Dielectric Fluid Immersed MEMS Tunable Capacitors

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Abstract— **Enhancement of MEMS tunable capacitors using dielectric fluids is reported. Micromachined tunable capacitors were tested and characterized in air and in mineral oil with a relative permittivity (ϵ_r) of 2.29. In oil the capacitors exhibit a factor of 2.2 to 2.29 increase in the initial capacitance as well as the achievable tuning range. The theoretical electrical and mechanical performance enhancements have been verified for capacitors with self-resonant frequencies of 18.3GHz in air. The high frequency testing device exhibited a capacitance of 344fF at 5GHz with a Q-factor of 72 in air, and a capacitance of 799fF with a Q-factor of 40 in oil. In addition, the devices immersed in oil have increased, tunable damping and a significantly higher breakdown voltage.**

I. Introduction

In recent years significant emphasis has been placed on the development of tunable capacitors with high quality factors (Q-factors) and large timing ranges. Modern communication systems require strict tolerances on passive components for intermediate and radio frequency filters as well as other system components and building blocks such as impedance matching networks, low noise amplifiers and voltage-controlled oscillators (VCO's) [1], [2], [3], [4]. Major limitations with current micro-electromechanical (MEM) based tunable capacitors are low tuning range, large footprint (low capacitance per unit area), high driving voltage requirements, mechanical noise and low damping.

In this work a dielectric fluid application for micromachined tunable capacitors is presented. Immersion in dielectric fluid can effectively address many of the key obstacles facing MEMS tunable capacitors. Operation in a dielectric fluid provides several important electrical and mechanical advantages compared to operation in air. The higher relative dielectric constant, (ϵ_r) provides an increase in the capacitance per unit, area. In addition, the force generated by electro-static actuators is increased proportional to ϵ_r, resulting in a factor of ϵ_r increase in tuning for a given drive voltage. Dielectric breakdown during switching transients can reduce the reliability of an electrostatic device and decrease its lifetime; the high dielectric strength of the immersion oil significantly increases the breakdown voltage. Furthermore, the anti-oxidation properties, chemical stability, and large thermal conductivity can all improve the long-term reliability of RF MEMS devices. Mechanically the oil provides damping to the system. Proper damping of the fundamental mode can increase tuning speed by reducing settling time, and also reduces the undesirable effects of external accelerations.

Work performed to date verifies the proposed electrical and mechanical theoretical functionality of MEMS tunable capacitors operating in dielectric fluid at RF and microwave frequencies.

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II. Device Design and Fabrication

The test device for mechanical characterization and low frequency capacitance measurements is a single crystal silicon, interdigitated comb-finger capacitor with separate banks of comb-fingers for the signal path and actuation. The devices were fabricated in a relatively simple process incorporating wafer bonding, deep reactive ion etching (DRIE) and electroless copper plating. A heavily doped, n-type silicon wafer with patterned release trenches is anodically bonded to a Pyrex 7740 glass wafer. A single DRIE process step is then performed to define and release the structures. Employing single crystal silicon as the structural material results in excellent, mechanical performance. Unfortunately even heavily doped silicon leads to large series resistances, and therefore low electrical Q-factors. Plating the entire device with copper greatly reduces the series resistance, allowing high Q-factors to be obtained [5]. The low conductivity of the glass substrate significantly reduces substrate parasitics and cross-talk between adjacent devices.

For the initial mechanical testing the high frequency and tuning performance of the tunable capacitor was not, optimized, rather emphasis was placed on reliability and validating the theoretical operation of the devices in oil. The designed thickness of the device is 70μm; the drawn width and spacing of the comb-fingers is 3μm. Overall the device has an area footprint of approximately 0.8mm x 1.0mm, excluding the area occupied by the bonding pads, and has an initial designed capacitance of 1.789pF. An SEM of the fabricated device after electroless copper plating is presented in Fig. 1a.

The test device employed for high frequency characterization is a metal MEMS parallel plate tunable capacitor. The parallel plate tunable capacitor is fabricated using a simple electroplating process on a Pyrex wafer. An electroplating seed layer is deposited by electron beam evaporation. A copper layer is then plated and patterned to form the lower electrode and contact pads. Next thick resist is spun to form a sacrificial layer, after patterning and e-beam deposition of a second seed layer nickel is plated to form the suspension springs and top electrode plate. The metal structural layers exhibit, very low series resistance,

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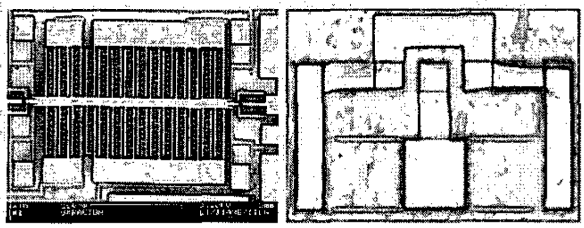


(a) (b)

Fig. 1. (a) An SEM of the comb-drive based device utilized for low frequency and mechanical characterization. (b) An optical micrograph of the parallel plate tunable capacitor employed for high frequency testing.

providing high Q-factors.

