CHAPTER 17.8

MEMS FOR COMMUNICATION SYSTEMS

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MEMS FOR WIRELESS COMMUNICATIONS

Introduction

The increasing demand for wireless communication applications, such as cellular telephony, cordless phone, and wireless date networks, motivates a growing interest in building miniaturized wireless transceivers with multistandard capabilities. Such transceivers will greatly enhance the convenience and accessibility of various wireless services independent of geographic location. Miniaturizing current single-standard transceivers, through a high-level of integration, is a oritical step toward building transceivers that are compatible with multiple standards. Highly integrated transceivers will also result in reduced package complexity, power consumption, and cost. At present, most radio transceivers rely on a large number of discrete frequency-selection components, such as radio-frequency (RF) and intermediate-frequency (IF) band-pass filters, RF voltage-controlled oscillators (VCOs), quartz crystal oscillators, and solid-state switches, to perform the necessary analog signal processing. These off-chip devices severely hinder transceiver miniaturization. MEMS technology, however, offers a potential solution to integrate these discrete components onto silicon substrates with microelectronics, achieving a size reduction of a few orders of magnitude. It is therefore expected to become an enabling technology to ultimately miniaturize radio transceivers for future wireless communications.

MEMS Variable Capacitors

Integrated high-performance variable capacitors are critical for low noise VCOs, antenna tuning, tunable matching networks, and so on. Capacitors with high quality factor (Q), large tuning range, and linear characteristics are crucial for achieving system performance requirements. On-chip silicon *pn* junction and MOS-based variable capacitors suffer from low quality factors, limited tuning range, and poor linearity, and are thus inadequate for building high-performance transceivers. MEMS technology has demonstrated monolithic variable capacitors achieving stringent performance requirements. These devices typically reply on an electrostatic actuation method to vary the air gap between a set of parallel plates or vary the capacitance area between a set of conductors or mechanically displace a dielectric layer in an air-gap capacitor. Improved tuning ranges have been achieved with various device configurations. Capacitors fabricated through using metal and metalized silicon materials have demonstrated superior quality factors compared to solid-state semiconductor counterparts. Besides the above advantages, micromachined variable

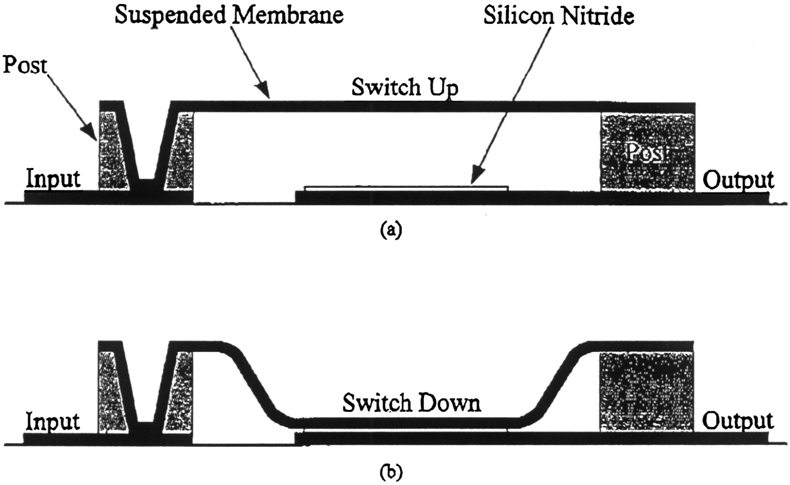

FIGURE 17.18.1 Micromachined RF switch: (*a*) switch up; (*b*) switch down.

capacitors suffer from a reduced speed, potentially a large tuning voltage, and mechanical thermal vibration commonly referred to as Brownian motion, which deserves great attention when used to implement low phase noise VCOs.

MEMS Switches

The microelectromechanical switch is another potentially attractive miniaturized component offered by micromachining technologies. These switches offer superior electrical performance in terms of insertion loss, isolation, linearity, and so on and are intended to replace off-chip solid-state counterparts switching between the receiver and transmitter signal paths. They are also critical for building phase shifters, tunable antennas, and filters. The MEMS switches can be characterized into two categories: capacitive and metal-to-metal contact types. Figure 17.8.1 presents the cross-sectional schematic of an RF MEMS switch. The device consists of a conductive membrane, typically made of aluminum or gold alloy suspended above a coplanar electrode by a few micrometers air gap. For RF or microwave applications, actual metal-to-metal contact is not necessary; rather, a step change in the plate-to-plate capacitance realizes the switching function. A thin silicon nitride layer with a thickness on the order of 1000 Å is typically deposited above the bottom electrode. When the switch is in on-state, the membrane is high, resulting in a small plate-to-plate capacitance; hence, a minimum high-frequency signal coupling (high isolation) between the two electrodes. The switch in the off-state with a large enough applied dc voltage, however, provides a large capacitance owing to the thin dielectric layer, thus causing a strong signal coupling (low insertion loss). The capacitive switch consumes near-zero power dissipation, attractive for low power portable applications. Superior linearity performance has also been demonstrated because of the electromechanical behavior of the device. Metal-to-metal contact switches are important for interfacing large bandwidth signals including dc. This type of device typically consists of a cantilever beam or clamped-clamped bridge with a metallic contact pad positioned at the beam tip or underneath bridge center. Through an electrostatic actuation, a contact can be formed between the suspended contact pad and an electrode on the substrate underneath. High performance on a par with the capacitive counterparts has been demonstrated. Microelectromechanical switches, either capacitive or metal contact versions, exhibit certain drawbacks including low switching speed, high actuation voltage, sticking phenomena due to dielectric charging, metal-to-metal contact welding, and so on, thus limiting device lift time and power handling capability. Device packaging with inert atmosphere (nitrogen, argon, and so on) and low humidity is also required.

