MICROMACHINED RF MEMS TUNABLE CAPACITORS USING PIEZOELECTRIC ACTUATORS

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ABSTRACT

In this paper, a RF MEMS tunable capacitors with low operation voltage, high linearity, high quality factor, and large tuning ratio have been fabricated by utilizing micromachined piezoelectric actuators. The fabricated tunable capacitor has a C_{max}/C_{min} ratio of 3.1 to 1 at bias voltages of 6 V and a quality factor of 210 at 1 GHz.

INTRODUCTION

Recently, RF MEMS tunable capacitors with a wide tuning range, high quality factor, and low operation voltage are being fabricated for applying in miniaturized RF/microwave communication module and systems due to the non linearity, low self resonance, and excessive resistive loss of the semiconductor varactors [1]. In RF MEMS, micro-mechanical tuning avoids the high resistive/capacitve losses associated with semiconductor varactors at high frequencies and the movement linearly of MEMS devices also allows the capacitors to tune linearly. Most of MEMS tunable capacitors have been fabricated using an electrostatic actuating mechanism [2-5]. The MEMS tunable capacitors can be also classified into two categories based on their tuning schemes such as gap and area tuning. In 1991, a MEMS area tuning capacitor with interdigitated comb structures was fabricated by using surface micromachining. It has a capacitance change of 0.035 pF to 0.1 pF for bias voltages of 80 V to 200 V [2]. In 1998, a MEMS area tuning capacitor with suspended interdigitated comb structures was fabricated by using silicon wafer bonding technique and deep reactive ion etch (DRIE) [3]. It has a quality factor of 34 for 5.19 pF at 500 MHz and a tuning range of 200% or 3 to 1 tuning ratio for bias voltages of 2 to 14 V. In 1997, a MEMS gap tuning capacitor with a Q factor of 9.6 at 1 GHz and a capacitance change of 4.0 pF to 4.4 pF for bias voltage 0 to 0.8 V was presented [4]. In 1999, a MEMS gap tuning capacitor with tuning range of 90 % and a quality factor of 256 at 1 GHz was fabricated by using polysilicon and electro-thermal actuating scheme [6]. These tunable capacitors can be utilized for constructing miniaturized tunable RF filters, low noise parametric amplifiers, harmonic frequency generators, VCOs, and matching circuits.

This paper describes a RF series-mounted MEMS tunable capacitor in a CPW transmission line circuit using the integrated PZT actuator operated at low bias voltages and flip-chip bonding technology. Compared with the MEMS tunable capacitors operated by the electrostatic actuating scheme, the tunable capacitor with piezoelectric actuators have several advantages such as lower driving voltages, approximately linear capacitance tuning, and avoiding the electrostatic charge collecting on the capacitor plates, and improvement in the reliability of tuning.

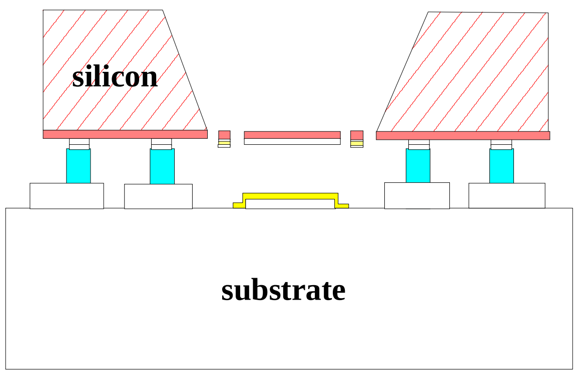

Figure 1. A conceptual schematic drawing of the proposed RF MEMS tunable capacitors with the flip-chip bonded piezoelectric actuator

