Extended Abstracts of the 2006 International Conference on Solid State Devices and Materials, Yokohama, 2006, pp. 906-907

C-10-3

# High-*Q* Piezoelectrically Actuated RF MEMS Tunable Capacitor

Michihiko Nishigaki[1], Toshihiko Nagano[1], Takashi Miyazaki[1], Takashi Kawakubo[2], and Kazuhiko Itaya[1]

[1]Advanced Electron Devices Laboratory, Corporate Research & Development Center, Toshiba Corporation
[2]Toshiba Research Consulting Corporation
1, Komukai-Toshiba-cho, Saiwai-ku, Kawasaki, 212-8582, Japan
Phone: +81-44-549-2432, Fax: +81-44-520-1501, E-mail: michihiko.nishigaki@toshiba.co.jp

## 1. Introduction

Recently, the number of RF components in mobile communication equipments such as multi-band cellular phone has increased. Consequently, the ability for widening to tune frequency ranges in RF circuits is important. One such method is using a tunable capacitor. Notably, a tunable capacitor fabricated using MEMS technology has a wide tuning range and high quality factor (*Q* factor) in principle [1].

The actuation mechanism of a MEMS tunable capacitor is classified into several types: electrostatic, electromagnetic, electrothermal and piezoelectric. Among these types, electrostatic tunable capacitor requires a relatively high actuation voltage. Electromagnetic and electrothermal tunable capacitors consume much more power, yielding it unsuitable for use in cellular phones. Piezoelectric tunable capacitor operates at low actuation voltage and consumes low power. These characteristics are suitable for use in cellular phone applications [2,3].

In this study, the tunable capacitors having piezoelectric bimorph actuators consist of AlN and Al as piezoelectric and electrode material which are compatible with conventional CMOS process. The tunable capacitor was formed on a quartz substrate to increase resistance and decrease parasitic capacitance.

Details of the electrical properties of the piezoelectrically actuated RF MEMS tunable capacitor are discussed.

## 2. Structure of RF MEMS tunable capacitor

A typical SEM image of fabricated piezoelectrically actuated RF MEMS tunable capacitor is shown in Fig. 1. A cross-sectional schematic view along the a-a' line in Fig. 1 is shown in Fig. 2. The actuator fabricated on a quartz substrate has the bimorph structure, which is a sandwich structure composed of two layers of AlN piezoelectric material between three layers of Al electrodes. One end of the actuator is supported by the substrate and the other end of it is suspended.

The actuator is driven by the inverse piezoelectric effect of two piezoelectric layers, in which opposite electric fields are applied. Lastly, a fixed electrode is below the tip of the actuator. As a result, tunable capacitor is formed between the fixed and movable electrodes.

Here, the actuator is a folded structure with the forward and backward beam canceling the curling induced by residual stress of each layer [3]. Variations of the folded structure (FF-Type, FB-Type, and FW-Type) are shown in Fig. 3, and these actuation mechanisms are summarized in Table I.

The signal path is also shown in Fig. 1. The input signal enters the probing pad, and passes through the fixed electrode. Then it passes through the movable electrode of the actuator, and reaches the GND probing pad via the tunable capacitor.

## 3. Characteristics of RF MEMS tunable capacitor

The observed $S_{11}$ parameter in FW-Type RF MEMS tunable capacitor is shown in Fig. 4. Capacitance increases with drive voltage of the tunable capacitor, as the movable electrode approaches the fixed electrode. The electrical characteristics of the tunable capacitor are dominated by impedance between the probing pads when the tunable capacitor is high impedance. The path resistance is then determined by the resistance between the probing pads through the substrate. On the other hand, for low impedance of the tunable capacitor, the signal passes through the movable electrode of the actuator yielding a path resistance of 6 Ω. (see Fig. 4.)

The capacitance and *Q* factor dependence on the drive voltage observed at 2 GHz is shown in Fig. 5(a) and (b) for each folded structure. In Fig. 5(a), although, as mentioned before, the capacitance increases with increasing the drive voltage and saturates when the movable electrode contacts the fixed electrode side. This voltage is defined as the saturation voltage in our study. The saturation voltage of the FW-Type is smaller than other ones due to the actuation of the both forward and backward beams.

The tuning ratio of the capacitance up to the saturation voltage was 7.3 - 9.8 for each structure. In Fig. 5(b), the *Q* factor was approximately 30 - 50 at the saturated capacitance. Because impedance between probing pads is extremely high, the *Q* factor is likely much higher than reported here (as high as several hundreds).

Table II summarizes and compares the characteristics and figure of merit (FOM) of the fabricated tunable capacitors and reported ones from the literature [4,5]. Here the FOM is defined by eq. (1).

$$\mathrm{FOM} = \frac{\text{tuning ratio}}{|\text{saturation voltage}|} \times \text{minimum } Q \text{ value} \qquad (1)$$

As shown in this table, the FOM of this study exceeds those of previous reports.

## 4. Conclusion

Piezoelectrically actuated RF MEMS tunable capacitors have been fabricated on a quartz substrate to increase resistance and decrease capacitance. These tunable capacitors have realized a wide tuning range, low actuation voltage and high $Q$ factor.

## References


[1] Th G S M Rijks *et al., J. Micromech. Microeng.* **16** (2006) 601.

[2] Gabriel M. Rebeiz, *RF MEMS: Theory, Design, and Technology* John Wiley & Sons New York (2003).

