MEMS and Si Micromachined Circuits for High-Frequency Applications

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Invited Paper

***Abstract*—RF micromachining and microelectromechanical structure (MEMS) technology promise to provide an innovative approach in the development of effective and low-cost circuits and systems. This technology is expected to have significant application in the development of low-cost antenna arrays and reconfigurable apertures, due to its potential to support novel systems architectures. This paper presents a brief history and the state-of-the-art in the development of RF MEMS devices, with primary emphasis on switches and Si-micromachined circuit components for use in high-performance high-density on-wafer packaged circuits.**

***Index Terms*—High-frequency circuits, on-wafer packaging, RF MEMS, Si micromachining, three-dimensional integration.**

I. RF MEMS

A. Introduction

RADIO-FREQUENCY (RF) microelectromechanical structure (MEMS) has been identified as a technology that has the potential to provide a major impact on existing RF architectures in sensors (radar) and communications by reducing weight, cost, size, and power dissipation [1]–[6]. Key MEMS devices for current RF architectures are switches in radar systems and filters in communications systems. Future communications require increasing functionality and endurance—features that can be addressed by the successful insertion of new highly integrated MEMS sensors and circuits.

To maximize data transfer, reduce size, and minimize operational cost, communications RF front-ends are forced to move to higher frequencies. RF micromachining and MEMS technology promise to provide an innovative approach in the development of effective and low-cost circuits and systems, and are expected to have significant application in the development of low-cost antenna arrays and reconfigurable apertures. Passive components currently take up $\sim$90% of the total transceiver board area. By achieving orders-of-magnitude reduction in the size of high-Q resonators, MEMS technology stands to greatly reduce this percentage. Due to their tiny size, nanowatt dc power consumption, and batch fabrication technology, MEMS devices can be used in large numbers to revolutionize the system transceiver architecture. In particular, with MEMS high-Q filters, architectures that currently must minimize the use of high-Q components to reduce size may give way to architectures that emphasize high Q to greatly improve efficiency of communication transceivers. Both transceiver size and battery size stand to benefit from such novel architectures.

With more selectivity provided by MEMS, transceivers will now be able to function in more electromagnetically hostile environments since co-site and other interference may become much less of a problem. The use of high-Q passive components in transceivers allows one to rethink the design specifications for the surrounding transistor circuits. In particular, dynamic range and phase-noise specifications can be greatly relaxed, allowing not only substantial power reduction (as described above), but also making possible the use of less expensive technologies for certain functions. For example, with relaxed power requirements attained via MEMS, low-noise and power amplifiers may now be achievable in silicon (Si), rather than GaAs, thus reducing the cost of the total system. In addition, in a fully integrated system using a merged circuits/MEMS technology, packaging costs can also be reduced since board-level assembly may no longer be needed.

Over the last ten years, MEMS technology as applied to microwave and millimeter-wave circuits has experienced an exponential growth. In 1991, Larson *et al.* described rotary MEMS switches with good performance at RF frequencies [7], [8]. Nguyen demonstrated the successful development of MEMS HF filters in 1993–1994 [9] and Yao *et al.* demonstrated a surface micromachined series switch for telecommunications applications in 1995 [10]. Recently, shunt microwave switches have been developed in the X- to K/Ka-bands [11]–[13] (see Fig. 1). These switches are usually electrostatic in nature and commonly driven by bias voltages in the 30–80-V range. Most recently, low actuation voltage switches requiring 9 V of dc actuation have been demonstrated [14], [15] and have opened new directions in systems implementation and communication architectures. Generally, MEMS switch designs trade off low actuation voltage for longer switching times, due to the use of softer spring constants. These MEMS devices are primarily designed for low-loss applications that do not require fast