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DESIGN AND FABRICATION

Fig. 1 shows a conceptual schematic drawing of the proposed miniaturized MEMS tunable capacitor with the integrated PZT actuator. As shown in Fig. 1, the fabricated PZT actuators on silicon substrate was diced and bonded onto the fabricated transmission line on a Quartz substrate by using flip-chip bonding technology. When bias voltages are applied into the control pads, the top electrode connected with the PZT actuator are moved vertically onto the dielectric layer on top of the fixed electrode of the tunable capacitor. Thus, the variation of the gap between top and bottom electrode results in a change in the device capacitance. Fig. 2 shows the fabrication process of the PZT actuated movable top electrode. On the front side of the silicon wafer coated with 2 μm-thick LPCVD low stress nitride, 150 nm-thick platinum is deposited as bottom electrode layer followed by deposition of 350 nm-thick PZT layer through multiple spin-coating and thermal curing process. On top of the PZT, 150 nm-thick RuO_2 layer is deposited (a). Metal/PZT/metal structure is delineated by self-aligned process using Cl_2/O_2 based plasma etching as in (b) and (c). After the gold top electrode is patterned (d), silicon under the movable top electrode and cantilever type hinges is removed by anisotropic etching in KOH (e). Finally, the cantilever type hinges and movable top electrode plate are released by RIE followed by dicing to individual chips (f). In Fig. 2, SEM images of the fabricated PZT actuated electrode are shown.

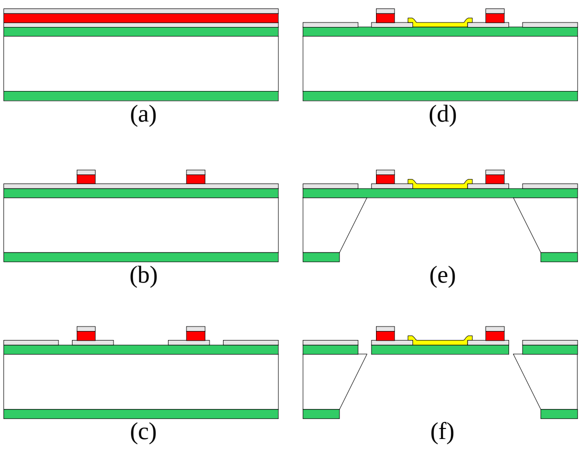
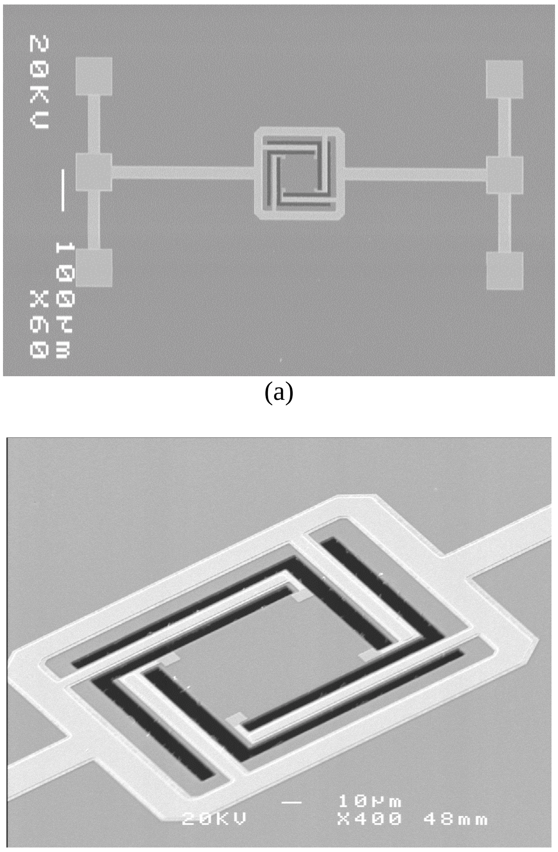


Figure 2. Fabrication sequences of the integrated PZT actuator on silicon wafer



(a)

(b)

Figure 3. SEM picture (a) and close up view (b) of the fabricated PZT actuator on a silicon substrate by using silicon bulk micromachining techniques to be used as a movable top electrode of the MEMS tunable capacitor

