DIGITALLY CONTROLLABLE VARIABLE HIGH-Q MEMS CAPACITOR FOR RF APPLICATIONS

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Abstract **This paper describes the novel design of an electrostatic digitally controllable variable MEMS capacitor constructed using Cronos MUMPS technology and flip-chip technology processing. The capacitor consists of an array of individual plates of equal area, which are connected to the bonding pads by springs of varying width. This creates a cascading snap-down effect when actuated by electrostatic forces. The capacitor has a measured Q-factor of 140 at 750MHz, and a tuning ratio of 4:1.**

I. INTRODUCTION

In the last few years, the demand for high Q variable capacitors has increased as the RF envelope is constantly being pushed to higher frequencies. This increases the RF performance required from mainstream IC components such as varactors commonly used in VCOs. Variable RF MEMS capacitors have proven lower inherent losses and high Q-factors, as well as lower power consumption and more linear RF characteristics. It is believed that variable MEMS based capacitors would be an excellent choice to replace current YIG and varactor tuners in the next generation of micro receivers due to their small size and better RF performance [1].

Previous analog variable RF MEMS capacitors have been thermally actuated [2]. In this paper a novel approach is described that utilizes electrostatic forces to actuate the variable capacitor. A more linear capacitance vs. voltage is achieved by having the individual capacitor plates connected to the bond pads by beam flexures of different widths (Fig. 2). As voltage is applied, the top capacitor plates move towards the substrate in a cascading manner depending on the stiffness of the individual support beam. This approach is somewhat similar to the Raytheon Group’s approach [3], but our new variable capacitor consumes only 15% of their chip-design area. A much better capacitance curve is also obtained by having 30 or more individual capacitor plates in one single device (Fig. 2). Whereas other digitally controlled capacitors have a very large tuning range [3], the eight individual MEMS capacitors used in that design increase the step size in the capacitance vs. voltage variation. In our new design the repeatability of capacitance vs. voltage is greatly improved as well as the reliability of the capacitor. In addition, electrostatic actuation results in higher switching speed and greater deflection stability than the thermally actuated variable capacitor [2].

II. CAPACITOR CONSTRUCTION

A. Mechanical Design

Fig.1 illustrates the design of the variable flip chip MEMS capacitor. The variable capacitor is constructed using the MUMPS technology provided by Cronos Corporation. This process includes three layers of polysilicon, two layers of oxide and one layer of gold [4].

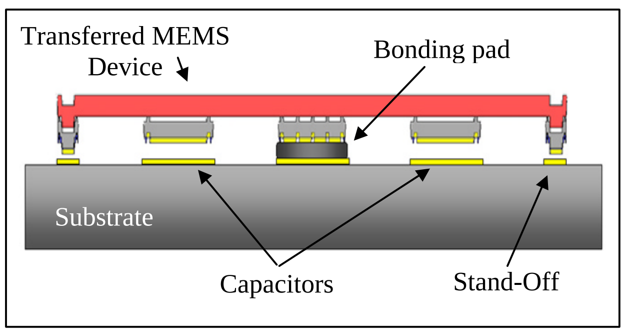

Fig. 1. Cross-sectional view of the capacitor flip-chip mounted on a substrate.

The top plate of the capacitor consists of 2.0 μm poly-1, 0.75 μm layer of oxide, 1.5 μm layer of poly-2 and the final 0.5 μm layer of gold. The final layer of gold increases the conductivity and is also used for the bonding pads. The top plate is actually an array of 30

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individual plates of equal area, which are connected to the bonding pads by springs of varying width (Fig. 2).

The variable capacitor is actuated using electrostatic forces between the top plate and the bottom plate. The electrostatic force exerted on each plate is uniform throughout the device. But, since each plate is connected to the bonding pad by a beam of different width (with different spring constant), the plates will snap down in a cascading manner.

