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Surface micromachined, complementary-metal-oxide-semiconductor compatible tunable capacitor with 14:1 continuous tuning range

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This letter reports a surface micromachined, complementary-metal-oxide-semiconductor compatible tunable capacitor utilizing a simply supported bridge structure, unlike traditional microelectromechanical-system bridges that use fully clamped boundary condition at the anchors. Through the implementation of a simply supported bridge driven by two 100-μm-long ZnO-actuated cantilevers, a compact tunable capacitor has been fabricated on silicon without any warping and shown to be capable of a 1400% continuous tuning from 0.13 to 1.82 pF. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2838447]

Radio-frequency (rf) tunable capacitor is one of the most important building blocks in many rf applications, such as tunable filters, matching circuits, and voltage-controlled oscillators (VCOs). Most of these applications require tunable capacitors with a high quality factor and a wide tuning range. The main types of tunable capacitors currently used in integrated circuit technology are semiconductor varactors, including diode varactors[1] and metal-oxide-semiconductor (MOS) varactors.[2] The voltage-dependent capacitance of a reverse-biased *p-n* junction is used for the diode varactor, while the capacitance tuning is realized through the variation of MOS capacitance in response to the gate bias voltage for the MOS varactor. However, these semiconductor varactors can typically provide limited tuning ratios.[3] Research has also been carried out to develop tunable capacitors based on ferroelectric materials.[4,5] Since the dielectric constants of ferroelectrics can be varied as a function of the applied voltage, the capacitance is accordingly changed. However, they typically suffer from low capacitance tunability and large losses in the ferroelectrics.

Another promising type of varactors is microelectromechanical-system (MEMS) tunable capacitors because of their large tuning ratio, low insertion loss, and high quality factor. Among various actuation mechanisms such as electrostatic,[6,7] piezoelectric, and thermal[8] actuations, electrostatic actuation has received the most attention for MEMS tunable capacitors, and been reported in numerous papers. Compared to the electrostatic actuation, piezoelectric actuation has several inherent advantages such as high linearity, bidirectional deflection, low driving voltage, no electrostatic charging effect, and wide dynamic range due to no "pull-in" phenomenon. In 2001, the first piezoelectric tunable capacitor with a 3:1 tuning ratio was achieved through lead zirconate titanate (PZT) actuation and a bulk micromachining process, which is not fully complementary MOS (CMOS) compatible.[9] A PZT unimorph cantilever actuator was reported for switching application in 2003.[10] However, PZT films contain a high-vapor-pressure oxide of PbO and require repeated annealing at temperature higher than 600 °C, which make it difficult to be CMOS compatible. Recently, a piezoelectric tunable capacitor using AlN bimorph actuator was reported without mentioning about its quality factor, and was shown to have a relatively small tuning ratio.[11] Interestingly, in all these piezoelectric tunable capacitors employing either PZT or AlN actuation, only unidirectional characteristics have been utilized and reported, despite the innate potential for bidirectional actuation and tuning.

Among the different types of capacitor structures, the gap-closing capacitor consisting of two parallel plates (one being movable and controlled by an applied voltage and the other being fixed) is most widely used. For a parallel-plate tunable capacitor, conventional cantilevers and bridge structures have their own drawbacks. If a cantilever is used for a parallel-plate tunable capacitor, the gap distance between the movable and stationary electrodes is not uniform across the whole capacitor, limiting the capacitance tunability. A bridge structure, on the other hand, provides uniform gap variation and complete gap closure. However, bridge-based MEMS structures usually suffer from the tension that gets developed as the bridges are deflected. As a result, relatively high voltage is typically required for the bridge deflection since the tension works against the bridge deflection.

Here, we describe a surface micromachined, CMOS compatible piezoelectric tunable capacitor employing bidirectional ZnO actuation and a simply supported bridge structure, and demonstrate large piezoelectric displacements and hence a wide capacitance tuning range.

