A frequency tunable half-wave resonator using a MEMS variable capacitor

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Abstract
A frequency tunable half-wave resonator at 3 GHz is presented with a microelectromechanical systems (MEMS) variable capacitor as the tuning element. The capacitor is fabricated using the multi-user MEMS process (MUMPs) technology provided by JDS/Cronos, and transferred to an alumina substrate by an in-house developed flip-chip process. This capacitor is electrostatically actuated. The resulting *C-V* response is linear with a slope of 0.05 pF/V for a wide range of actuation voltages. The MEMS device has a capacitance ratio of 3:1 for 0-70 V bias, with a *Q*-factor of 140 measured at 1 GHz. A half-wave tunable microstrip resonator with bias lines is designed to include this MEMS device, which exhibits linear tuning over 180 MHz (6 percent) centered around 3 GHz with a constant 3 dB bandwidth of 160 MHz over the entire tuning range. The power consumption of the MEMS device was measured to be negligible.

1. Introduction

In RF systems, there is a continuous movement towards smaller systems that have increased functionality and reduced power consumption without sacrifice in reliability for both commercial and military applications (Yao, 2000). Microelectromechanical systems (MEMS) have been substantially researched as a potential solution (Rebeiz and Muldavin, 2001). The major driving factors for this development are the promising advantages of MEMS over commonly used YIG or varactor-based components. Some of the inherent limitations for these devices are large power requirements and low *Q*-factors. In contrast, electrostatically actuated MEMS devices have demonstrated very low power consumption due to negligible current, since there is no loss mechanism comparable to intrinsic semiconductor resistive losses or ferromagnetic material losses (Yao, 2000). An additional advantage of MEMS devices is the immunity to capacitance drift as a function of RF power. With the benefits of small size and increased RF performance, variable MEMS capacitors could prove to be an excellent alternative in the next generation of microwave components (Dec and Suyama, 2000; Goldsmith *et al.*, 1999; Yao, 2000).

This paper focuses on an electrostatically actuated continuously variable MEMS capacitor and its demonstration in a frequency tunable resonator. Tunable resonators have use in a variety of applications, such as tunable filters (Goldsmith *et al.*, 1999) and voltage controlled oscillators (VCOs) (Dec and Suyama, 2000). To measure the tuning range and compatibility with microstrip circuits, this MEMS device is flip-chip mounted into a simple gap-coupled resonator, shown in Figure 1. The tuning range and *Q*-factor of the device are compared to a high-quality commercial varactor diode. Simple transmission-line models agree with measurements of the frequency-tuning range and package-associated parasitics.

2. Design and fabrication of the MEMS variable capacitors

Two-plate electrostatically actuated MEMS capacitors ordinarily have a tuning limit of a third of the gap distance before undergoing a snap-down effect (Dec and Suyama, 2000; Irwin *et al.*, 1998; Yao, 2000). This device utilizes the snap-down effect to its advantage by connecting an array of 30 individual capacitors in parallel to a single bond pad by springs of varying widths, shown in Figure 2. This array design allows flexibility in the range of continuous capacitance tuning. Even though the electrostatic force exerted on each plate is uniform throughout the device, the individually varying support beams create a cascading snap-down effect. As a result, the *C-V* curve is linear for a large value of actuation voltages (Hoivik *et al.*, 2001b).

All microstructures in this research have been constructed using the JDS/Cronos silicon surface micromachining multi-user MEMS process (MUMPs) (http://www.memsrus.com), which features three layers of polysilicon (poly0, poly1 and poly2), two layers of sacrificial silicon oxide and one layer of gold (deposited onto poly2). Micromachined devices generally use all of these layers, but the design of this high-*Q* RF device utilizes only the top two layers of polysilicon and the metal layer. This allows a flip-chip assembly process and the removal of the native substrate. This transfer step is critical for high-performance of the MEMS device, since the native silicon substrate has a low resistance and will degrade the overall RF performance (Harsh *et al.*, 2000). An inhouse developed flip-chip process enables transfer of a micromachined device to a new receiving substrate (Harsh *et al.*, 2000; Hoivik *et al.*, 2001a; Irwin *et al.*, 1998). This enhances the initial three-layer process into a five-layer process. A hydrofluoric acid (HF) sacrificial layer etch releases the device from the native silicon substrate. Figure 3 details the entire fabrication and assembly process.

