Interconnect and Packaging Technologies for Terahertz Communication Systems

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***Abstract*—Using newly developed silicon micromachining technology that enables low-loss and highly integrated packaging solutions, we are developing vertically stacked transmitters and receivers at terahertz frequencies that can be used for communication and other terahertz systems. Although there are multiple ways to address the problem of interconnect and packaging solutions at these frequencies, such as system-on-package (SOP), multi-chip modules (MCM), substrate integrated waveguide (SIW), liquid crystal polymer (LCP) based multilayer technologies, and others, we show that deep reactive ion etching (DRIE) based silicon micromachining with vertical integration allows the most effective solutions at terahertz frequencies.**

***Index Terms*—Terahertz, Micromachining, DRIE, interconnects, packaging.**

I. Introduction

Emerging applications of millimeter- and submillimeter-wave frequencies such as broadband communications, sensing, and imaging require the development of high-performance and highly compact systems. Communication systems at terahertz frequencies to utilize the higher available bandwidth is increasingly gaining ground [1]. Any communication system requires synergistic coexistence of hardware and software, and it is no different for terahertz communication systems. However, implementing the hardware part at terahertz frequencies has been challenging. One of the key obstacles has been low-loss integration techniques of different components at system level at these frequencies. There has been dramatic improvement of component and subsystem technologies at millimeter-wave and terahertz frequencies over the last decade [2]. However, the integration of the various components to build a compact and high-performance system is still a challenge.

Researchers have been looking into different solutions for the packaging and interconnects for millimeter-wave and terahertz systems. Majority of the techniques are similar to the existing techniques at microwave frequencies which have been adapted at higher frequencies. In this paper, an overview of different packaging and interconnect techniques at terahertz frequencies are discussed and the details of some new and innovative solutions are provided.

II. Interconnect Technologies

Packaging and interconnect technologies at millimeter-wave and terahertz frequencies have been evolving over the last several years. For complex communication systems, system-on-chip (SoC) solutions are being looked into but not mature enough at this time. Techniques such as system-on-package (SOP) where multi-chip module (MCM) and integrated substrate technologies utilizing multi-layer processing are employed has been used at millimeter-waves [3]. Fig. 1 shows some details of SOP concepts that are developed by different groups. However, due to increased loss as higher millimeter-wave and terahertz frequencies, low-loss alternatives such as non-radiative dielectric waveguide (NRD-guide) [4], substrate integrated waveguide (SIW) [5], and liquid crystal polymer (LCP) based multilayer technologies [3] are being explored.

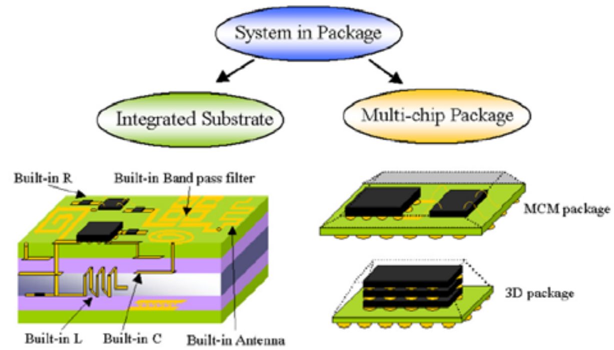

Fig. 1: Schematic of different system-on-package (SOP) technologies that are being investigated currently.

NRD-guide structures are typically made of dielectric strips functioning as waveguides where two parallel-plates clamps the dielectric strips. In recent years, NRD-guide structures have been integrated with other planar transmission lines to develop components such as filters, oscillators, and mixers at millimeter-wave frequencies. However, due to higher dielectric loss at higher frequencies, NRD-guide structures are not practical at terahertz frequencies.

Substrate integrated waveguide (SIW) techniques for interconnects and packaging has been found to be very versatile and useful due to the ease of integration with MMICs and other components, simple fabrication process, and its suitability of integration with a wide range of SIW based components into a single substrate [6]. SIWs are similar to metal waveguide structures. They are fabricated by using two parallel metal plates connected by two rows of metallic cylinders or slots embedded in a dielectric filling the two parallel plates. The advantage of this technique is that one can fabricate non-planar metallic waveguide-like structure using planar fabrication techniques. The best thing about SIWs is that they exhibit propagation characteristics