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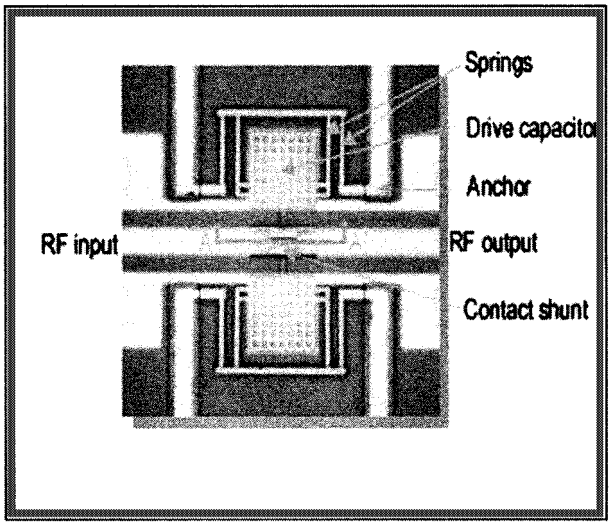


Fig. 1. Rockwell Science Center's microrelay.

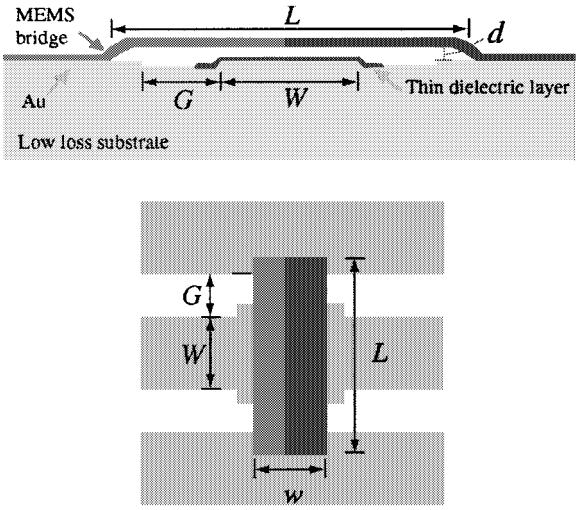


Fig. 2. Typical shunt capacitive membrane or air-bridge switches over a CPW shown in cross section in the up position and top view. Membrane switches have w of the order of L, while air-bridge switches have w much less than L.

switching rates such as in airborne and/or satellite communication. The advantage of MEMS switches over their solid-state counterparts such as FETs or p-i-n diodes is their extremely low series resistance and low drive power requirements. However, the RF power handling of MEMS switches is currently limited to about 1 W because of "hot switching" effects. In addition, since MEMS switches do not respond to the RF voltage, they exhibit negligible intermodulation distortion and, as a result, they provide better linearity at microwave and millimeter-wave frequencies. The above properties of the MEMS switches have created a lot of excitement and anticipation and have driven many research efforts in the U.S., U.K., and Japan. A variety of RF MEMS switch designs have been introduced and successfully demonstrated; however, only a small number of them will be featured in this section. Further details on the remaining designs may be found in the literature.

There is a number of ways to classify various switches. The classification followed herein places switches in three main groups, i.e., *fixed–fixed beam switches*, *cantilever beam switches*, and *compliant beam switches*. Each of these can be categorized by the type of the switch, *series versus shunt*, the type of contact, *metal-to-metal versus capacitive*, and the actuation voltage required for the switch operation.

B. Fixed–Fixed Beam Switches

All of the demonstrated fixed–fixed beam architectures are of capacitive type, but they may operate in a series or shunt form. One of the very first few demonstrations was by Goldsmith *et al.* [11]–[13]. The switch consists of a lower electrode fabricated on the surface of the integrated circuit (IC) and a thin aluminum membrane suspended over the electrode (see Fig. 2). The membrane is connected directly to the grounds of the coplanar waveguide (CPW) line, while a thin dielectric covers the lower electrode in order to avoid direct metal-to-metal contact. The metal membrane moves between the up and down positions with the use of an externally applied dc voltage between 30–55 V. This membrane switch is of shunt type and operates normally on a CPW transmission line. The air-gap between the two conductors determines the on-to-off capacitance ratio and specifies the switch isolation in the frequency range of interest.