Since the variable capacitor utilizes the snap-down effect, a dielectric layer between the capacitor plates is essential to prevent shorting. Surface coatings have previously been deposited on released MEMS structures using chemical vapor deposition (CVD) and self-assembling monolayer (SAM) techniques (Maboudian *et al.*, 2000; Stoldt, *et al.*, resulting in performance improvements of the MEMS devices. The device presented in this paper uses a novel atomic layer deposition (ALD) technique to deposit the dielectric material between the electrodes (George *et al.*, 1996). A major advantage of ALD coating compared to other techniques is the unique conformality of the deposited films. The ALD films cover all sides of a released MEMS device including bottom surfaces, such as underneath cantilever beams, which significantly improves

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Figure 1
Photographs of fabricated resonator and semi-packaged MEMS (inset). The 1 × 2 mm MEMS device is on a 5 × 5 mm alumina substrate

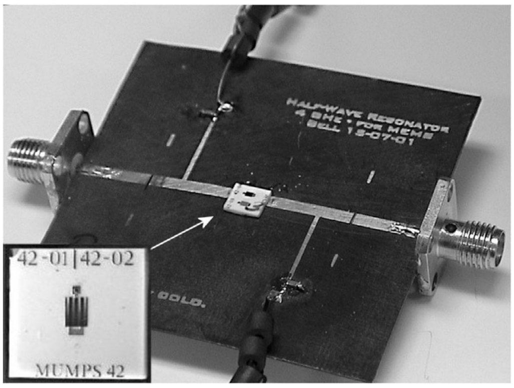
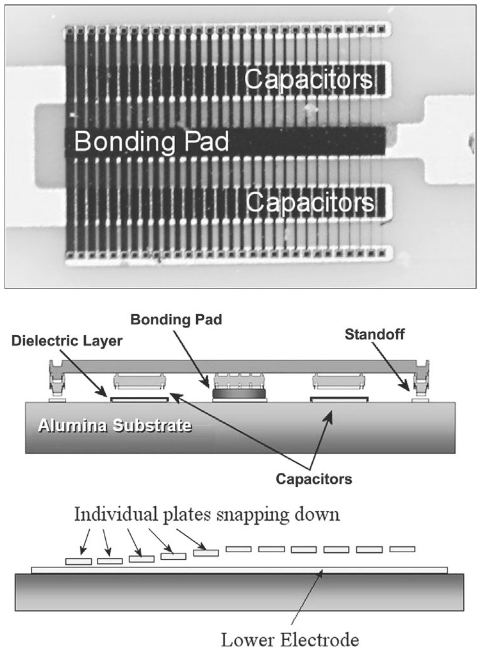


Figure 2
Top-view photograph and cross-sectional illustrations of capacitor. Varying the width of the support beams enables a cascading snap-down effect during actuation

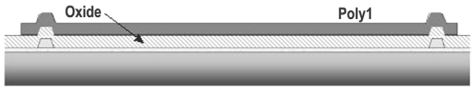


the performance of electrostatically-actuated devices (Hoivik *et al.*, 2002a). Another advantage of this process is that it can be carried out at temperatures as low as 150°C – significantly cooler than typical CVD temperatures, allowing the coating of composite devices without the risk of damaging the individual layers in the MEMS device. Currently, several MEMS devices have been coated with alumina of various thicknesses ranging from 20 to 80 nm (Hoivik *et al.*, 2002b).

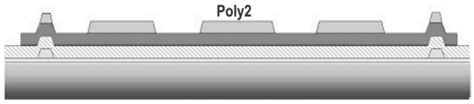
In prior work, the top plate capacitor array was bonded to the receiving substrate by two bonding pads. Thermal mismatch between the alumina substrate and polysilicon device features caused warpage and buckling in the capacitor plates, which hindered the electrostatic actuation of the device (Hoivik *et al.*, 2001a). The MEMS device presented in this paper eliminates these problems by using a single bonding pad. The ends of the beams are not directly attached to the substrate. Instead, a standoff created by the surface micromachining process provides support for the beam without creating internal stresses due to thermal mismatch. In addition, the symmetric design of the array doubles the overall capacitance, while maintaining electrostatic balance on both sides of the array.