The drawn area overlap of the parallel plate capacitors is 210μm x 230μm with a gap of 1μm, resulting in an initial designed capacitance of 428fF in air. An optical micrograph of the tunable parallel plate capacitor is provided in Fig. 1b.

III. Measurement and Device Characterization

A. Mechanical and Low Frequency Device Characterization

The single crystal silicon based devices were tested and characterized in air and while immersed in dielectric fluid following fabrication. Mechanical and electrical characterization was performed on unpackaged die and the devices were directly probed. To test, the mechanical performance the device was actuated by DC as well as frequency swept waveforms. For electrical measurements in oil the devices were immersed in DIALA AX oil, a highly refined petroleum hydrocarbon (mineral) transformer oil from Shell. The oil has a reported dielectric constant of 2.29, a dielectric strength of 30 and a viscosity of 9.45cSt at 40°C.

The capacitance measurements were performed on chip via wafer probing of the device. The measurement, signal applied to the device had an amplitude of 50mV and a frequency of 100kHz. The device was subjected to an applied DC bias from 0 to 40V and measurements were performed at 1V intervals. These measurements were repeated in both air and while operating in oil. The initial capacitance in air was measured to be 1.94pF with a tuning percentage of 9.175% at 40V; in oil the initial capacitance was 3.96pF with 15.737% tuning at 40V.

The frequency response of the device operating in air and in fluid was obtained by optically measuring the relative displacement of the device while driven by a fixed amplitude sine wave. In air the mechanical Q-factor of the device was approximately **30**, in oil the Q-factor was reduced to less than unity (the damping ratio was 3.65.)

B. Microwave Device Characterization

The metal parallel plate MEMS tunable capacitors were probed on wafer. Stepped frequency values from 45 MHz to 26.5 GHz were applied in a 1601 point linear sweep at power level of -10dBm and 1 port, S-parameter measurements (S_{11}) were taken with an IF bandwidth of 100Hz. The devices as well as dembedment structures were measured in air and while immersed in DIALA AX oil, the DC tuning bias was applied through the GSG probe.

In air the self resonant, frequency of the device is 18.3 GHz, while in oil it is 12.5 GHz. The initial capacitance in an air ambient, was measured to be 334fF at a frequency of 5 GHz, the corresponding measured Q-factor is 65; in oil at the same frequency the capacitance is 799fF while the Q is 38.

IV. Discussion

A. Mechanical and Low Frequency

Using well established equations for modeling interdigitated capacitors the theoretical and experimental results for the low frequency, mechanical test structure can be compared [6], [7].

The initial capacitance of the device in air is calculated from:

$$C_0 = 2N_B N_f \epsilon_0 \epsilon_r \frac{h x_{ov}}{g} \quad (1)$$

In this equation ϵ_0 is the permittivity of free space, ϵ_r is the relative permittivity of the dielectric material, N_B is the number of comb-finger banks and N_f is the number of fingers per bank, while h is the height of the fingers, x_{ov} is the initial overlap of the fingers and g is the finger gap. For operation in a dielectric fluid ϵ_r in the equation is simply the relative permittivity of the fluid.

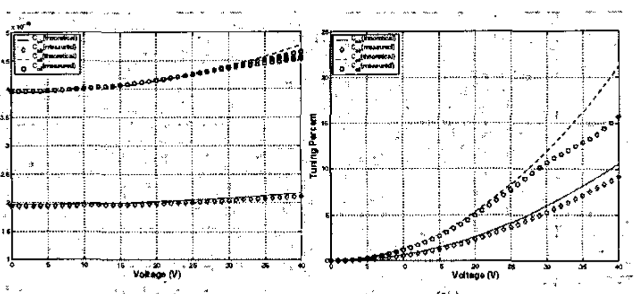
The force generated by the comb-drive actuators is proportional to the square of the applied voltage (V) and is described by the relation

$$F = 2N_B N_f \epsilon_0 \epsilon_r \frac{hV^2}{g} \quad (2)$$

Ergo, when immersed in oil the force is increased by a factor of the relative permittivity of the oil (2.29 in the presented example), compared to the case when the dielectric is air.

A plot of the theoretical and measured capacitance for the devices in air and oil are presented in Fig. 2a; the experimental data in this plot consists of ten data sweeps taken over a period of approximately 2 hours, the theoretical plot, is based on measured geometries from the fabricated devices. The experimental measurements indicate very good agreement with the theoretical results; as predicted the capacitor exhibits an increase in capacitance by a factor of 2.2, slightly less than the expected value of 2.29 from the ϵ_r of the oil. The difference between theory and measurement is accounted for by the small parasitic capacitances through the Pyrex substrate between the electrodes, which is not tuned by the fluid. Variations in capacitance values above 30V are a result, of non-linearities in the crab-leg springs as the displacement, is increased.