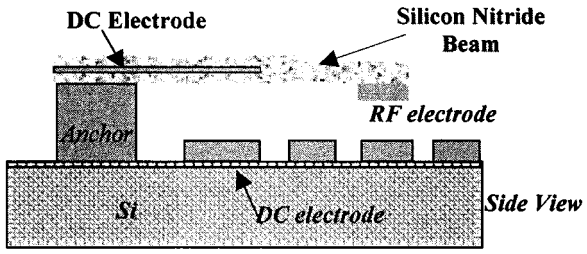


Fig. 3. Side view of the cantilever-beam switch.

With no applied actuation voltage, the residual intrinsic stress keeps the membrane in the upper position and effectively makes it act electrically as a wide air bridge, which may require appropriate compensation for membrane parasitic capacitance. When a dc voltage is applied, the resulting electrostatic field creates positive and negative charges on the electrode and membrane conductor surfaces and, thus, applies an attractive electrostatic force, which causes the membrane to collapse onto the surface of the lower electrode. Details related to MEMS device design, fabrication, and RF characterization can be found in [11]–[13]. Recently, air-bridge MEMS switches have been developed successfully at The University of Michigan at Ann Arbor by Rebeiz *et al.* [17], [18] (see Fig. 2). Air-bridge switches differ from membrane switches in that their metallic beam is narrow, thus requiring higher activation voltages. However, they are similar to membrane switches in terms of mechanical properties and RF performance.

C. Cantilever Beam Switches

A number of efforts have been reported on the development of cantilever beam switches [10], [16] and [19]. A schematic of such a switch is shown on Fig. 3. The primary structural difference between this architecture and the fixed–fixed beam switch

is in the use of the dielectric layers to support the beam and provide isolation between the dc and RF electrodes. This allows for a metal-to-metal contact in a series or shunt switch architecture. Cantilever beam switches require a lower activation voltage than fixed–fixed beam switches and could exhibit higher isolation.

Even in the absence of an applied voltage, the cantilever beam deviates from the horizontal position due to high residual stresses in the metal and dielectrics. The observed vertical displacement increases with the length of the beam to reach a few tens of micrometers for beam lengths of a few hundred micrometers. In these switches, a multilayer cantilever structure has been developed to minimize the effects of residual stress and provide less distortion. The stress gradient is reduced via use of appropriately designed thin dielectric films placed above and below the dc electrode, as shown in Fig. 3 [10], [16], [19]. A plated or evaporated gold center electrode is sandwiched between two layers of the dielectric, Si_3N_4 or SiO_2 beam, with appropriately designed thickness. Furthermore, the residual intrinsic stress can be controlled by process development and temperature control of the switch itself under operating conditions [19]. Stress gauges can also be effectively utilized to specify the necessary fabrication conditions for the minimization of the vertical stress gradient.

Measurements of the microwave scattering parameters have shown very low insertion loss over a very broad frequency range from a few megahertz to at least 10 GHz (X-band). As shown by these measurements, the series switch has very low insertion loss (0.2 dB) up to 40 GHz and isolation which starts at -40 dB at 500 MHz and degrades to -15 dB at 40 GHz. A detailed description of the design, fabrication, and experimental verification for this switch are provided in [16], [19], and [10], respectively. To extend the switch performance to higher frequencies while keeping the isolation below -30 dB, combinations of resonant switches are required.

D. Compliant Beam Switches

One of the disadvantages of the switches presented above is the need to operate under relatively high dc voltages varying from as low as 30 V to as high as 120 V. For MEMS switches to become useful for wireless handheld communications systems, actuation voltages less than 6 V are required. The primary goal of this section is to discuss the design as well as dc and RF properties of low-actuation-voltage electrostatic shunt microwave switches. Ultra low-loss low-actuation-voltage RF MEMS switches have been successfully fabricated at The University of Michigan at Ann Arbor, as shown in Fig. 4 and described in [14] and [15]. These switches are designed for use with finite ground coplanar waveguide (FGCPW), but the design methodology and fabrication approach are very general and can be utilized toward the development of any low-actuation voltage switch design. In order to lower the pull-in voltage of the structure, the following three different design approaches may be pursued:

1) increase the area of actuation;
2) diminish the gap between the switch and bottom electrode;
3) design a structure with low spring constant.