Figure 3
Device fabrication steps: surface micromachining, flip-chip assembly, and removal of host substrate

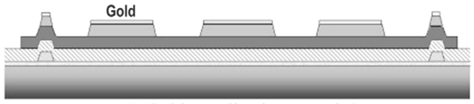
(a) Initial layer of polysilicon deposited onto silicon nitride



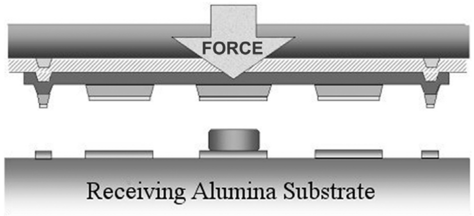
(b) Sacrificial oxide and structural polysilicon layers



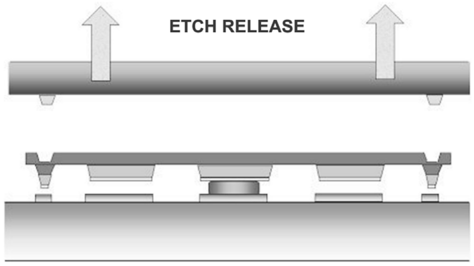
(c) Polysilicon deposition



(d) Gold metalization on poly2



(e) Alignment of MEMS with receiving substrate and thermo-compression flip-chip bonding



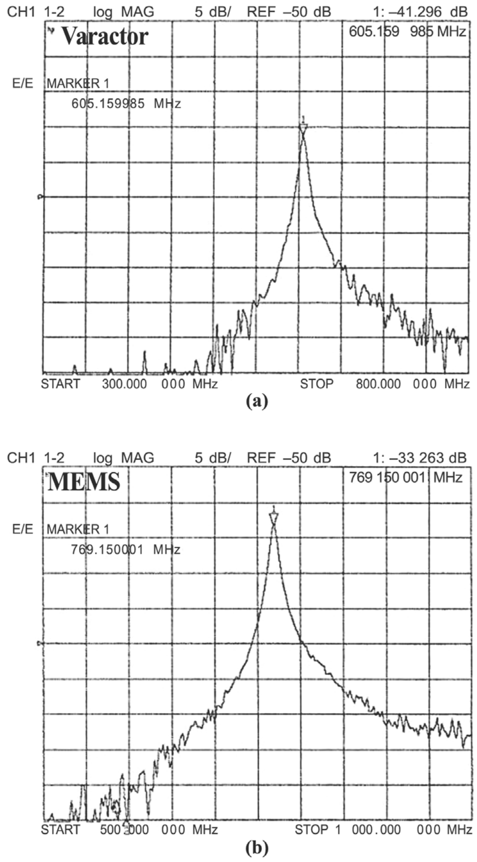
(f) Etch step releases MEMS and removes silicon substrate

3. *Q*-measurements and comparison of MEMS and varactor diode devices

The *Q*-factor of the assembled MEMS device was measured using a high-*Q* resonator method at 750 MHz, described by (Hoivik *et al.*, 2001b). The MEMS tunable capacitor was compared with a high-quality Alpha 1405 packaged varactor diode mounted in the same resonator. Figure 4 shows the measured resonance curves of the varactor and MEMS devices at 1 pF capacitance, showing respective *Q*-factor values of 100 and 140.

As expected, the MEMS device has a superior quality factor due to lower losses. The high-*Q* cavity is not designed to be used as a component or to measure the tuning range. The exact value of the *Q* depends highly on the package parasitics and we notice a variation between 130 and 150 for the MEMS *Q*-factor depending on the wire-bond length used in assembly. The varactor diode consumes 250 mW of power, while the MEMS power consumption is negligible.

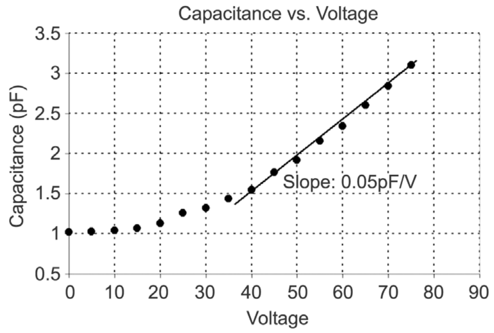
Figure 4
Q measurements of varactor (a) and MEMS (b) devices biased for equal resonator loading. Varactor exhibits a *Q* of 100 compared to the MEMS device at 140



(a)

(b)

Figure 5
Measured capacitance vs voltage for the MEMS device. Above a threshold voltage this *C-V* curve is linear, with a slope of 0.05 pF/V



4. MEMS-loaded tunable resonator

In an application, it is likely that the MEMS device would be integrated in a microstrip circuit. A 3 GHz MEMS-loaded microstrip resonator (Figure 1) is used to test the tuning range and determine parasitics associated with hybrid integration. This open-circuit resonator is gap-coupled and includes bias lines to provide the control signal to the MEMS device. Since the *Q*-factor of the microstrip resonator alone is low, measured to be around 30, it dominates the overall loaded resonator *Q*. Simultaneously, this low-*Q* allows for broad tuning when the capacitance value changes with applied bias.