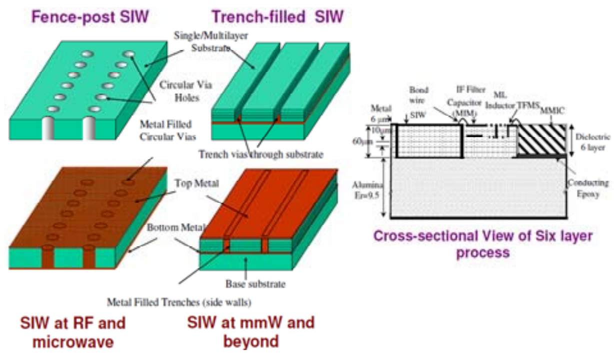

Fig. 2: Schematic of different substrate integrated technologies used for packaging technologies at microwave and millimeter-wave applications.

including field patterns and dispersion characteristics similar to standard rectangular metallic waveguides. Although it is generally difficult to achieve fine conductor geometries to realize trench-filled vias and compact, high performance passive components at frequencies beyond 100 GHz. However, use of advanced multilayer thick-film photo imageable ceramic technology has been found to work frequencies up to 200 GHz. In this technique, instead of using standard SIW with metallic cylinder vias, advanced photoimaged trench-filled vias form continuous metal side walls, enabling SIW to provide low loss and extending its frequency of operation [7]. Fig. 2 shows different SIW technologies that are being used for packaging and interconnect applications.

All the different technologies discussed above are limited to up to 100-200 GHz. Packaging and interconnecting technologies at frequencies beyond 200 GHz still remains challenging. The primary fabrication technique for terahertz components and packaging systems has been CNC milling. However, it is quite clear that they do not provide a compact solution for packaging and interconnects. One of the way to address this problem is using vertically stacked component architecture. In this architecture a three dimensional (3-D) arrangement of active and passive components coupled with micromachined waveguides which are fabricated on thin layers of metals or substrates. Metal milling of waveguide packaging which is preferred at terahertz frequencies are not suitable for this architecture due to the limitations of aspect ratios and planarity of the metal machined parts.

Micromachining has the most potential as a process for developing low-loss packaging and interconnect technologies at terahertz frequencies. There are several micromachining techniques that can be used for terahertz systems: permanent thick resists [8], thick-resist electroforming [9], laser micromachining [10], and silicon deep reactive ion etching (DRIE) [11]. There have been some good results from all these different techniques. However, DRIE-based silicon micromachining has shown to have the most potential to solve packaging and interconnect technology at terahertz frequencies. The waveguide circuits developed with DRIE-based silicon micromachining has shown to have low loss, similar to metal machined waveguides, but provide a very high level of integration solutions. Moreover, they provide the capability to integrate complex passive circuits with active components. In the next section we will primarily focus on the DRIE based circuits, interconnects, and packaging.

III. DRIE Based Packaging Technologies

DRIE micromachining is a dry etching technique, relying on plasma etching of bulk silicon. There are two primary techniques applied, cryogenic and Bosch etching. Both are known to produce near vertical sidewalls, high aspect ratio features, and are applicable to mass production. Although cryogenic DRIE naturally has lower sidewall roughness, the Bosch process is more commonly used to fabricate terahertz components because of its higher etch rate and selectivity. The Bosch processes utilizes SF_6 and C_4F_8 as the main gases, with alternate sequences of etching and passivation steps. Various masks can be used for DRIE-based silicon micromachining, including photoresist, oxide/nitride, or metals [12].

Majority of the packaging and interconnect work that has been done in DRIE based silicon micromachining uses either one or two-etch depths. Even though these processes have been successful, they were limited in terms of complexity of packaging systems where multiple active and passive devices need to be assembled and integrated. For DRIE based packaging system to be successful, one would need multiple-depth etching process where devices such as ortho-mode transducers (for polarization diversity in communication systems or provide good isolation between transmit and receive paths), hybrid structures, and antennas can be fabricated on a single wafer.