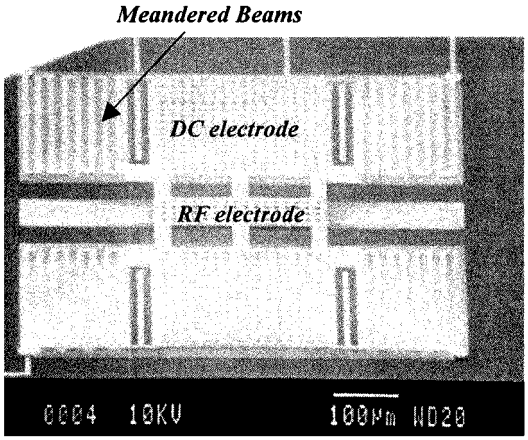


Fig. 4. Low-activation voltage switch designed and fabricated at The University of Michigan at Ann Arbor.

In the first case, the area can only be increased by so much before compactness becomes a prevailing issue. In the second case, the return loss associated with the RF signal restricts the gap size to a minimum, which is of the order of 1 or 2 μm. The third design approach is the one with the most flexibility since the design of the springs does not considerably impact the size, weight, and/or RF performance of the circuit. Fig. 4 shows a scanning electron micrograph (SEM) of a shunt switch design appropriate for operation with a FGCPW interconnect. In general, a softer spring constant should increase switching time by many tens of microseconds. This slower switching speed is still compatible with many applications, such as wireless handsets. The development of RF MEMS devices continues at present in government laboratories, industry, and academia with substantial emphasis on packaging and reliability.

II. Three-Dimensional Integration and Packaging Using Si Micromachining

A. Introduction

Emerging military space, and commercial communications systems, as well as unique military applications in radar and missile seekers, are placing a high premium on low-cost, small lightweight RF electronic components, while at the same time, increasing demands for higher functionality. Systems are using higher and higher frequencies, in part for size considerations and in part for bandwidth. For example, commercial and military satellite, some commercial terrestrial, and spaceborne communications systems are operating in or being designed for the Ka-band (25–40 GHz). On these satellite systems, electronic packaging can account for up to 30% of the overall spacecraft mass while the telecommunication subsystem can account for 15% or more of the dry mass. At the same time, external organizational considerations are driving space agencies to reduce mission cost and failure probability (and, hence, reduce system complexity). Innovative approaches to the integration and packaging of RF systems are keys to achieving these goals.

In the 1980s, great effort was placed on the development of planar monolithic microwave integrated circuits (MMICs) that combine many functions on a single circuit while providing

high performance and low cost. Communications and radar systems benefited from these advances through steady decreases in both cost and weight. However, it has become clear that the performance advantages inherent in MMICs cannot be realized by conventional packaging at the system level [20], [21]. Consequently, many new packaging technologies have evolved at the chip level, such as ball grid arrays and multichip modules (MCMs), which are made of ceramic materials, thin films over Si [also known as high-density integration (HDI)], or printed wiring board. Their main feature is that they combine RF distribution networks, biasing lines, and multiple MMICs in a package. Despite these advances, MCM technology has not fully realized its expectations for low-cost very small-size high-performance systems operating at higher frequencies. High losses in the interconnects and passive components, coupling between circuits, and resonances within the package severely degrade the system performance.

Si micromachined microwave and millimeter-wave circuit integration provides a comprehensive technique to integrate a very large degree of functionality on a single substrate with extremely high density and at a relatively low cost. The micromachined circuit is essentially self-packaged, without the need for external carriers or external hermetic shielding [22], [31]. Since the components are all shielded by the micromachined structure, there is no significant electromagnetic coupling and no spurious resonances caused by the package. The vertically layered structure of the micromachined circuit presents an excellent opportunity for three-dimensional integration, resulting in substantial reductions in size, and enables circuit architectures not possible or practical in a single planar layout.

Micromachined passive components have been developed, which replace large off-chip components that formerly required an expensive, bulky, and heavy hybrid circuit integration, with planar devices that integrate directly into the micromachined layered framework. Micromachined circuits are an ideal way to integrate MEMS devices and provide components with performance and size advantages from 1 GHz to the terahertz regime. However, they demonstrate their greatest promise at X-band and above. Micromachining is truly an overarching master integration technology with the opportunity for an order of magnitude or more reduction in the size, weight, and cost of planar circuits, which can have a major impact on radar and communications applications in the military, commercial, and space arenas.