The overall size of the device is 0.5x1.0 mm mounted on a receiving RF substrate (Alumina) of 5x5 mm.

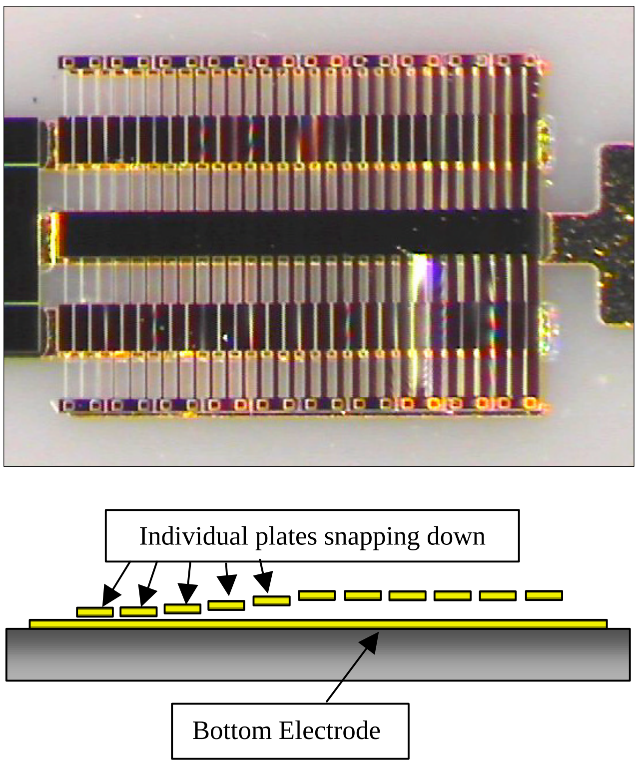
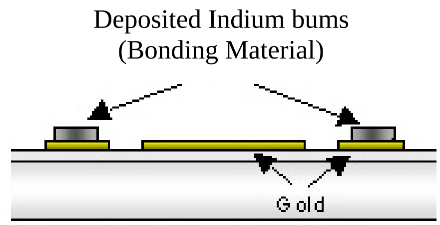


Fig. 2. Cross sectional view and top view picture of MEMS capacitor after release and post processing.

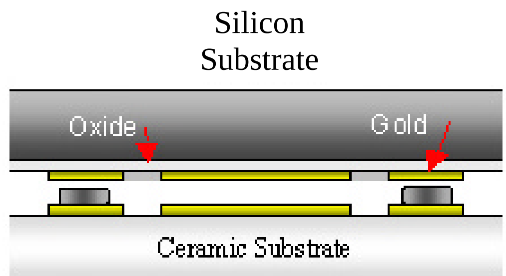
B. Capacitor Fabrication

By avoiding the use of the poly-0 layer and only using the two top layers of polysilicon plus the metal layer, the MEMS device can be transferred to a receiving substrate by a flip-chip process (Fig. 3).

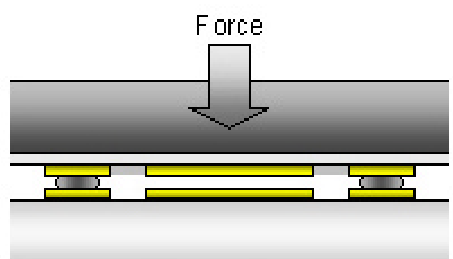
The doped host silicon substrate of the MUMPS process used to fabricate these MEMS devices is highly conductive, and is therefore removed through a release step after the flip-chip process. This processing step is necessary in order to ensure improved performance in the microwave range. Generally, RF MEMS devices



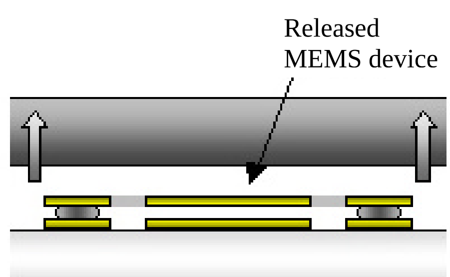
(a) Deposition of bonding material onto the gold bonding-pads of the receiving ceramic substrate.



