Silicon Micromachined RF Components: Review

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Abstract

In this paper, a possibility of building various types of RF passive components using the silicon micromachining technique has been examined with special emphasis on the wireless and mobile communication applications. Silicon micromachining technique is compatible with conventional silicon IC process and could provide a possibility of integrating base-band signal processing units and RF passive and active circuit components all in one silicon wafer rendering implementation of system-on-chip paradigm for future mobile and wireless communication systems.

Introduction

With the advance of public telephone network and communication technologies, mobile communication systems and access to internet have become integral part of information age. Easy and fast network access from mobile station via wireless telephone network system and high speed data transfer are being more demanding and technically challenging to implement. Among the many difficulties, the development of small and long-lasting power-efficient mobile station is the key issue of the successful deployment of wireless communication devices. With these demands, numerous research efforts are being focused on the development of new RF circuit components characterizing small, three-dimensional, low-loss, low-power consumption, and efficient operations.

Silicon micromachining technique had been developed by the MEMS (microelectromechanical system) community from early 1970's and has been introduced recently to the microwave and millimeter-wave circuit and antenna applications [1]-[2]. The use of this MEMS technology for microwave frequency region has resulted in various types of novel RF circuit components such as low-loss, high performance transmission lines [3]-[6], high-Q filters [7]-[11], RF switches [12]-[16], antennas [17]-[18], and other passive/active circuit components [19]-[20]. These studies demonstrate the possibility of constructing high frequency circuits and antennas based on the silicon micromachining technique. GaAs and other semiconductor materials can be also used for micromachining devices.

In mobile communication systems, size, weight and performance are very critical trade-offs in system design. In conventional designs on printed circuit boards, several discrete components can be identified which take quite large real estate and thus prevent high-density integration. Components such as antennas, duplexers, and bandpass filters are historically considered as the most problematic in terms of high-density integration. This problem can be alleviated by integrating the above discrete components in one or a few wafers/chips using the silicon micromachining technology and finally realizing system-on-chip paradigm.

In this paper, application of silicon micromachining technique for the development of high frequency circuit components, such as low-loss transmission lines, bandpass filters/resonators, RF MEMS switches, and antennas will be discussed.

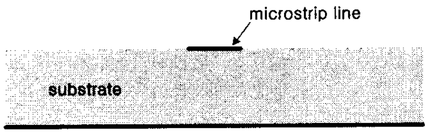

Fig. 1 Conventional microstrip line

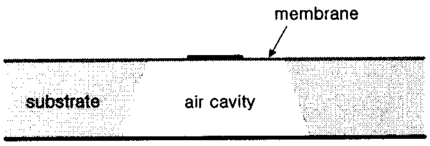

Fig. 2 Membrane-supported microstrip line

Low-Loss Transmission Lines

One of the first application of the silicon MEMS technology in the microwave and millimeter-wave arena is the low-loss high-performance transmission lines built on membrane [3]-[6]. The basic idea is rooted on the fact that the conventional planar transmission lines such as stripline (refer Fig. 1) and microstrip support TEM or quasi-TEM type of field distributions and the dielectric materials surrounding the signal conductor cause non-zero dielectric loss in addition to conductor loss which is indispensible in these types of lines. As a result, removing the dielectric material partially or entirely around the conductor using selective silicon etching technique (refer Fig. 2, 3, 4) provides much lower insertion loss compare to the conventional transmission line topologies.

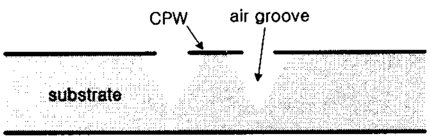

Fig. 3 Grooved coplanar waveguide transmission line (CPW)

Low-loss characteristics of these types of new transmission lines are mainly coming from the reduced dielectric loss and resulting near-TEM field distribution. In the microshield line case, the radiation as well as the dielectric loss can be minimized and thus presents total loss less than that of the line on quartz substrate. Note that the membrane is a 1.5um thick tri-layer of $SiO_2/Si_3N_4/SiO_2$ which is grown on a silicon wafer using thermal oxidation and low pressure chemical vapor deposition [4]. The effective dielectric constant of the membrane is about 1.12 depending on the transmission line geometry.