Several tunable resonator designs use distributed shunt MEMS capacitors (Brank *et al.*, 2001; Liu *et al.*, 2001; Muldavin and Rebeiz, 2000). The design of this particular MEMS device allows series mounting of the capacitor into the resonator. A series variable capacitance in the resonator effectively changes the electrical length and thus changes the resonant frequency of the circuit. A proof-of-principle test of this circuit design uses the Alpha varactor diode from the *Q*-factor comparison above and results in 300 MHz tuning (10 percent) for a capacitance range of 0.6-2.6 pF (larger than 4:1 ratio). The measured tuning agrees with circuit models.

The MEMS capacitance was measured using an HP4363B LCR meter at 10 kHz resulting in the values shown in Figure 5. The 60 plates give a practically continuous *C-V* curve, despite the digital snap-down response of the actuation. The measured capacitance values from 1 to 3 pF (a 3:1 ratio) are used to simulate the resonator tuning.

After the flip-chip process, the MEMS devices are semi-packaged as discrete devices on a diced 5 mm square alumina substrate. They are glued in the center of the resonator and attached to the microstrip with 25 μm diameter gold wire-bonds. Gold plating of the microstrip traces allows for better adhesion of the wire-bonds. Quasi-static calculations estimate the bond wire inductance to be between 6 and 8 nH for the length of the wire used with this MEMS package.

RF measurements from 2 to 4 GHz using an HP 8510C network analyzer show shifting of the first resonance. Figures 6 and 7 show the simulated and measured transmission coefficients (S_{21}), respectively for 10 V bias voltage steps between 0 and 70 V. Using the 3 dB bandwidth, the loaded *Q*-factor of this microstrip resonator is around 20 over the entire tuning range. The frequency tuning of 180 MHz (6 percent) is predicted accurately, with disagreement between the simulated and measured resonant frequency within 50 MHz (0.16 percent), shown in Figure 8. Simulations show that a reduction of 0.1 nH in inductance accounts for this disagreement in resonant frequency. This small variation in parasitic reactance may occur as an effect of lowering the beams of the MEMS capacitor.

An unloaded resonator has a measured peak value of − 30 dB, which agrees with simulations. The presence of the MEMS device changes the resonator, dropping the peak resonance value by 5 dB, as predicted by the circuit model to within 2 dB at − 35 dB levels. However, this model does not predict the slight change in peak value (− 35 dB to − 36.8 dB) as the bias is increased. As the plates collapse and contact the dielectric layer on the lower electrode, the loss increases slightly due to the dielectric medium between the plates changing from primarily air to alumina. The current model does not include this effect, which explains this discrepancy. The peak resonance value also depends critically on the coupling to the resonator (Kapilevich and Lukjanets, 1999), and improved coupling methods are also currently under study.

5. Discussion and conclusion

Along with alternative coupling schemes to improve the peak transmission of the resonator, the sensitivity of the location of the MEMS is also under study. Simulations of a variable capacitor in an open-circuit half-wave microstrip resonator show the most sensitivity to capacitance change with the variable capacitor located in the null of the voltage standing wave. Examination of the second resonance shows very little resonance shifting with the variable capacitor in the center of the resonator, which is at the peak of the second-harmonic standing wave. As an illustration of this effect, Figure 9 shows simulation results of the higher harmonics of a 1 GHz resonator, with the MEMS located in the center of the resonator. The resulting transmission coefficient shows that the odd resonances (1st, 3rd, 5th) tune with changing capacitance, while the even ones remain unchanged. For the odd resonances the tuning element is at a voltage null, where the first derivative of the voltage is

Figure 6
Simulated tuning of resonance peak as the bias voltage is varied from 0 to 70 V