(b) Align the MEMS chip above the bonding pads on the receiving substrate.



(c) Thermo-compression bonding of the MEMS device to the receiving substrate.



(d) Release etch to free the MEMS device and to remove the silicon host substrate.

Fig. 3. Steps involved in the flip-chip process used to transfer a MEMS device to a receiving substrate. [After Ref. 6]

fabricated on silicon will have a lower Q-factor as demonstrated by previous research [5]. The bonding pads are fabricated out of evaporated Indium, using liftoff technology on a patterned Alumina substrate.

Thermo compression bonding is used for the flip-chip transfer. The gap between the plates in this MEMS device is determined by the initial bump height and bonding condition [7,8]. In this design a final gap height of 2 microns is achieved. The Indium bonding pads also act as conductive paths for DC bias as well as the RF signal. After bonding the MEMS device is released from sacrificial oxide in a HF acid etch. This process is much more cost effective that manufacturing similar components on RF compatible materials such as GaAs.

III. Results and Discussion

The variable MEMS capacitor is tested using a resonator connected to a HP 8510B Network Analyzer measuring from 300MHz to 3.0 GHz. The resonator is constructed of a coaxial line with rectangular outer conductor and circular inner conductor, and resonates at a designated frequency. The resonator exhibits a very high Q-factor, allowing the feasibility of accurate measurements of the MEMS device. The MEMS device is connected to the resonating rod and a bias voltage is applied to actuate the device. The equivalent circuit for the test device is illustrated in Fig. 4.

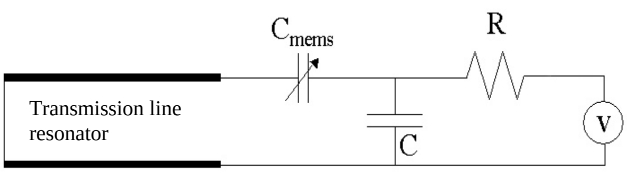


Fig. 4. Equivalent Circuit for testing the MEMS device

In this circuit the current limiting resistor, R, has a value of 10 kΩ and the Chip Capacitor, C, has a value of 150pF. The chip capacitor provides a ground path for the RF signal, and the resistor acts as a RF choke on the bias line. The Q factor for this unloaded circuit is 274 at 1.04GHz. The Q of the MEMS capacitor is calculated using equation 1. Where Q_o is the unloaded Q of the circuit and Q_{Load} is the measured value at testing. The Q factor is measured using the –3dB point method.

$$\frac{1}{Q_{Load}} = \frac{1}{Q_o} + \frac{1}{Q_{mems}} \tag{1}$$

The shift in the frequency as a function of voltage is shown in Fig. 5. This figure depicts the actual measurement from the network analyzer.

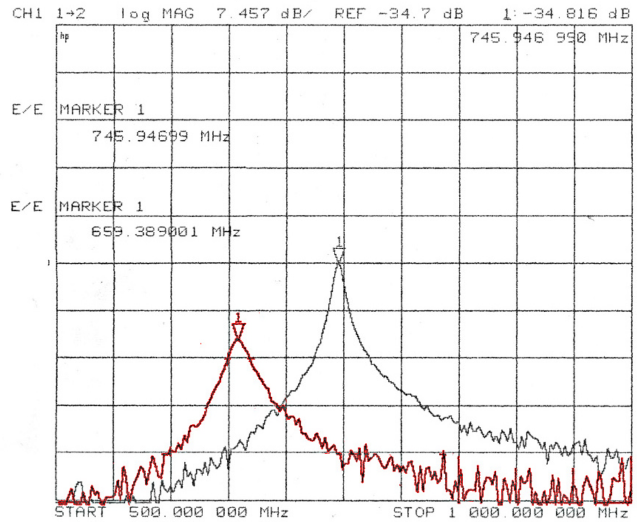


Fig. 5. Demonstration of shift in resonant frequency with applied voltage

The two peaks are at 0V and 35Vand the Q factor at 745MHz corresponds to 140. The capacitance ratio vs. voltage is presented in Fig. 6.