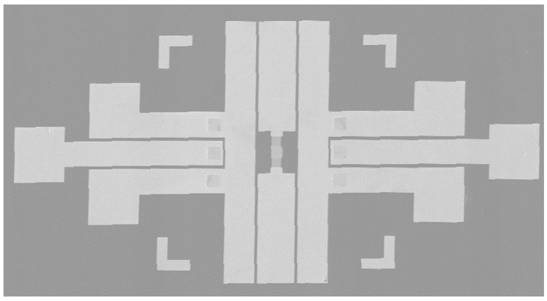
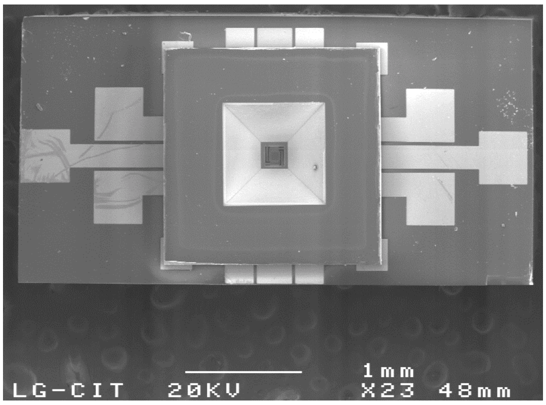


Figure 4. A SEM picture of the patially plated CPW transmission line with solder bumps on a Quartz substrate to be used as a fixed bottom electrode of the MEMS tunable capacitor

CPW type transmission line (bottom electrode of the tunable capacitor) and control electrodes composed of Pt/Au/Cr metals are formed on a Quartz substrate by using a lift off technique. After depositing dielectric or insulating layer, it is wet-etched selectively to form the parallel plate capacitor. In order to reduce resistive loss of the MEMS tunable capacitor, the thick copper or gold is electroplated partially on top of transmission line, ground plane, and the control electrode for applying bias voltage to operate the PZT actuator. Finally, the solder bumps are formed on bonding pads fabricated on the substrate by using lift off or electroplating techniques. The fabricated PZT actuator is accurately bonded on the formed solder bumps of the Quartz substrate by using flip chip bonding technology. The air gap between the movable electrode and fixed electrode of the MEMS tunable capacitor is determined by the initial height of bumps, the thickness of the plated copper or gold, and the flip-chip bonding conditions. The air gap was designed to be 2.5 um in the fabricated MEMS tunable capacitor. Fig. 3 shows the fabricated PZT actuator to be used as the movable top electrode of the MEMS tunable capacitor. Fig. 4 shows the partially electroplated CPW type transmission line with solder bumps for being used as the fixed bottom electrode of the MEMS tunable capacitor. Fig. 5 shows a SEM picture of the fabricated MEMS tunable capacitor with the flip-chip bonded PZT actuator.

RESULTS AND DISCUSSIONS

Table 1 shows structural geometry parameters of the proposed miniaturized RF MEMS tunable capacitor with the movable electrode comprised of the integrated PZT actuator. Fig. 6 shows P-E hysteresis curve of the 380 nm-thick PZT unimorph actuator before release etching. The PZT capacitor shows very stable P-E hysteresis characteristics as shown in Fig. 6. The polarization characteristics degraded during the fabrication process, especially RIE steps, is well recovered by a RTA process at 650℃. The leakage current is less than 10^{-6} A/cm^2 level at 10 V bias. Annealed PZT capacitors shows the remnant polarization of 18 μC/cm^2 and the dielectric constant as high as 1100. Fig. 7 shows the actuation characteristics of the fabricated PZT actuator and the variation of capacitance of the fabricated tunable capacitor as a function of dc bias voltages. As shown in Fig. 7 (b), it has a C_{max}/C_{min} ratio of 3.1 to 1 at the bias voltages of 6 V and a quality factor of 210 at 1 GHz. The increment of the size of PZT actuator reduces the driving voltage and increase C_{max}/C_{min} ratio by increasing the displacement of PZT actuator. However, it reduces the resonant frequency of the RF MEMS tunable capacitor.



