previously mentioned performance objectives, the thin films must have low losses at microwave and millimeter-wave frequencies, as well as compatibility with semiconducting and conducting materials. Furthermore, mechanical consider-

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ations include reduced sensitivity to applied pressure and temperature variations, along with increased membrane or diaphragm sizes.

Micromachined On-Wafer Package: Silicon micromachining can offer what conventional means have not been able to provide; packages which conform to the circuit geometry, require much less space, and provide superior mechanical, thermal, and electrical performance. Recently, at the University of Michigan, Si micromachining was used to develop self-packaged circuit components which have demonstrated superior electrical performance when compared to conventionally developed components. These micromachined components are of microstrip or coplanar waveguide (CPW) type and they are surrounded by an air-filled cavity in the upper region and a substrate-filled cavity in the lower region. Both cavities are integrated monolithically with the circuits to provide completely shielded geometries which are appropriate for a broad range of applications including high density interconnect networks and vertical transitions. The use of on-wafer packaging can lead to elimination of unwanted parasitic mechanisms such as parasitic coupling and parasitic radiation.

3.0 MICROMACHINED TRANSMISSION LINES

Transmission lines and circuits printed on dielectric membranes have demonstrated zero dispersion, very loss and very small parasitics. The presented results confirm the capability of these circuits to provide excellent performance in millimeter-wave frequencies. In the following, many of the presented measurements have been performed in the Ka and W bands. In all cases, measurements were made on a vector network analyzer (HP8510) and a Thru-Reflect-Line (TRL) calibration technique was employed to de-embed the measurements to the reference planes of the circuits.

3.1 Effective Dielectric Constant

During Ka and W-band measurements, data were taken that allowed the extraction of the effective relative dielectric constant ($\varepsilon_{r,eff}$) of the microshield line from 10-40 GHz to 75-100 GHz [5]. The measured values of $\varepsilon_{r,eff}$ show a very minor influence of the membrane on the propagation characteristics of the microshield line. The membrane is a 1.5 micron thick tri-layer composite of $SiO_2/Si_3N_4/SiO_2$ with thicknesses of 7000Å/3000Å/4000Å. The dielectric constant of the oxide is 3.9 and of the nitride is 7.5. The presence of the dielectrics results in a value of 1.08 for $\varepsilon_{r,eff}$, instead of the unity value that would be expected if the signal were propagating entirely in air. Also, very low dispersion is indicated, since the measured $\varepsilon_{r,eff}$ remains very nearly constant vs. frequency. This fact means the absence of substrate moding i.e. single-mode TEM wave propagation over a very wide bandwidth.

3.2 Attenuation in Micromachined Lines

The attenuation in membrane micromachined lines is due conductor losses only, if the lines are shielded, and it may be augmented by radiation losses if the lines are operating in an open environment. In the following two sections we will briefly describe how each type of loss varies with frequency and ways to reduce it or eliminate it.

3.2.1 Ohmic Losses

Conductor loss in membrane lines critically depends on the operating frequency, size of the circuit and aspect ratio. For a microshield line where the line geometry simulates a coplanar waveguide, the aspect ratio (s+2w)/s (see Figure 1) plays a very important role. Specifically, lines where the inner conductor is very narrow and the slots are also narrow, will have a much higher conductor loss from lines of the same characteristic impedance but with wider inner conductor and wider apertures. Furthermore, lines of higher impedance tend to exhibit lower conductor loss. For all the above reasons the measured loss of a microshield line has been found to be much lower than the loss of a coplanar waveguide of the same aspect ratio. On wafer and electro-optic sampling measurements performed at Michigan has demonstrated the low loss characteristics of the microshield line. Measured loss shows that the microshield attenuation constant in dBs/mm is three times lower than that of the conventional coplanar waveguide for frequencies up to 40 GHz. These measurements have shown that losses in these membranes lines remain extremely low as we cross 100GHz and move toward 1000GHz operating frequencies. This is due to the fact that the membrane line has only conductor loss contrary to the conventional CPW which suffers from dielectric and radiation loss in addition to ohmic loss. Furthermore, the conductor loss in dB per guided wavelength varies as the inverse of the square root of the frequency. As a result, circuits which are scaled so that their electric lengths remain the same will have lower conductor loss in W band from the loss they would exhibit in Ka band. Attenuation constant measurements have also been performed through the application of an electro-optic sampling technique [6]. These results confirm the superior performance of the membrane line as it has been discussed in previous sections. Based on the above observations, we have been able to design microshield lines for operation in W band with very low losses. Specifically, low-pass and band-pass filters in W band have exhibited losses with less than 1 dB insertion loss. Similar observations apply to the membrane microstrip.