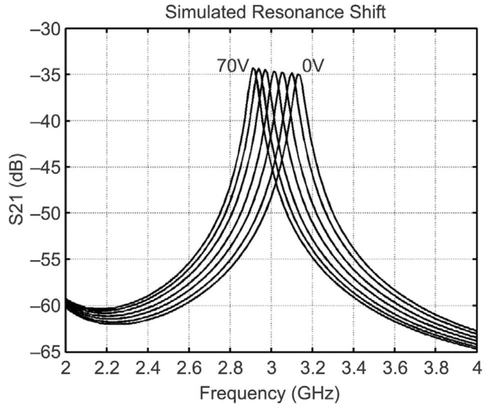
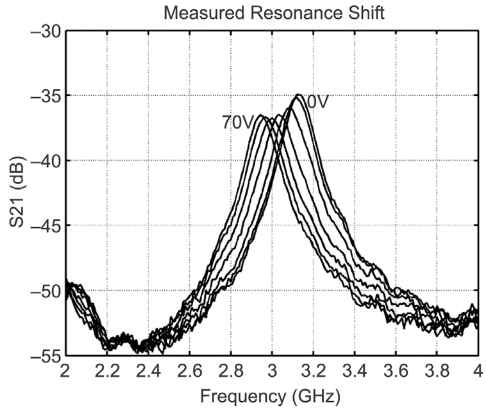


Figure 7
Measured tuning of resonance peak as the bias voltage is varied from 0 to 70 V



increasingly large for higher order resonances. The increase in Q-factor with resonance order is reflected in Figure 9 where the higher frequency resonances are sharper and accompanied by smaller tuning ranges. In contrast, for the even mode resonances the tuning element is at the voltage maxima of the standing wave, where the spatial voltage derivative is very small, resulting in a negligible tuning effect on the resonant frequency.

Figure 8
Comparison between measured and simulated tuning of resonant frequency. Simulations show that a 0.1 nH change in inductance accounts for the disagreement between the measurement and simulation

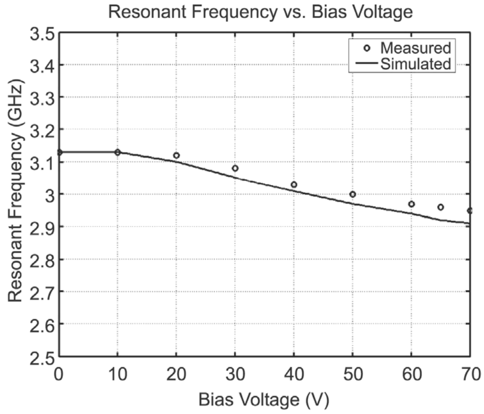
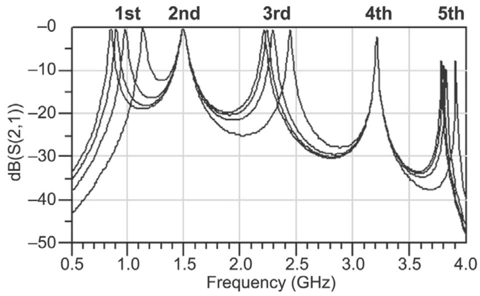


Figure 9
Simulated shifting of higher order resonances. Shifting occurs only for odd modes where the tuning element is located at the voltage null



The MEMS device presented here is a proof of concept that demonstrates the hybrid flip-chip integration of MEMS in standard microstrip circuits with good performance. For applications at higher frequencies, however, the device must be reduced in size in both the package substrate and the chip. In future designs the MEMS device will be directly mounted into the resonator circuit, thus eliminating the inductance introduced by the bond wires.

Improvements in the MEMS device design include optimization of the dielectric thickness for actuation at lower voltages, the plate area for increased force, and spring compliance. In addition, in order to reduce the overall device loss, thin metal strips can be placed strategically in the signal path of the device. Other improvements can also be obtained by varying the ALD deposited material to remove trapped charges. These topics are under current investigation.

In summary, an electrostaticically actuated flip-chip tunable MEMS capacitor has been successfully fabricated and characterized. A novel ALD coating process ensures a conformal dielectric layer to prevent an electric short when actuated. Stresses induced in the MEMS device due to thermal mismatch between the MEMS device and the substrate have been eliminated by only using one bonding pad. A linear relationship between capacitance and voltage has been obtained by the specific design of this MEMS device. The tunable MEMS device is packaged using flip-chip assembly, and hybrid integration is used in a half-wave microstrip resonator. The device exhibits a high Q-factor of 140 at 750 MHz with a capacitance ratio of 3:1. In the microstrip resonator, 180 MHz of tuning range with constant 3 dB bandwidth was measured around 3 GHz. No current is detectable on an ammeter with 1 μA sensitivity, and we conclude that the power consumption of this device is negligible.

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