MEMS Resonators

Microelectromechanical resonators based on polycrystalline silicon comb-drive fingers, suspended beams, and center-pivoted dick configurations have been proposed for performing analog signal processing. These microresonators can be excited into mechanical resonance through an electrostatic drive. The mechanical motion will cause a device capacitance change resulting in an output electrical current when a proper dc bias voltage is applied. This output current exhibits the same frequency as the mechanical resonance, thus achieving an electrical filtering function through the electromechanical coupling. The resonators can obtain high-quality factors close to 10,000 in vacuum with operating frequencies above 150 MHz reported in literatures and size reduction by a few orders of magnitude compared to discrete counterparts. These devices with demonstrated performance are attractive for potentially implementing low-loss IF band-pass filters for wireless transceivers design. Future research effort is needed to increase the device operating frequency up to gigahertz (GHz) range. As with other MEMS devices, the micromachined resonators also have certain drawbacks. For example, vacuum packaging is required to achieve a high-quality factor for building low loss filters. The devices may also suffer from a limited dynamic range and power-handling capability. The mechanical resonant frequency is strongly dependent on the structure dimensions and material characteristics. Thus, a reliable tuning method is needed to overcome the process variation effect and inherent temperature sensitivity.

Micromachined Inductors

Integrated inductors with high-quality factors are the key components for implementing low noise oscillators, low loss matching networks, and so forth. Conventional on-chip spiral inductors suffer from limited quality factors around 5 at 1 GHz, an order of magnitude lower than the required values from discrete counterparts. The poor performance is mainly caused by substrate loss and metal resistive loss at high frequencies. Micromachining technology provides an attractive solution to minimize these loss contributions; hence enhancing the device quality factors. *Q* factors around 30 have been achieved at 1 GHz matching the discrete component performance. Three-dimensional coil inductors have been fabricated on silicon substrates by micromachining techniques. Levitated spiral inductors have also been demonstrated. All these devices exhibit three common characteristics: (1) minimizing device capacitive coupling to the substrate, (2) reducing winding resistive loss through employing highly conductive materials, and (3) nonmovable structures upon fabrication completion.

MEMS FOR OPTICAL COMMUNICATIONS

Introduction

High-speed communication infrastructures are desirable for transferring and processing real-time information such as voice and video. Optical fiber communication technology has been identified as the critical backbone to support such systems. High-performance optical data switching network, which routes various optical signals from their sources to destinations, is one of the key building blocks for system implementation. At present, optical signal switching is performed by using hybrid optical-electronic-optical (O-E-O) switches. These devices convert incoming lights from input fibers to electrical signals first and then route them to the proper output ports after signal analyses. At the output ports, the electrical signals are converted back to streams of photons or optical signals for further transmission over the fibers to their next destinations. The O-E-O switches are expensive to build, integrate, and maintain. Furthermore, they consume a substantial amount of power and introduce additional latency. It is therefore highly desirable to develop all-optical switching network in which optical signals can be routed without intermediate conversion into electrical form, thus minimizing power dissipation and system delay. While a number of approaches are being considered for building all-optical switches, MEMS technology is attractive for providing arrays of tiny movable mirrors, which can redirect incoming beams from input fibers to corresponding output fibers. These micromirrors can be batch fabricated using silicon micromachining technologies, achieving a low-cost integrated solution. A significant reduction in power dissipation is also expected.

MEMS Mirrors

Various micromachined mirrors have been developed over the years. They can be typically divided into two categories: (1) out-of-plane mirrors and (2) in-plane mirrors. The out-of-plane mirrors are usually fabricated by polycrystalline silicon surface micromachining techniques. After sacrificial release, the mirror structures can be folded out of the substrate and position secured by silicon hinges. The mirror surface can be moved by an electrostatic vibromotor, comb-drive fingers, and other electrostatic means. These mirrors can achieve one degree of freedom and thus are attractive for routing optical signals in a two-dimensional switching matrix and also for raster-scanning display applications. The in-plane mirrors are typically fabricated using a thick single crystal silicon layer on the order of a few tens micrometers from a SOI wafer by deep RIE and micromachining techniques. The thick structural layer minimizes mirror warping, critical for high-performance optical communication applications. Self-assembly technique relying on deposited film stress has also been employed to realize lifted-up micromirror structures. The mirror position can be modulated by a vertical actuation of comb-drive fingers and electrostatic pads or a lateral push-pull force. Micromirrors with two degrees of freedom have also been demonstrated by similar techniques. These mirrors with an analog actuation and control scheme are capable of directing optical beams to any desired position, and are thus useful for implementing large three-dimensional optical switching arrays to establish connections between any set of fibers in the network.