In Fig. 2b the tuning percentage (defined as $(C_{tune} - C_{initial})/C_{initial}$, i.e. 10% is a 110% tuning ratio) is plotted against applied voltage. From the previously presented equations the force should be multiplied by ϵ_r for devices



(a) (b)

Fig. 2. (a) Plot of theoretical arid measured values of the capacitance at applied voltages from 0V to 40V in air arid immersed in trarisforirier oil at 100kHz. (b) A plot of the calculated arid experiirierital tuning percentages in air and in oil.

in oil, resulting in a corresponding increase in the tuning percentage. Again there is notable deviation at high voltages as the springs become non-linear, this problem can be eliminated *by* the use of optimized spring designs.

Mechanically the oil provides damping to the system, properly damping the fundamental mode of motion will reduce settling time and provide the ability to tune to the desired capacitance value quickly. In addition, damping can reduce the effects of externally applied accelerations on the capacitor. Modeling the fluid damping using Stokes flow damping the mechanical Q-factor of the device is

$$Q = \frac{g}{\mu A}\sqrt{k_x m}, \quad (3)$$

where μ is the dynamic viscosity of the fluid, g is the gap distance between the moving elements, A is the overlap area, k_x is the stiffness and m is the moving mass.[8] In air ($\mu_{air} = 190\mu P$) the measured Q factor was 30, while in oil the damping ratio was 3.65 ($\zeta = \frac{1}{2Q}$.) The larger viscosities of transformer oils results in higher damping and lower Q values; ideally the viscosity of the oil should be chosen to bring the system close to critical damping.

The measured and theoretical mechanical frequency responses of the tunable capacitor in air and in DOW 200; 5cSt ($\mu_{oil} = 4{,}728\mu P$) oil, a silicone oil readily available in a wide range of viscosities, are presented in Fig. 3.

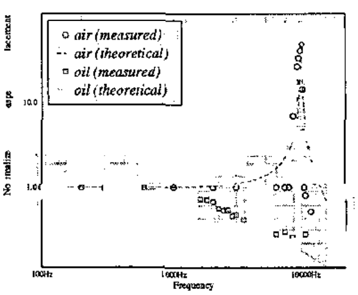


Fig. 3. Mechanical frequency response of the turiable capacitor. measured in air arid in low viscosity oil.

Fig. 4 shows the time domain response of the system to a 30V step input.

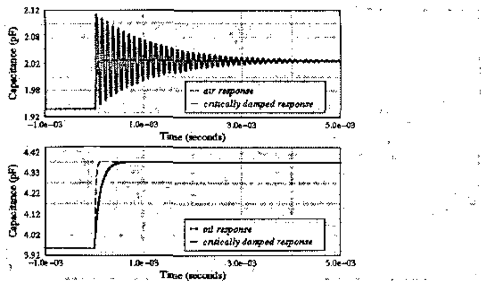


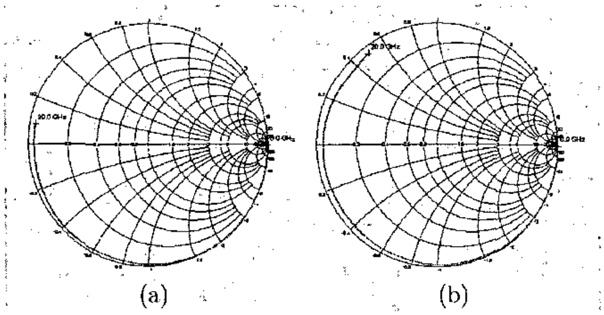
Fig. 4. Time domain response of the tunable capacitor to a 30V step at t=0.

Transformer oils are available in a range of viscosities, combined with optimized device design the selection of an oil with the proper viscosity allows high tuning rates with minimal ringing or settling time.

The breakdown voltage of electrostatic devices is important, as transients in actuation signals may occur; small, infrequent, arcing currents may not cause immediate device failure, however, long term device operation and reliability may he adversely affected. Large transient spikes may result in catastrophic device failure. The initial breakdown voltage in air occurred at voltages between 60V and 70V, while no dielectric breakdown occurred during voltage sweeps from 0 to 500V in oil.

B. RF and Microwave: 45MHz to 20GHz

Smith chart plots of the measured S-parameters in air and in oil are presented in Fig. 5a and b respectively. From these plots it is immediately evident,that the capacitance of the structure is increased while immersed in oil, and there is not, significant, loss in the fluid up to the capacitor's self-resonant frequency in oil (12.5GHz).