As shown in Fig. 1, a rectangular plate is completely released and initially floats on two piezoelectrically actuated cantilevers composed of Al(0.1 μm)/plasma enhanced

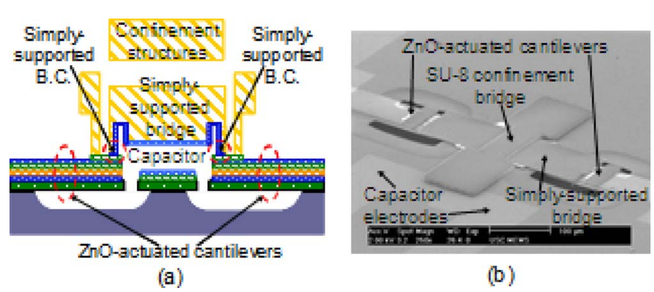

FIG. 1. (Color online) (a) Schematic illustration of a piezoelectrically actuated tunable capacitor with simply supported bridge structure. (b) Scanning electron microscope (SEM) image of the fabricated tunable capacitor.

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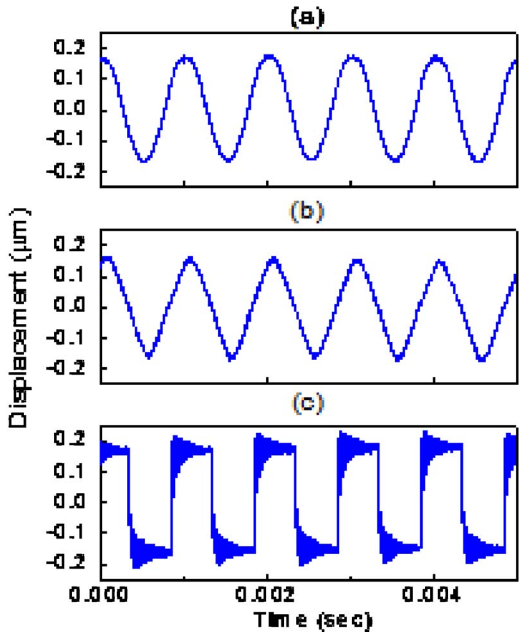

FIG. 2. (Color online) Measured piezoelectric displacements for unbiased (a) sinusoidal, (b) triangular, and (c) square voltage waveforms at 1 kHz.

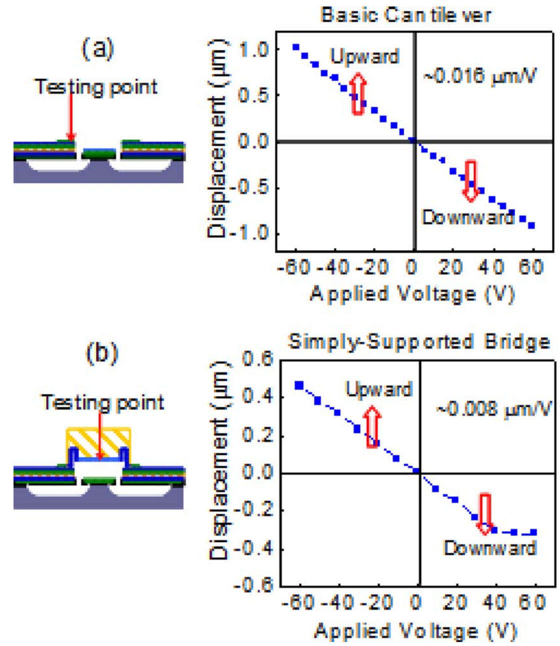

FIG. 3. (Color online) Measured piezoelectric displacement versus actuation voltage for (a) the cantilever and (b) the simply supported bridge.

chemical vapor deposition SiN(0.1 μm)/ZnO(0.4 μm)/Al(0.1 μm)/low pressure chemical vapor deposition (LPCVD) Si_xN_y(0.4 μm)/SiO_2(0.03 μm) on a 10 kΩ cm silicon wafer. The plate is then pulled down by a direct current (dc) voltage and becomes a simply supported bridge. The parallel-plate tunable capacitor has a variable air gap formed between a movable top capacitor electrode on the simply supported bridge and a fixed bottom capacitor electrode on the same substrate. A dc voltage applied between the top electrodes of the two piezoelectrically actuated cantilevers maintains the simply supported boundary condition at the bridge anchors. Applied electric fields across the ZnO films of the two piezoelectrically actuated cantilevers produce lateral contraction (or expansion) in the ZnO films, giving rise to a bending moment in the beam cross-section. In our design, ZnO is above the neutral plane of the cantilever beam. As the beam moves downward upon the expansion of the ZnO film, the air gap of the capacitor is reduced, and the capacitance increases consequently. Oppositely, an upward movement upon ZnO film contraction can lead to a capacitance decrease. Since the released bridge, simply supported by two cantilevers, is free to move without much resistance from built-in stress, a large and uniform capacitance variation can be attained without high actuation voltage.