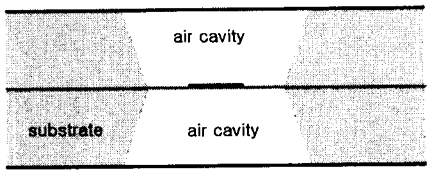

Fig. 4 Microshield membrane-supported stripline

MEMS RF Filters

Thus realization of devices for reliable, low-power, high frequency (GHz region) operation is the key issue to be solved in this area. Two different types of MEMS based RF filters are reported: one is based on bulk silicon micromachining and the other one is fabricated using the surface micromachining technique. As shown in Fig. 5 and 6, the first type of approach is rather straightforward than the second type. The cavity-backed resonator/BPF structures can be constructed by bonding multiple micromachined wafers. The unloaded quality factor of this type of geometry can be reached as close as 500 for air filled cavity and the size of the cavity can be reduced with low-loss high-index material for mobile communication frequency bands. Fig.6 depicts an example of frequency response of the cavity-backed slot-coupled BPF for C-band application. One of the potential problem with this technology is the temperature sensitivity of the materials. However, this problem may easily be alleviated with recent advances in material science. Fig. 7 shows another bulk silicon micromachined low-pass filter on synthesized substrate. Synthesized silicon substrate is fabricated by selectively etching silicon substrate.

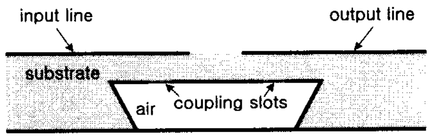

Fig. 5 Cavity-backed slot-coupled BPF/resonator

Surface micromachining technique can be also used to achieve extremely narrow and sharp passband characteristics with very small size as shown in Fig. 8 and 9. Even though the operating frequency is limited up to few hundred megahertz region at this moment, many efforts are being devoted on achieving higher operating frequency.

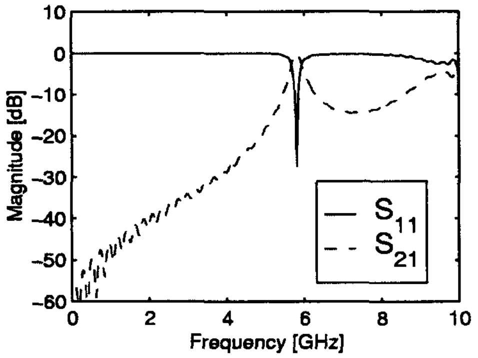

Fig. 6 Micromachined cavity BPF ε_r = 500.

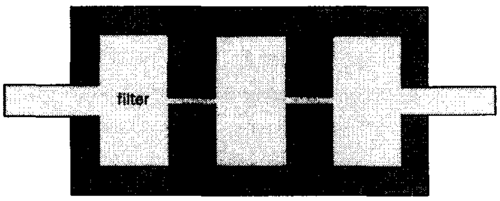

Fig. 7 Microstrip/stripline filter on synthesized micromachined substrate

RF Switches

MEMS switches found applications in the microwave and millimeter-wave frequency region and are characterized as low DC voltage operation, low insertion loss, high cutoff frequency, fast switching speed, and excellent linearity. Among the many cantilever and rotary type switch topologies, capacitive switches are easy to fabricate and provide reliable and fast RF switching functionality. These devices offer the potential for building a low loss highly linear microwave circuits for next generation mobile and phased array antennas.

Fig. 8 MEMS filter

Antennas

Planar microstrip antenna has been extensively used for various purposes, and feeding network and active circuit components are being integrated into one single unit system. Recently, mulitilayer microstrip patch antennas are built on silicon substrate accommodating baseband signal processing units and all other RF passive and active circuitries and thus allowing fully integrated RF systems. To achieve efficient antennas on high index silicon material and to prevent propagation of higher order surface waves, backside silicon material can be selectively etched away. This approach has been proved to be very effective for W-band phased array systems.

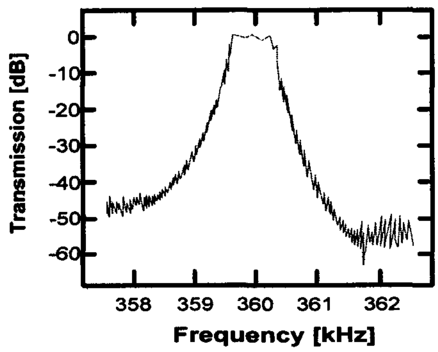

Fig. 9 MEMS filter frequency response

Conclusions

In this paper, current state-of-the-art silicon micromachined microwave and millimeter-wave circuits and antennas are reviewed for possible application of MEMS technology in mobile communication and radar systems. It is a challenging but promising next generation technology.

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