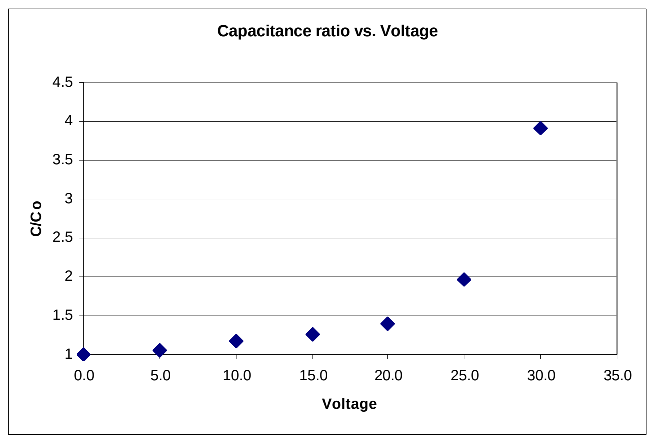


Fig. 6. Capacitance ratio versus voltage

Planarity issues in the flip chip process explain the shift in capacitance versus voltage curve in the 20 to 30V range. As the MEMS device is bonded to the receiving substrate, a misalignment in the planarity will be permanent in the final device. In this specific test run, the devices were all assembled with a small angle relative to the substrate (Fig. 7). In this figure non-planar misalignment is exaggerated for illustration. When a voltage is applied, the top capacitor plates will not snap down as a function of voltage and beam stiffness alone, but will also highly depend on the initial gap between the top plate and bottom electrode.

The difference in gap (D_1 versus D_2) will hinder the device to perform as initially designed. The capacitance will have two regions where the plates snap down linearly as a function of voltage. As a result of this planarity error, the first region of the top capacitor plates snap down at a relative low voltage, whereas the second region will require a much higher voltage in order to obtain a cascading snap down effect.

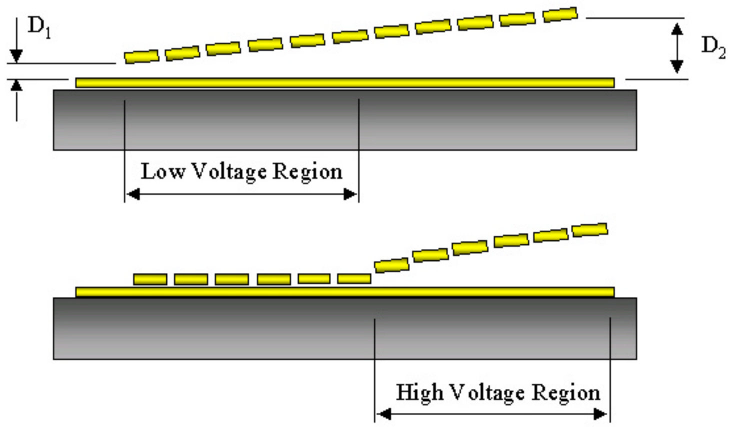


Fig 7: Illustration of how planarity error will lead to different voltage regions in an electrostatic actuated device.

The error in planarity between the MEMS chip and the receiving substrate during the flip chip procedure is being resolved by adjustments to the flip chip bonding machine.

IV. Summary

A flip-chip assembled variable MEMS capacitor has been successfully developed and tested. Through the use of the flip-chip process the Q factor of the final device is increased compared to other devices fabricated out of and left on silicon [4]. The measured Q factor is 140 at 745MHz and the tuning ratio is approximately 4:1.

Acknowledgements

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