The fabricated devices were tested with a focused-beam laser Doppler vibrometer (Optodyne VS-5010). As a signal of ± 10 $V_{peak\text{-}to\text{-}peak}$ was applied, the 100-μm-long cantilever deflected at the same frequency (1 kHz) as the applied signal, and the displacement amplitude was equally around 0.32 μm peak-to-peak for different waveforms (Fig. 2). The displacement responses have been measured for different applied voltages and frequencies. To actuate the simply supported bridge, a dc offset voltage of 20 V was applied between the top electrodes of the two actuators to attract the floating bridge down to the cantilevers by electrostatic force. Then alternating current (ac) electric fields with the same magnitude and phase were applied across the ZnO films of the two separate cantilevers to piezoelectrically actuate the cantilevers and the simply supported bridge accordingly.

The deflection is bidirectional and highly linear. The displacement for the simply supported bridge (0.008 μm/V) is around 50% of the value for a cantilever (0.016 μm/V), indicating that deflection can be achieved without much tension developed in the bridge (Fig. 3). The bridge deflected downward continuously until the 0.35-μm-wide gap was closed. It is noted that the initial gap is smaller than the designed 1-μm-wide gap because the cantilevers were slightly curved down. For the mechanical resonant frequency characterization, sinusoidal signals were applied, and the measured frequency responses of the basic cantilever and the simply supported bridge are shown in Fig. 4. The fundamental resonant frequency was measured to be around 40 kHz (with a quality factor of about 24) for the cantilever, and no resonance peak was observed for the bridge due to squeeze film damping (Fig. 4). The squeeze film damping effect can be avoided through vacuum packaging of the capacitor and when there is no squeeze film damping effect, the mechanical resonance of the structure will limit the frequency response (to about 40 kHz in the current design). The mechanical frequency response that determines the tuning speed of the capacitor is a function of the mechanical structure and

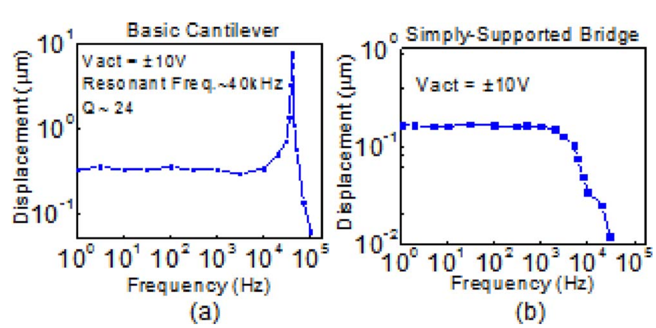

FIG. 4. (Color online) Measured mechanical frequency response for (a) the cantilever and (b) the simply supported bridge.

