MICROMACHINED VARIABLE CAPACITOR WITH WIDE TUNING RANGE

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ABSTRACT

In this paper, ultra-thin silicon wafers, SU-8 bonding and DRIE technology have been combined for the fabrication of a folded spring, dual electrostatic drive, vertical plate variable capacitor device with displacement limiting bumpers. The SU-8 bonding replaces the use of expensive SOI wafers and enables a more flexible design. The thick SU-8 also decreases the parasitic substrate capacitance. Due to the presence of the bumpers, our variable capacitor has two tuning voltage regimes: first a parabolic region that achieves roughly a 290% tuning range, then a linear region that achieves an additional 310%, making the total tuning range about 600%, possibly the largest range reported in the literature to date.

INTRODUCTION

Electronically tunable capacitors are key elements in communications circuits such as voltage controlled oscillators and tunable capacitor filters. Numerous papers address variable capacitors[1-16]. In an integrated circuit design, a variable capacitor is usually realized with a reversed p-n junction, which can give a 335% tuning range[13]. However, the silicon p-n junction usually has large series resistance plus parasitic capacitance to the substrate. The variable capacitors manufactured with micromachining technology can accommodate large voltage swings so that the phase noise can be improved by allowing a large voltage swing across an LC circuit. This is normally not possible with p-n junction capacitors, where the designer must ensure that the junction does not become forward-biased over the tuning voltage range. Additionally, micro-mechanical capacitors are not expected to respond to microwave frequencies, which are normally 10,000 times higher than their mechanical resonant frequencies. Hence these devices are not expected to produce a large amount of harmonic distortion.

For electrostatic drive variable capacitors fabricated using micromachining processes, Yao, et al., [13] have reported a capacitor with a tuning range of 200% based on lateral comb structures on an SOI substrate. Feng, et al., [16] have used a thermal actuator in their variable capacitor and achieved a tuning range of 270%. In this paper, ultra-thin silicon wafers, SU-8 bonding and DRIE technology have been combined for the fabrication of a folded spring, dual electrostatic drive, vertical plate device with displacement limiting bumpers. The total tuning range of this variable capacitor is about 600%.

DESIGN AND THEORY

Figure 1 shows a simplified electrical/mechanical schematic of our variable capacitor and LC drive circuit. The device consists of sets of fixed and movable vertical plates, forming separate drive and sense capacitors. Figure 2 shows several microscope images of the fabricated device. In Fig. 2a, two separate drive capacitors are

Figure 1. Electrical/mechanical schematic of micromachined variable capacitor and LC drive circuit. C_d , the drive capacitor, has an electrode spacing that is three times that of C_s , the sense capacitor. L is about 0.1 mH.

Figure 2. (a) Top view of fabricated device. The drive voltage is applied between the common electrode E_p and the drive electrodes E_{d1} and E_{d2} . The capacitance is sensed between E_s (shorted E_{s1} and E_{s2}) and the common electrode E_p . The movable fingers are mounted to a center support beam and connected to the E_p electrodes by $4 \mu\text{m}$ wide, $730 \mu\text{m}$ long, $29.5 \mu\text{m}$ thick springs. (b) Close up image showing a portion of the folded spring. (c) Close up image of drive capacitor showing placement of movable fingers with smallest asymmetric electrode spacing $3d=9 \mu\text{m}$ and bumper spacing nominally $0.93d=2.8 \mu\text{m}$. The bumpers are always at the same potential. (d) Close up image of sense capacitor showing smallest electrode spacing $d=3.0 \mu\text{m}$.

Figure 3. Fractional displacement at pull-in, x_{pin} , versus drive electrode wide to narrow gap spacing ratio, $N > 1$.

placed symmetrically on the ends of the structure, and the sense capacitor occupies the center region. The sense and drive capacitors share a common electrode E_p , which is connected through four folded springs to a movable support beam with attached fingers. A portion of a folded spring is shown in Fig. 2b. As shown in Figs. 2c and 2d, C_d and C_s actually consist of wide and narrow air gap capacitances. In both cases, the net capacitance

Figure 4. Two mask process schematic for micromachined variable capacitor

is strongly dominated by the narrow gap behavior. The narrow drive gap spacing is designed to be three times that of the narrow sense gap so that a maximum sense electrode displacement can be achieved at the lowest possible applied voltage without causing drive electrode pull-in. The $2.8\mu\text{m}$ long bumpers in Fig. 2c, which are always at the same potential, limit the maximum displacement to less than the full $3\mu\text{m}$ sense gap distance. Before the electrode E_p contacts the bumpers, the capacitance increases parabolically with increasing applied voltage. After contact, the capacitance increases approximately linearly. This is similar to a previous report in [17] where curved electrode actuators were used to extend the travel range.

The voltage for transition from parabolic to linear behavior can be estimated analytically by calculating the drive electrode

pull-in voltage, V_{pin} . Balancing the electrostatic and mechanical forces before pull-in gives

$$\frac{\epsilon_0 V^2 A}{2(d_0 - \Delta d)^2} - \frac{\epsilon_0 V^2 A}{2(Nd_0 + \Delta d)^2} = k\Delta d \quad (1)$$

where N is the wide to narrow gap spacing ratio for the drive electrode, (N.B., $N > 1$) and Δd is the displacement. A , ϵ_0 , V and k are the capacitor area, permittivity of free space, applied voltage and spring constant, respectively. An expression for the fractional displacement at pull-in, $x = \Delta d/d_0$, is found by maximizing equation (1). Thus differentiating (1) with respect to displacement, multiplying by Δd , and subtracting (1), gives

$$\frac{1 - 3x_{pin}}{(1 - x_{pin})^3} - \frac{N + 3x_{pin}}{(N + x_{pin})^3} = 0 \quad (2)$$

where the normalized displacement at pull-in depends only on N . Figure 3 shows a plot of x_{pin} versus N . Observe that x_{pin} decreases dramatically as N approaches 1. For example, at $N=2$, $x_{pin}=0.3069$. When N is infinite, $x_{pin}=1/3$, which is the well known result for a single parallel plate system.