Micromachining techniques can be applied to any semiconductor substrate, but the use of Si substrate layers as the foundation of the micromachined structure has major advantages in cost and the direct integration of SiGe and CMOS circuits. High-resistivity Si has mechanical, thermal, and electrical properties that compare well with the best ceramics and, as a result, has been successfully demonstrated as the substrate of choice in three-dimensional ICs [20]–[27]. Moreover, Si can be bulk micromachined very rapidly by isotropic wet etching or anisotropic reactive ion etching. Cost comparisons have been made for simple circuit applications and show one and two orders of magnitude reductions in the cost compared to the same circuit packaged in ceramic. Circuit integration based on micromachined fabrication technology promises to be the key to achieving the very demanding cost, size, weight, and simplicity goals required for the next advances in communications and radar systems for commercial, spaceborne, and military applications. Micromachining has been used to develop a variety of high-frequency circuits, as described in detail below.

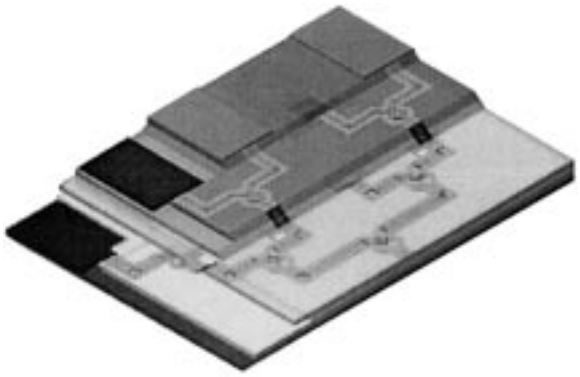


Fig. 5. Three-dimensional interconnect network.

B. Three-Dimensional Packaging and Integration

The hallmark of micromachined IC is the collection of diverse interconnects offered by this technology, each appropriate for specific applications. Micromachining techniques enable the fabrication of CPW with the semiconductor material etched out between the conductor elements, thus substantially reducing dielectric loss and surface-wave modes in the substrate [26], [27]. Layers of substrate can be added to the micromachined structure, with cavities cut to fit over the surface elements of the adjoining layer, providing shielding for the enclosed circuit elements [24], [25]. Metallization can be applied to the enclosed structure to further electromagnetically isolate the circuit elements. Isolations of 40 dB or better have been demonstrated between transmission lines similar to those in Fig. 5, but separated by as little as 100 μm [22]–[25]. This is 20–30 dB greater than the isolation between conventionally fabricated lines.

These shielded and micromachined circuit elements can then be geometrically laid out in much denser circuit architecture. Using these approaches, radiation and substrate losses can be essentially eliminated, leaving only the ohmic loss of the metal. At higher frequencies, FGCPW and variations of it have been found to be most useful due to its ability to transition easily vertically through the wafers [24], [25], [39]. However, for some applications, finite ground microstrip line could be the interconnect of choice. This micromachined layered structure is a natural way to achieve three-dimensional circuit integration. The underlying techniques were demonstrated in a conformably packaged W-band power module architecture, with the goal of integrating four power amplifier MMICs, the input and output power distribution networks, the antenna feed structure, and a 16-element antenna array in a chip of unprecedented small size, 0.36 cm^2 $\times$1 mm in thickness (see Fig. 6) [24], [40]. To accomplish this feat very low-loss passive circuit elements have been developed, including vertical interconnects and distributed Wilkinson power dividers, and subsequent research has

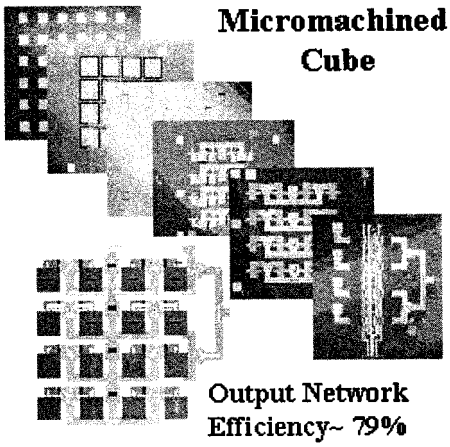


Fig. 6. W-band power cube.

