A Sticking-Free and High-Quality Factor MEMS Variable Capacitor with Metal-Insulator-Metal Dots as Dielectric Layer

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***Abstract* — This paper describes a novel design of a MEMS variable capacitor with high operating reliability and high quality factor. Metal-Insulator-Metal (MIM) dots between a fixed electrode and a movable electrode in a variable capacitor is proposed. A Fabricated MEMS capacitor was operated one billion or more times without sticking. It demonstrated a high quality factor of 200 at 0.5 pF. It was experimentally confirmed that MIM dots effectively achieve a sticking-free and high-quality-factor MEMS variable capacitor.**

***Index Terms* — MEMS, capacitor, RF, MIM, sticking, tunable.**

I. Introduction

Due to multiple RF communication systems providing services, a multi-band RF frontend for future cellular phones needs to be developed. Different numbers of filters, amplifiers, and antennas have to be installed corresponding with each RF band. However, the limited size of cellular phones allows only a small number of these to be installed. Because of this, filters, amplifiers, antennas need tunable and deal with each band flexibly [1]-[5].

A valuable impedance device is necessary to achieve tunable RF frontend. The valuable capacitor of a varactor diode has problems of low linearity and low-quality factor. As a solution to these problems, an MEMS valuable capacitor is attracting increasing attention.

An MEMS valuable capacitor is constructed with a fixed electrode and a movable electrode facing each other. By applying voltage between two electrodes, electro static traction force decreases the distance and increases capacitance between the two electrodes. Thin film of dielectric material on the fixed electrode prevents two electrodes from electrical contact and provides larger capacitance within a limited area. The on state of contacting a movable electrode and dielectric film provides maximum capacitance, while the off state of a movable electrode provides minimum capacitance. Repeatedly changing between on/off states causes electric charge to accumulate on the surface of dielectric film. Enormous accumulation of electric charge causes static traction force and results in movable electrodes and dielectric film sticking [6].

We have thus developed a sticking-free MEMS valuable capacitor with plenty of metal coated dielectric dots on a fixed electrode. This paper reports details of dot dielectric and a construction of an entire MEMS valuable capacitor and a measured performance of the fabricated device.

II. MIM Dots

We propose Metal Insulator Metal (MIM) dots to achieve a sticking-free, high-quality-factor MEMS valuable capacitor. The concept of MIM dots is shown in Fig. 1. The dielectric surface is coated with metal to prevent it from local charges. The dielectric is divided into small dots to make charges tiny and prevent discharges from making metal surface and movable electrodes weld and stick when they make contact. Circuit model of MIM dots is shown in Fig. 2.

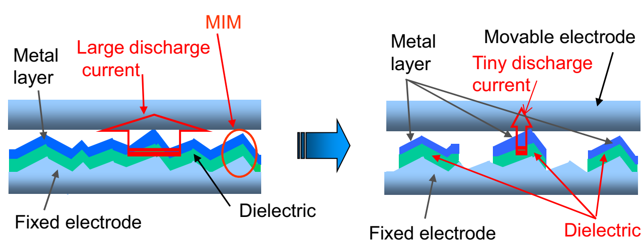

Fig. 1. Concept of Metal Insulator Metal (MIM) dot structure. (a) Metal coating on dielectric. (b) Dielectric divided into tiny dots to prevent them from welding.

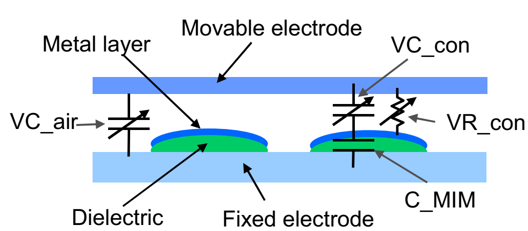

Fig. 2. MIM dot circuit model.

VC_air: Capacitance between fixed electrode and movable electrode.

C_MIM: Capacitance between fixed electrode and metal thin film on surface of dielectric dot.

VC_con: Capacitance between metal thin film on surface of dielectric dot and movable electrode.

VR_con: Contact resistance of metal thin film on surface of dielectric dot and movable electrode.