By substituting x_{pin} into equation (1), the pull-in voltage can be written as

Figure 5. A portion of the sense capacitor at various drive voltages

$$V_{pin} = \sqrt{\frac{x_{pin}}{1 - x_{pin}} \frac{2d_0^3 k}{\epsilon_0 A} \frac{1}{(N + x_{pin})^2}} \quad (3)$$

As discussed in the following section, the analytical results can be compared with simulation results obtained using MEMCAD (now COVENTOR) finite element analysis software. Using this tool, the spring constant for our system is estimated to be about 13 N/m.

FABRICATION AND RESULTS

Figure 4 shows the main fabrication steps. The process starts with SU-8 photolithography on an oxidized silicon wafer to form a cavity. The realized cavity depth is about $22\mu\text{m}$ at 3000 rpm. An ultrathin silicon wafer[18] was bonded to the silicon substrate by SU-8 bonding[19] at 105°C , using an EVI 501 universal bonding system. Aluminum was then sputtered onto the bonded wafer stack, and patterned by HP_3O_4 etching at 40° after photolithography. The devices were released by deep reactive ion etching (DRIE) using the BOSCH process in a Unaxis/Plasma-Therm inductively coupled plasma system. Finally, the photoresist was removed using oxygen plasma etching. The aluminum on the structure, besides allowing good external electrical contact, also decreases the device series resistance, improving its Q factor.

Figure 6. The measured capacitance C_{s1} , between E_{s1} and E_p (left axis), and the percentage change in capacitance (right axis) versus voltage

Figure 7. Optical profile of device sidewall after DRIE etching

Figure 5 shows sense capacitor photos at 0V, 20V, 40V and 57.5V when voltage was applied on only one drive electrode. As

expected, the capacitor electrodes move closer when the voltage increases.

Figure 6 shows the measured sense capacitance value C_s between one sense electrode E_{s1} , and the common electrode, E_p . The figure also shows the percentage change in capacitance. The capacitance is measured using an HP 4284A precision LCR meter. The amplitude and frequency of the testing signal were 5mV and 1MHz, respectively. When voltage is applied on both drive electrodes, the capacitance parabolically increases from 0.945pF at 0V to 3.657pF at 26V, and then increases nearly linearly to 6.57pF at 70V. This corresponds to tuning ranges of 287% at 26V and 595% at 70V. When voltage is applied on one drive electrode, the capacitance increases parabolically from 0.945pF at 0V to 3.696pF at 37.1V, and then nearly linearly to 5.55pF at 75.1V. This corresponds to tuning ranges of 290% at 37.1V and 497.5% at 75.1V. For each measurement, the results are reproducible and without discernable DC hysteresis. In addition, the final displacement appears only to be limited by dielectric breakdown, which exceeds 80V for these devices in air. Figure 7 shows the capacitor sidewall image using a VEECO NT3300 optical profilometer. It shows that the ultrathin silicon wafer is approximately $29.5\mu\text{m}$ thick. In addition, the image reveals the capacitor surface microroughness induced by the Bosch etching process. The RMS roughness is about 71nm.

Table 1 provides a comparison of the measured transition voltages to analytical and COVENTOR 2001 pull-in simulation results. For completeness, COVENTOR simulation parameters are also given in the table. Good agreement is found for the two cases, when voltage is applied either to only one or to both drive electrodes. Note that the measured transition voltage is slightly higher than the analytical and simulation results, but this can easily be attributed to non-parallel electrodes or other effects neglected in the theory. The possibility of non-parallel electrodes (i.e., a few degree DRIE sidewall slope) is suggested by the observation that the drive electrodes never seen to make full contact at the top surface of the device. While we have achieved a wide tuning range in these capacitors, we note that even with the addition of aluminum, the measured Q factor is only ~ 100 at 1MHz. We attribute this result to the use of relatively high resistivity, 1–10 Ωcm , ultra-thin silicon wafers. We are currently fabricating improved devices using heavily doped silicon, as well as softer springs and improved drive electrodes to lower the drive voltage.

Table 1. Comparison of measured transition voltage to analytical and COVENTOR simulation results

	Measured transition voltage	Calculated pull-in voltage	COVENTOR pull-in voltage
Voltage on one electrode	37.1V	35.0V	34.25V
			27 node element for meshing 20583 total nodes convergence ratio= 5×10^{-3}
Voltage on both electrodes	26.0V	24.75V	23.91V
			27 node element for meshing 22869 total nodes convergence ratio= 5×10^{-3}

CONCLUSIONS

In summary, combining ultra-thin silicon wafers, SU-8 bonding and DRIE, we have designed and fabricated a micromachined variable capacitor that exhibits two tuning regimes, parabolic and linear, and has achieved roughly a 600% tuning range.

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