3.2.2 Radiation Losses

Radiation losses have a different frequency and geometry dependence. The membrane microshield geometry has exhibited tremendously low radiation to the point where we do not even consider it. Band-pass filters at 250 GHz have demonstrated a loss less than 1 dB. For the membrane microstrip the situation changes. W-band band-pass coupled resonator filters have exhibited high radiation loss. However, this loss can be suppressed through the use of Si micromachined packages. Measured W-band self-packaged band-pass filters with 16% bandwidth have exhibited less than 0.6 dB loss throughout the pass-band.

4.0 MICROMACHINED COMPONENTS

The performance advantages of membrane supported transmission lines can be clearly demonstrated by observing the characteristics of various distributed circuits which are common to planar microwave circuitry and MMICs. The broadband TEM propagation afforded by membrane supported transmission lines permits a significant increase in performance levels for typical planar circuits such as filters, stubs, and power dividers. As part of this presentation, a variety of micromachined components will be presented and their performance will be discussed and compared to that if conventional circuits.

5.0 CONCLUSIONS

A new micromachined technology suitable for three-dimensional planar circuit configurations has been presented. At higher frequencies, problems associated with the substrates make conventional approaches unfeasible, and membrane supported circuit components offer the only planar alternative to costly waveguide-based approaches. Micromachined transmission lines and circuits have been shown to perform very well in frequency bands all the way up to W-band (110 GHz). Circuits commonly used in CPW implementations are shown to have superior performance when realized with membrane supported transmission lines like the microshield line. The microshield line has a relative effective dielectric constant of 1.07 through 100 GHz and, as a result, it exhibits zero dispersion and zero substrate loss. The micromachined CPW has the lowest attenuation yet demonstrated for planar transmission lines. Filters and resonant stubs have been measured up to 250 GHz and have demonstrated an unparalleled electrical performance. Micromachining has also opened the doors to techniques for fabricating circuits that were previously restricted by cumbersome machining processes. Interdigitated filters were thought to be limited to very low frequencies where they could be manufactured using mechanical techniques, but membrane technology has allowed them to become high performance alternatives at 30 GHz. Membrane millimeter-wave microstrip inductors have been developed and fabricated on a high-resistivity silicon substrates using micro-machining techniques with resonant frequencies in the submillimeter-wave region. Last but not least, on-wafer packaging can eliminate parasitic coupling and radiation by component-specific electromagnetic shielding without disturbing the monolithic character of the circuit

6.0 ACKNOWLEDGEMENTS

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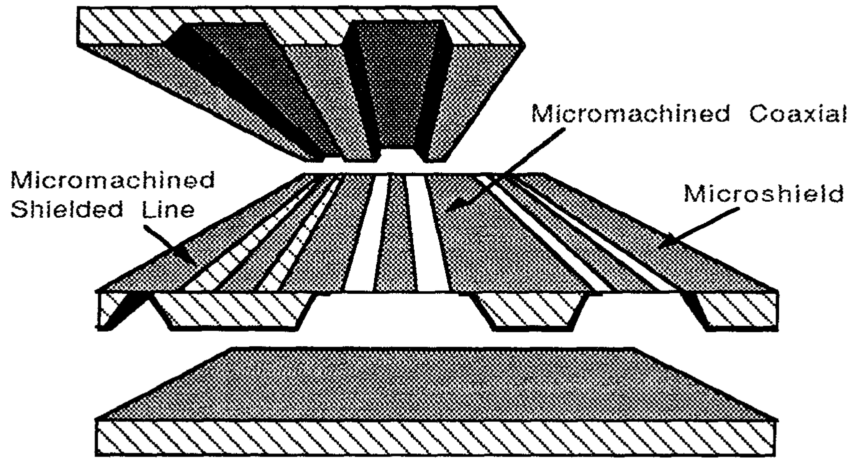
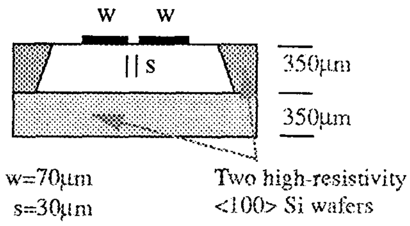
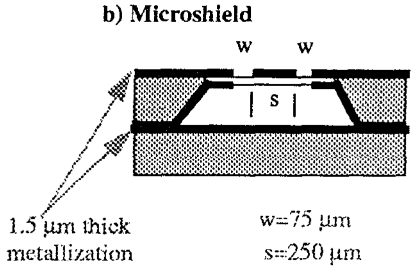
Figure 1: Micromachined Three-Dimensional Interconnects



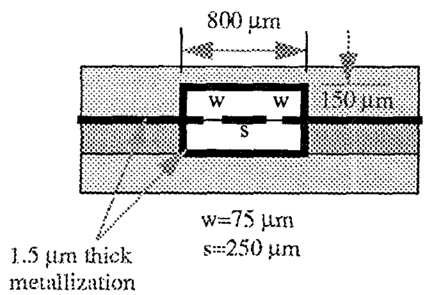
a) Membrane Coupled Strips



b) Microshield



c) Membrane Coaxial



d) Membrane Microstrip