A 1-bit capacitance value is the series composite of capacitance value between the movable and fixed electrodes and value of the fixed capacitor constructed in MEMS valuable capacitor described later. Equivalent circuit of the 1-bit capacitor is constructed as shown in Fig. 3.

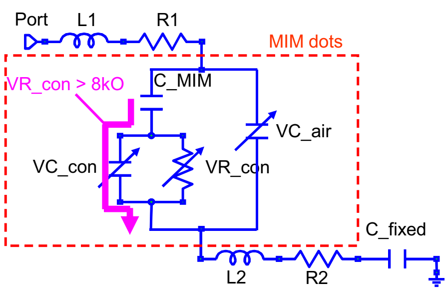

Fig. 3. 1bit capacitor equivalent circuit.

C_fixed: Fixed capacitor

L1, R1, L2, R2: Residual inductances and resistances.

Simulation is done with parameters of VR_con and result is shown in Fig. 4. As shown in red arrow in Fig. 3. the large value of VR_con results in impedance being defined as the series composite capacitance of C_MIM and VC_con. Consequently, a high Q value and a smaller 1-bit capacitance value are expected. In contrast, the small value of VR_con results in impedance being defined as the series composite of C_MIM and VR_con. Consequently, a low Q value and a larger 1-bit capacitance value are expected.

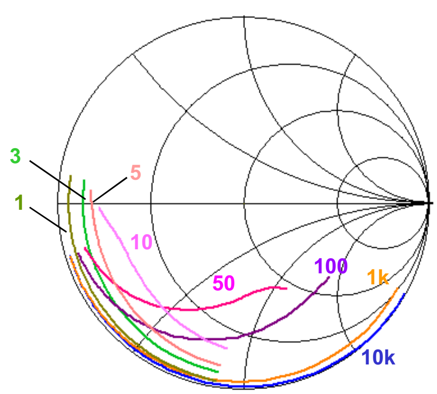

Fig. 4. Simulation results of 1 bit capacitor equivalent circuit with parameter of contact resistance (0.5-8GHz).

The power requirement of a MEMS valuable capacitor is more than 1 W for application of a power amplifier circuit and antenna matching circuit. The switching cycle life reliability requirement is more than 10 billion cycles. These requirements make it challenging to maintain low contact resistance for VR_con (MEMS metal to metal contact switch). Thus, we chose VR_con to maintain high contact resistance and VC_con to maintain large contact capacitance, and we selected aluminum, which is easily oxidized for metal thin film on dielectric dots and movable electrodes.

III. DESIGN OF MEMS VALUABLE CAPACITOR

We designed a 3-bit MEMS valuable capacitor using MIM dots. Fig. 5 shows the entire chip structure, and Fig. 6 shows a cross sectional view of A-B in Fig. 5. A fixed aluminum electrode is patterned on the substrate, and both ends of the fixed electrode are RF input and RF output. Aluminum coated dielectric dots are placed on the fixed electrode. Consequently, MIM dots are constructed with a fixed electrode, thin film dielectric, and metal coating. A movable electrode is placed above the MIM dots. Both ends of the movable electrode are connected to the ground on a substrate via a fixed capacitor. The movable electrode is connected to the driving pad via thin-film resister RF block to stop RF signal leaking from the signal line to the driving circuit. By applying a driving voltage between signal line and driving pad, electro static traction force decreases the distance and increases capacitance between the two electrodes.

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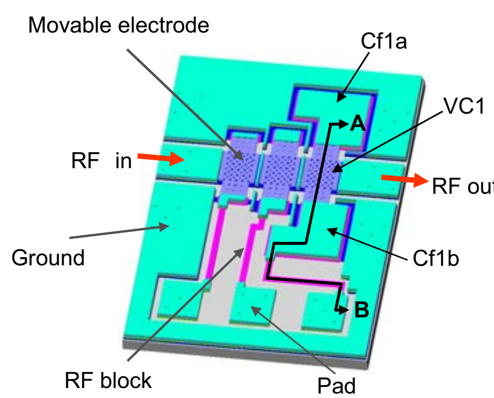

Fig. 5. Structure of valuable MEMS capacitor

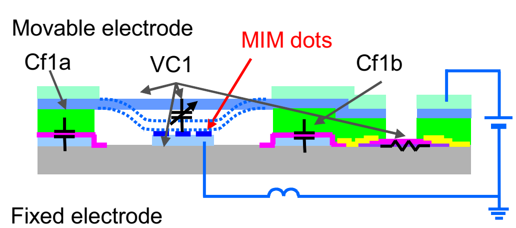

Fig. 6. A-B cross section of A-B in fig. 5.