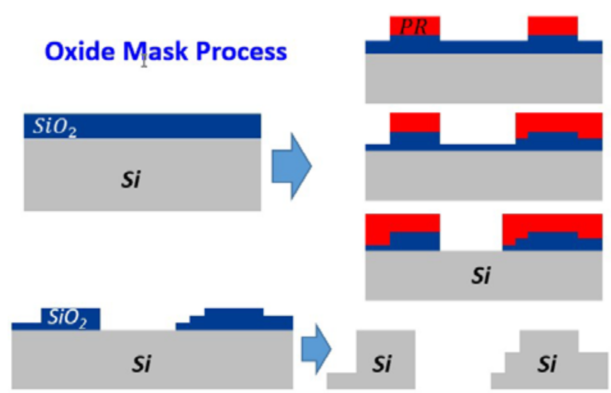

Fig. 3: Schematic showing details of multi oxide mask based DRIE process which results in multi-etch depth waveguide packaging.

Complex structures with multiple-etch depths require multiple etch steps, and hence a multi-mask processing techniques. The Micro-Electromechanical-Systems (MEMS) community has been using this technique where a sequence of oxide, photoresist, and metals are used to generate multiple etch masks that are used before DRIE processing.

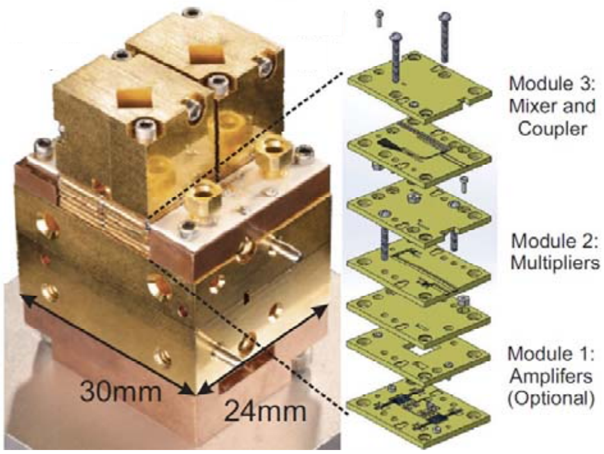

Fig. 4: Photo of the assembled terahertz transmitter and receiver packaged in DRIE-based silicon micromachined wafers vertically stacked to leverage the advantage of these techniques.

However, in this process, there is always a possibility of metals masks being redeposited by plasma and as a result, it contaminates the process producing higher surface roughness. We developed a process where multiple oxide masks with different thickness are used, where each oxide thickness corresponds to one etch depth in silicon [12]. All lithographic steps are performed prior to DRIE to avoid any photoresist coverage issue. Because of the high selectivity of the DRIE process between silicon and silicon dioxide, the masking layer only needs to be a few micrometers thick. Fig. 3 shows the details of such multiple oxide-mask based DRIE etching process. In this process, photoresist is used to do the SiO_2 patterning. Etching of different patterns is done to ensure precise control of the final target. That is done using an inductive coupled plasma (ICP) process, with an etch rate of ~70nm/min). Finally, DRIE process is used to etch the silicon, with oxide as the sole mask, without any

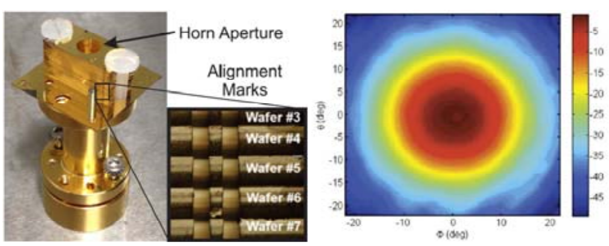

Fig. 5: Photograph of a 340 GHz silicon micromachined corrugated horn antenna with circular to rectangular transition (left). The inset shows the alignment details. Measured beam pattern (right).

photoresist.

One of the advantages of these micromachined based packaging techniques is that it can lead to vertical integration of components, resulting in low-loss and highly compact instrumentation. Fig. 4 shows such a vertically stacked instrument developed by our group. Here, the various transmitter and receiver components are packaged in silicon micromachined components and are vertically stacked. Using similar techniques, we also developed a corrugated horn antenna working at 340 GHz where more than 30 silicon pieces were stacked to package the device. Fig. 5 shows the picture of the antenna along with its performance.

Conclusion

Interconnect and packaging technologies are becoming increasingly important for millimeter-wave and terahertz systems, especially for communication applications. Complex systems require technologies from different areas to be integrated in a seamless package. There are various techniques that have shown promise at millimeter-waves. However, they do not work as well as the frequency moves towards terahertz frequencies. DRIE-based silicon micromachined interconnect and packaging on the other hand has been shown to work well at terahertz frequencies where transmitters, receivers, and antennas can be packaged in a low-loss vertical assembly.

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