[3] T. Kawakubo *et al.*, *Proc. IEEE 2005 IEDM* (2005) 303.

[4] D. Young *et al.*, *in Proc. Custom Integrated Circuit Conf.* (1997) 431.

[5] Borwick R. L. *et al.*, *Proc of 15th IEEE Int. Micro Electro Mechanical Systems Conf* (2002) 669.


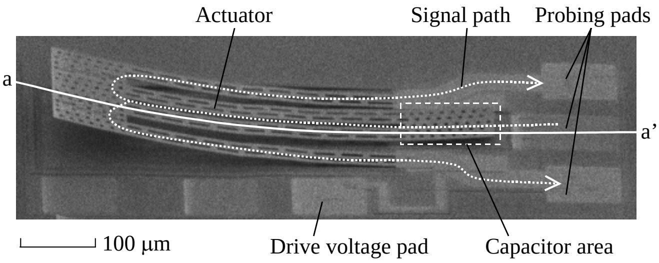


Fig. 1 SEM image of tunable capacitor and signal path.

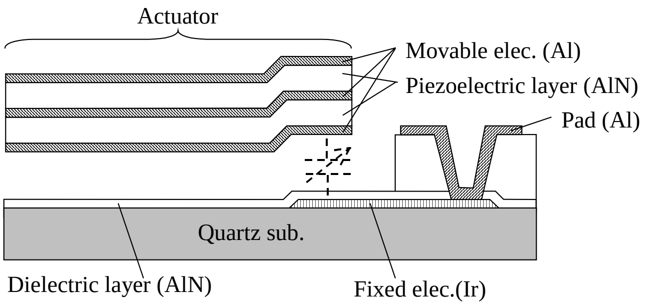


Fig. 2 Cross-section schematic view of a-a’ line in Fig. 1.

Table I Actuation mechanism of folded structures.

| Actuation type | Actuation mechanism |
|---|---|
| FF-Type | Only forward beams are actuated |
| FB-Type | Only the backward beam is actuated |
| FW-Type | Forward beams and the backward beam are actuated |

Table II Characteristic of fabricated tunable capacitors and comparison with other organizations.

| Type | Saturation voltage | Tuning ratio | Minimum $Q$ factor | FOM |
|---|---|---|---|---|
| FF-Type | 10.4 V | 7.3 | 50 | 35 |
| FB-Type | 10.4 V | 9.8 | 31 | 29 |
| FW-Type | 5.7 V | 9.8 | 39 | 67 |
| UCB [4] | 5.5 V | 1.2 | 52 | 6 |
| Rockwell [5] | 8.0 V | 8.4 | 2 | 2 |

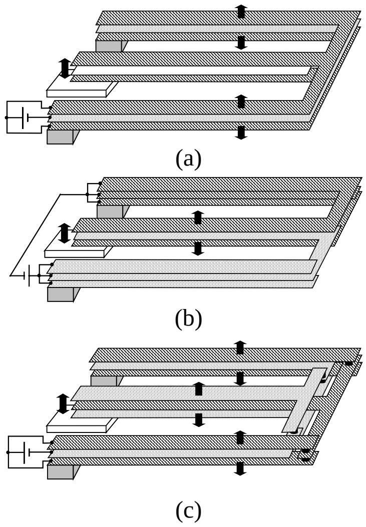


Fig. 3 Variation of the electrode arrangement of the folded structure. (a) FF-Type, (b) FB-Type, (c) FW-Type.

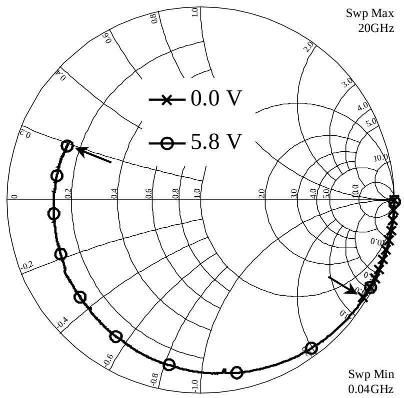


Fig. 4 $S_{11}$ parameters of FW-Type tunable capacitor.

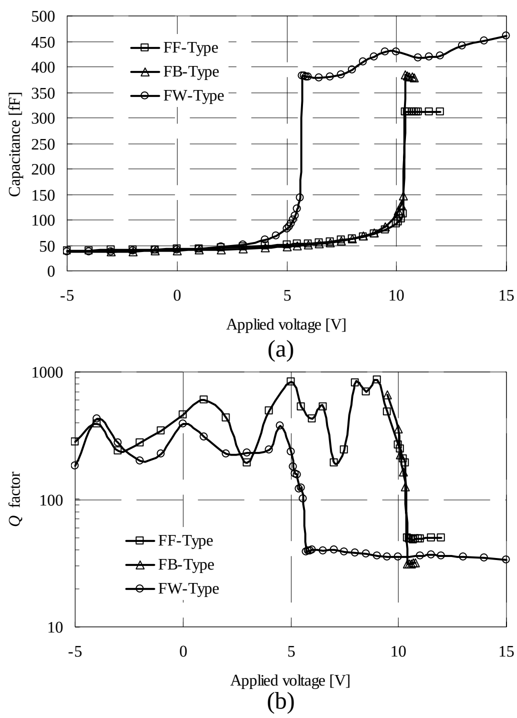


Fig. 5 Applied voltage dependence of (a) capacitance and (b) $Q$ factor in three folded structures.