The 1-bit capacitance value is the series composite of capacitance value between the movable and fixed electrodes and value of the fixed capacitor. The capacitance value of the 3-bit MEMS valuable capacitor is the total capacitance of the parallel circuits of each 1 bit. The capacitance value of each fixed capacitor is adjusted to provide eight-level capacitance value.

IV. RESULTS AND PERFORMANCE

Configuration of the fabricated MEMS capacitor is shown in Fig. 7 (a). The MEMS capacitor achieved a compact size of 1.2 mm × 1.6 mm × 0.3 mm. It is fabricated on a glass substrate. Thin-film electrodes, thin-film dielectric, thin-film resister for RF blocking, and sacrifice layer are formed using thin-film deposition and photolithography. The sacrifice layer is etched last to release movable electrode. Fig. 7 (b) is an enlarged view of the movable electrode. Fig. 7 (c) shows a close up view of MIM dots taken after the upper electrode had been removed. It is observed that MIM dots of 3 µm radius and 0.2 µm height are orderly arranged under the movable electrode with square halls for sacrifice layer etching.

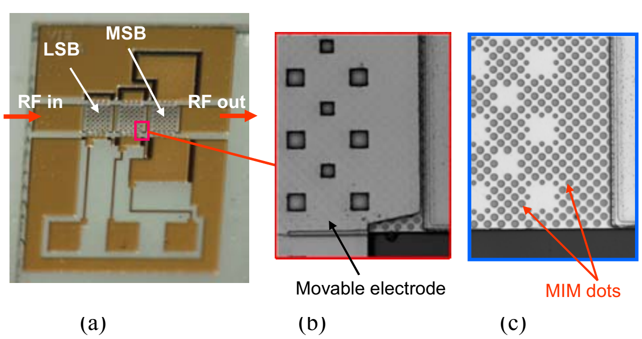

Fig. 7. Fabricated MEMS valuable capacitor. (a) Whole chip view. (b) Close up view of movable electrode. (c) Close up view of MIM dots after movable electrode had been removed.

Fig. 8 shows a measured return characteristic Smith chart of the fabricated MEMS capacitor at minimum capacitance of state C000 and at maximum capacitance of state C111 from 0.5 GHz to 8GHz. Measured data are on the outskirts of the Smith chart, showing signal loss to be very small. Capacitance value and quality factor at 2 GHz are 0.5 pF and 200 in state C000 and 4.8 pF and 30 in state C111, respectively. A high-power input signal on a fixed electrode induces actuation of the movable electrode and degrades linearity. To prevent self-actuation caused by 1 W, which is for amplifier and antenna application, the driving voltage for movable electrode is set to 15 V. A simple DC/DC converter generates more than 15 V in a battery operated system.

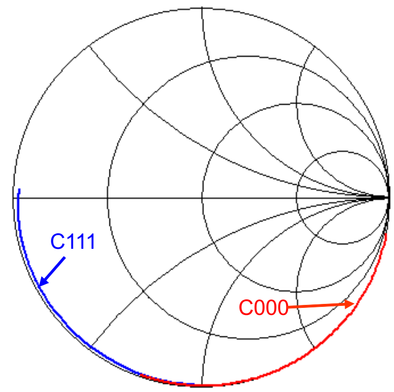

Fig. 8. Measured return characteristic of fabricated MEMS capacitor at minimum capacitance state C000 and maximum state C111 (0.5-8GHz).

The measured transmission characteristic of the fabricated MEMS capacitor in eight capacitance value states is shown in Fig. 9. As capacitance increases in each eight capacitance states, attenuation increases in eight different levels. Because RF signal pattern is carefully designed, no residual resonation is observed in Fig. 9.