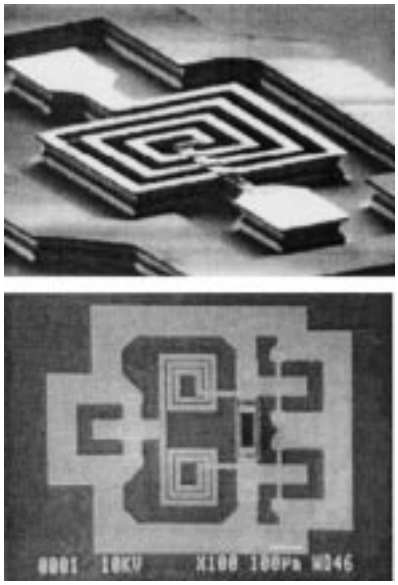
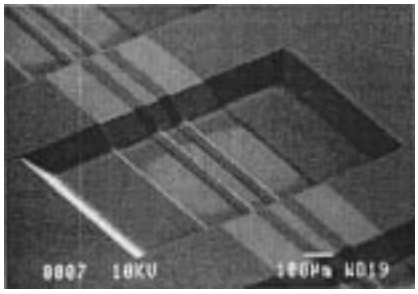


Fig. 7. Micromachined inductor and Wilkinson power divider.

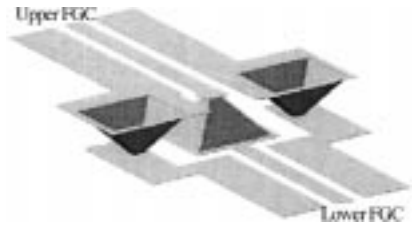
demonstrated lumped-element Wilkinson dividers and a novel vertical transition using the slanted wall of an anisotropically etched slope [34], [35], [39]. This layered arrangement, with each layer hermetically bonded to the one below it, is essentially a self-packaging structure, without the need for additional container material [33]. The electromagnetic properties, including coupling, are designed into each layer, so that unanticipated electromagnetic effects of the package are eliminated, and the circuit is relatively isolated from its environment.

C. Lumped Passive Components

At microwave and millimeter-wave frequencies (up to Ka-band), a novel technology has been developed to design and realize high-performance lumped passive components such as Wilkinson power dividers and hybrid couplers leading to substantial reduction in size. The basis of this novel technology is the development of high-Q, micromachined lumped components such as spiral inductors, metal–insulator–metal (MIM) capacitors, and thin-film resistors (TFRs). For example, by removing the Si wafer around a spiral inductor through selective etching, as shown in Fig. 7, inductors with a high resonant frequency (38 GHz for a 1.5-nH inductor), high-Q-factor ($\sim$30), and high linearity are possible [34], [35]. Compared to standard printed circuit technology, these micromachined spiral inductors can then be used to design dividers, hybrids, and couplers at X-, K-, and Ka-band with almost two orders of magnitude reduction in size, in addition to improved electrical performance in terms of insertion loss and bandwidth. Recent work has demonstrated, for the first time, X- and K-band power dividers with low loss (0.6 dB) and wide bandwidth (25% bandwidth for 15-dB return loss) [34], [35]. Due to the use of high-Q spiral inductors, the loss introduced by the lumped Wilkinson power divider is even lower than some distributed designs [37]. One of the most important reasons for using lumped design is the smaller chip size. Using lumped components to replace transmission lines, the chip size of the X-band design is reduced by a factor of six per dimension (to 0.3 mm $\times$ 0.5 mm). These lumped components can be fabricated on a variety of III–V substrates and are expected to provide similar size reduction and performance improvement to a multistage MMIC module. Besides the impact of this technology on RF power distribution circuits, micromachined passive components have the potential to revolutionize high-frequency RF circuit design and to lead to tremendous reductions in systems cost and size.