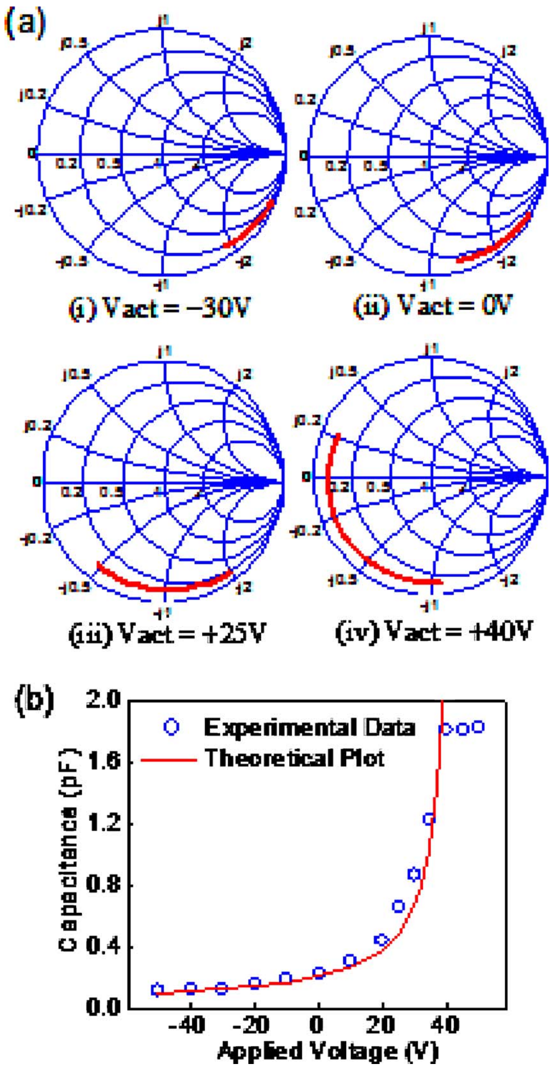

FIG. 5. (Color online) (a) Measured S_{11} Smith charts for tunable capacitor at actuation voltage (V_{act}) of (i) −30 V, (ii) 0 V, (iii) +25 V, and (iv) +40 V, from 2 to 5 GHz. (b) Comparison of experimental and theoretical capacitance-versus-voltage curves.

can be optimized for applications requiring high-speed tuning.

The capacitance variation has been measured at gigahertz with a HP 8753D network analyzer and Cascade Microtech's coplanar waveguide (CPW) microprobe with a ground-signal-ground configuration. The measured S_{11} Smith charts of the tunable capacitor at different actuation voltages are shown in Fig. 5(a). The quality factor Q of the tunable capacitor is calculated as $Q=-\mathrm{Im}(Z)/\mathrm{Re}(Z)=-1/2\pi fRC$,[6] where Z, f, R, and C are the impedance, frequency, series resistance, and capacitance, respectively. The Q of the tunable capacitor at 0.42 pF at 2 GHz was measured to be around 20. In our design, the top plate of the capacitor is self-supported and electrically isolated from the anchors. The energy is well confined in the parallel plates and the anchor loss is ignorable. The Q can be further improved if we increase the thickness of Al plate electrodes to reduce the series resistance. The measured and theoretical capacitance at 3 GHz as a function of the actuation voltage is shown in Fig. 5(b). With a nominal static capacitance of 0.23 pF (after deembedding the 0.2 pF parasitic capacitance of CPW), the maximum capacitance of 1.82 pF and the minimum capacitance of 0.13 pF were attained at +40 and −30 V, respectively. Thus, the capacitance tuning ratio is as large as 14 to 1.

The theoretical capacitance curve due to a 0.008 μm/V gap variation fits the experimental data fairly well, as shown in Fig. 5(b). The deviation of the measured capacitance from the theoretical value at voltages larger than +40 V is caused by the incomplete closure of the gap possibly due to the unavoidable particles in the testing environment and the surface roughness and thickness nonuniformity of the evaporated sacrificial silicon layer.

There are several approaches to further reduce the operation voltage while keeping a good capacitance tuning range. First, since the piezoelectric displacement is proportional to the square of the length of the cantilever,[12] we can reduce the operation voltage by using longer cantilevers. With the cantilever length increased to 200 μm and the thickness of each composing material optimized for largest displacement, a 10:1 tuning ratio can be theoretically achieved with an operation voltage of only 5 V. Second, the tuning range is also determined by the initial air gap and the attainable maximum capacitance, in particular, when the two plates are in contact. To strictly control the initial air gap in our case, the thickness ratios between the compressive SiO_2 and the tensile LPCVD-Si_xN_y layers can be optimized to get a completely flat cantilever. Third, since the maximum capacitance achievable is highly affected by the surface roughness of the two electrodes, a chemical mechanical polishing step can be performed to smooth the surface of the evaporated sacrificial silicon layer before Al deposition.

In conclusion, a surface micromachined piezoelectric tunable capacitor employing ZnO actuation has been designed and fabricated. The large capacitance tuning is achieved through the design and implementation of a simply supported bridge structure instead of the conventional cantilever or bridge structure. Piezoelectric displacement and frequency performances of the fabricated devices have been thoroughly characterized with a laser vibrometer. The deflection is demonstrated to be linear and bidirectional. With the design of a simply supported bridge structure driven by two ZnO-actuated cantilevers, a 1400% continuous capacitance tuning range (from 0.13 to 1.82 pF) is achieved with applied voltages from −30 to +40 V.

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