(a) (b)

Fig. 5. Smith chart of S_{11} measurements in air (a) arid oil (b) froiri 45MHz to 20GHz.

The extracted effective capacitance values are plotted for frequencies from 45MHz to the self-resonances in Fig. 6a. In the Fig. 6b the capacitance values are plotted for frequencies at which this capacitor would normally be employed, from 45MHz to 5GHz. In this frequency range there is nearly perfect agreement, between the measured capacitance and expected capacitance, as shown in the plot,. Table I provides measured capacitance and Q-factor values for frequencies between 1GHz and 5GHz.

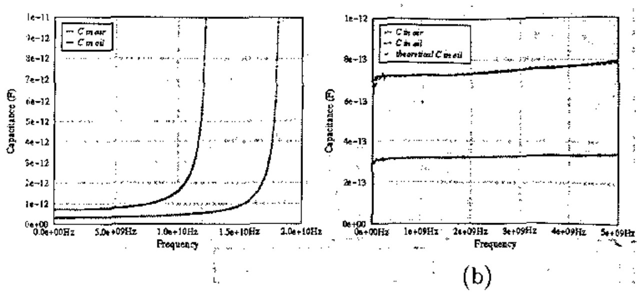


Fig. 6. Capacitance in air arid oil plotted to beyond the self-resoriarice (a), arid between 45MHz arid 5GHz in (b).

TABLE I
MEASURED CAPACITANCE AND Q-FACTOR FOR FREQUENCIES FROM 1GHz TO 5GHz.

Frequency	C_{air}	Q_{air}	C_{oil}	Q_{oil}
1 GHz	317fF	426	725fF	216
2 GHz	322fF	218	732fF	110
3 GHz	330fF	142	750fF	65
4 GHz	336fF	88	770fF	47
5 GHz	344fF	72	799fF	40

Fig. 7 shows a plot, of the measured effective dielectric constant ($\epsilon_{eff} = \frac{C_{oil}}{C_{air}}$) as well as the Q-factor ratio ($Q_{ratio} = \frac{Q_{oil}}{Q_{air}}$). The effective dielectric constant shows excellent, agreement with the expected value of 2.29. The expected decrease in Q-factor is $\frac{1}{\epsilon_r}$ as the capacitance is increased by a factor of ϵ_r and the Q can he described as $Q = \frac{|X|}{R}$ for an ideal capacitor. The measured Q values show good agreement, with the predicted values: the error is more pronounced at low frequency and may be attributed to small errors in the measurement, of the real part of the impedance being significant coinpared to the small series resistance at low frequencies.

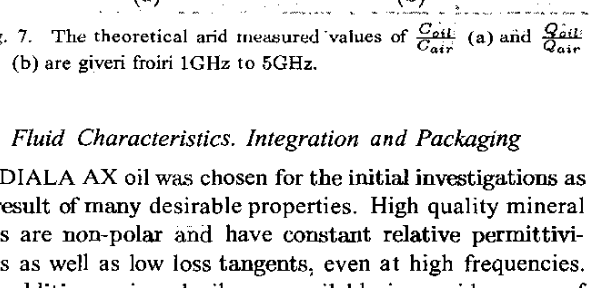


Fig. 7. The theoretical arid measured values of $\frac{C_{oil}}{C_{air}}$ (a) and $\frac{Q_{oil}}{Q_{air}}$ (b) are giveri froiri 1GHz to 5GHz.

C. Fluid Characteristics. Integration and Packaging

DIALA AX oil was chosen for the initial investigations as a result of many desirable properties. High quality mineral oils are non-polar and have constant relative permittivities as well as low loss tangents, even at high frequencies. In addition, mineral oils are available in a wide range of viscosities, have excellent, insulating capabilities and are predominantly chemically inert,.

The DIALA AX oil's relative permittivity (ϵ_r or ϵ') as well as loss tangent ($tan\delta$) where measured to 50GHz using modified techniques from [9]. Additionally the temperature dependence of the relative permittivity and loss tangent were measured from 25°C to 100°C and verified to be acceptable.

In previous work micromachined devices for microfluidic applications have been encapsulated in hermetically sealed packages [10], [11], [12]. Employing similar packaging techniques allows these tunable capacitors to be utilized in hybrid packages with active devices to create practical, viable systems.

V. CONCLUSION

A dielectric fluid application for electrostatic MEMS tunable capacitors has been demonstrated. Several advantages of operating the tunable capacitor in oil have been identified, these include: an increase in the capacitance and tuning percentage by a factor of ϵ_r, a more ideal, tunable damping coefficient, and increased breakdown voltage. Furthermore, the presented fluidic application can be applied to virtually any electrostatic MEMS capacitor or actuator to improve performance.

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