(a)



(b)

Fig. 8. (a) Micromachined interconnects. (b) Three-via through-wafer transition.

D. Vertical Through-Wafer Transitions

In three-dimensional integration, a transition through the full thickness of the wafer is an essential element of the circuit architecture. A variety of high-performance transitions appropriate for multilayer interconnect geometries have been demonstrated and have indicated the viability of the vertical interconnection concept at very high frequencies. Fig. 8(a) shows an FGCPW line transitioning from the top surface to a micromachined surface of an Si wafer using the sidewalls of

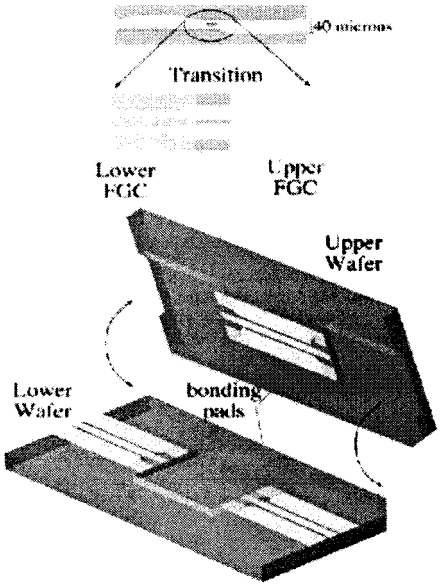


Fig. 9. RF bumps for wafer bonding.

a micromachined window anisotropically etched to a depth of 100 μm [39]. This transition has exhibited excellent performance in the whole microwave and millimeter-wave spectrum with an insertion loss of less than 0.1 dB (equivalent to the measurement error) up to Ka-band. A similar transition can be made from the top surface to the bottom surface of the same wafer by wrapping the FGCPW line around the sharp edge of the sidewall. Fig. 8(b) shows a three-via transition developed specifically for the W-band power module architecture [24], [40]. This transition has shown less than 0.5–0.6 dB of insertion loss at 94 GHz with better than 15% bandwidth.

E. RF Bumps for Wafer-to-Wafer Transitions

In a multiwafer stack, such as the one shown in Figs. 5 and 6, a major opportunity for circuit design is the ability to place circuit elements on both the bottom surface of an upper wafer and the top surface of a lower wafer, and then to make electrical connection between them directly across the interface [33]. This means that each interface between wafers can contain two separate, but interconnected circuits, with each of these circuits connected to the other side of their respective wafers using the through-wafer transitions discussed above. To protect and isolate the two facing circuits, shallow air cavities are etched above the line as it traverses from lower to upper wafer. Care is also required to avoid crosstalk by laterally offsetting critical circuit elements. A novel technique used to make the low-loss vertical connection between facing circuit wafers was developed based on RF electroplated bumps on the FGCPW transmission lines. Fig. 9 illustrates the transition concept using a simple example of a through line. The circuit on the upper side of the lower wafer is externally probed through a window etched through the upper wafer. Measurements of the transition are made in a back-to-back configuration for on-wafer probing, as shown in the figure. Preliminary results show that a low loss of 0.1 dB is achievable at W-band [37], [40].

F. Wafer-to-Wafer Bonding

The bonding of Si wafers is a well-established commercial technology for applications such as power devices, silicon-on-insulator (SOI), MEMS sensors, die attachments, sealing, and other MEMS components [28]–[32], [41]. Thermocompression bonding of gold-to-gold intermediate layers is the bonding method selected for the multilayer architecture of Figs. 5 and 6 because it can be achieved at a sufficiently low temperature so that metallization and interconnects of the circuits on the various layers are undisturbed. This type of wafer-to-wafer bonding can be hermetic so that the final multilayer structure forms a complete hermetically sealed package. This wafer bonding technique is used for vacuum cavities in MEMS pressure sensors, and shows exceptional promise for RF circuits as well. This is the same technique used to form the RF bump electrical transitions described above in Fig. 9, and these RF bump bonds form part of the mechanical bonding of the wafer layers, as well as an electrical connection.