(a)

(b)

Figure 5. SEM pictures of the fabricated MEMS tunable capacitor with filp-chip bonded PZT actuator: (a) picture was taken at a PZT actuator side and (b) picture was taken at a glass side

Table 1. Structural parameters of the fabricated RF MEMS tunable capacitors

Geometry parameters	MEMS tunable capacitor in Fig. 1
Length and width of transmission line (μm)	300 x 100
Parallel plate capacitor area (μm^2)	150 x 150
Air gap height (μm)	~ 2.5

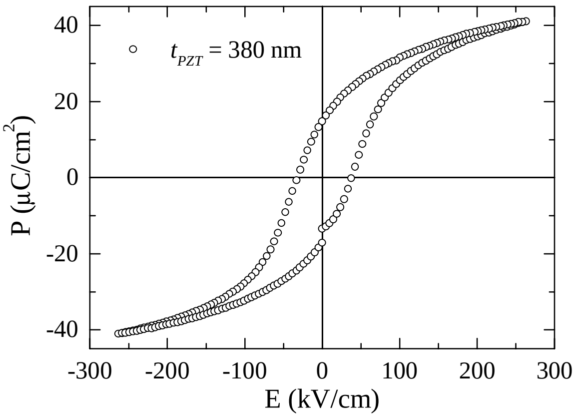
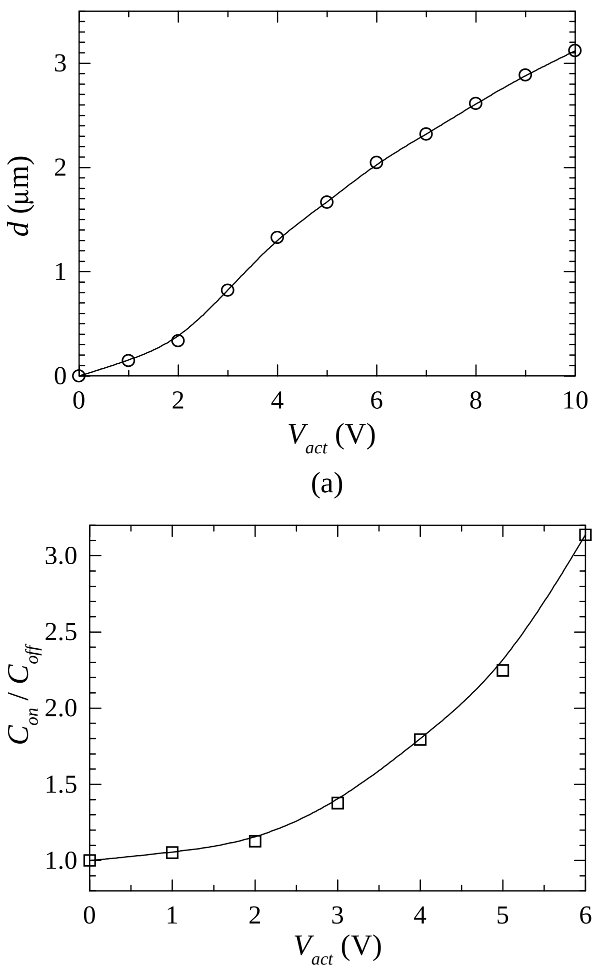


Figure 6. P-E hysteresis curve of the 380 nm-thick PZT unimorph actuator before release etching



(b)

Figure 7. Displacement of the electrode of the integrated PZT actuator in (a) and capacitance change of the fabricated tunable capacitor in (b) with respect to the applied voltage.

CONCLUSIONS

RF MEMS tunable capacitors with low operation voltages, high quality factor, and large tuning ratio have been fabricated by utilizing micromachined piezoelectric actuators. These tunable capacitors can be applied in miniaturized tunable RF filters, low noise parametric amplifiers, harmonic frequency generators, low phase noise voltage contrlled oscillators, and matching circuits.

ACKNOWLEDGMENT

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