G. Application of Three-Dimensional Integration to a W-Band Power Module—Power Cube

The W-band power module of Fig. 6 is a challenging circuit integration demonstration with the goal of combining four MMIC amplifier chips in a 0.36 cm^2 IC and radiating the combined power [24], [38], [40]. Using an Si-micromachined three-dimensional architecture, high density is achieved by integrating wafers vertically and by utilizing both sides of the wafer for printing the circuit components. To achieve on-wafer packaging while integrating multiple circuit functions, the same wafers carry the circuit components in addition to the monolithic fabricated cavities that provide shielding and good circuit isolation. In addition to packaging, the shielding cavities are utilized to reduce parasitic mechanisms generated by the stacking of the wafers and the close proximity of extended metallic planes. The power distribution network is comprised of multiple bends, impedance steps, tee-junctions, and Wilkinson dividers (as shown in Fig. 6). Individual component performance is critical to the overall efficiency of the feed network and, for this reason, geometry optimization for lowest insertion and return loss is the center of the circuit design effort. The optimal design of the individual components has led to excellent performance of the distribution network at W-band demonstrating an efficiency of better than 80% [24], [40]. This circuit demonstrates the effective utilization of micromachined high-resistivity Si to vertically integrate a complex RF function in a confined circuit area and volume.

H. Micromachining and Three-Dimensional Vertical Integration of a Power-Combining Structure

The experimental results obtained in the power cube demonstration clearly show the potential for three-dimensional integration of high-density low-cost circuits. However, the ability to integrate in three dimensions can accomplish more than just increasing the density of circuit integration and reducing costs. It can provide added performance that cannot be achieved in a conventional planar circuit architecture. The

number of combining stages in a circuit-based power combiner is severely limited because the network losses increase with the additional circuit complexity [36]. Micromachining can significantly reduce the losses in the transmission lines. At 32 GHz, micromachined line losses as low as 0.05 dB/mm can be achieved [26]. These lower losses significantly improve the combining efficiency for a planar combining network. Of more importance, three-dimensional vertical integration can significantly reduce the horizontal line lengths required to reach across all the MMICs in the planar integration because they can be vertically stacked directly above and below each other. In this integration concept, the MMICs are stacked on separate substrate layers above and below the Wilkinson combiners. Transmission lines make the vertical transitions to the substrate level of the Wilkinson on slanted sides of anisotropically etched apertures in the 100-μm-thick Si substrate. For a 50% combining efficiency, the vertical stacking architecture allows five combining stages, for a total of 32 combined amplifier MMICs. The total loss is significantly less than that for the micromachined two-dimensional planar approach, even though the low-loss micromachined lines cannot be used along the slanted faces in the three-dimensional vertical stacking approach.

It is possible to mix the two circuit approaches of three-dimensional vertical stacking and two-dimensional planar networking. In this hybrid architecture, shown in Fig. 5, amplifier MMIC chips can be combined using micromachined lines in a two-dimensional network on two or more substrate layers with levels combined using the vertical integration method described previously. Using such a hybrid technique, seven stages of combining, or 128 amplifier MMICs, can be integrated with 50% combining efficiency. However, even though the three-dimensional integration has a greater density than the planar integration, there are many layers with very sparse occupation. These sparsely populated layers provide an opportunity to run liquid coolant in micromachined channels between the power sources (see, for example, [43]–[47]). The three-dimensional vertical integration, in conjunction with the low-loss micromachined transmission lines and integrated micromachined cooling, enable unprecedented levels of circuit power combining using solid-state planar fabrication technology.

III. Conclusions

Micromachined Si ICs and RF MEMS devices have the potential for providing an overarching circuit integration technology, which can significantly reduce the size, weight, and cost of microwave and millimeter-wave components. The capability to integrate diverse substrate technologies opens the door for real multifunction chips, combining analog, digital, RF, and opto-electronic functions. Three-dimensional vertical integration combined with high-Q high-performance MEMS devices can not only provide higher density circuits, but by freeing RF circuit design from the tyranny of the two-dimensional layout, can reach levels of performance and functionality not possible in a planar geometry.

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