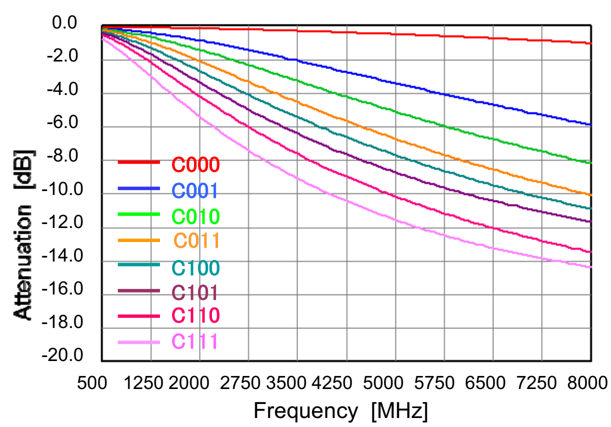

Fig. 9. Transmission characteristic of fabricated MEMS capacitor. Eight different curves of different states.

Sticking-free performance is evaluated in parameters of numbers of switching cycles. The driving signal for the movable electrode is applying reverse voltage in turn with short reverse voltage just before turn off, as shown in Fig. 10. The transmission characteristic is measured in parameters of numbers of switching cycles by applying RF 1 mW to RF input. Sticking occurs at 2×10^7 switching cycles in MEMS capacitor without metal coating on the surface of the dielectric dot indicated as conventional in Fig. 11. In contrast, no sticking occurs until 10^9 switching cycles in the MEMS capacitor with MIM dots.

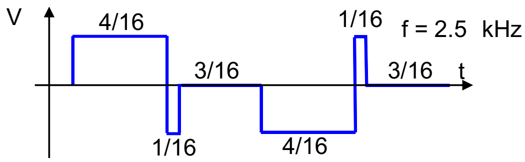

Fig. 10. Driving wave form for switching cycle test.

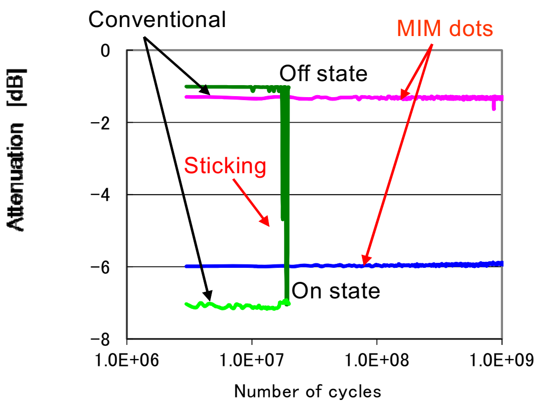

Fig. 11. Switching cycle test result of MIM dot MEMS valuable capacitor and conventional one.

Next, sticking-free performance after 100 hours of applying driving voltage was evaluated. Transmission characteristics were measured both on state at A, B and off state at C, D, as shown in Fig. 12. Result of this evaluation confirms that no sticking was observed. These confirm that MIM dots free MEMS capacitor from sticking.

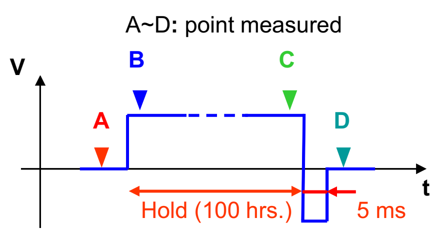

Fig. 12. Driving wave form and measuring point for sticking test.

RF power-proof performance of the fabricated variable capacitor was also evaluated in the Inter Modulation 3 (IM3) method. The valuable capacitor is set maximum capacitance of state C111, and various-power two-tone signal of CW 2.5 GHz ± 5 kHz is applied to RF-in port. RF-out signal spectrum is observed as shown in Fig. 13. Measured IM3 is more than 53 dB, which is the same as a ceramic capacitor even when 30dB (1W) power is applied. These results indicate that a fabricated MEMS variable capacitor has sufficient power-proof performance for mobile phone application.

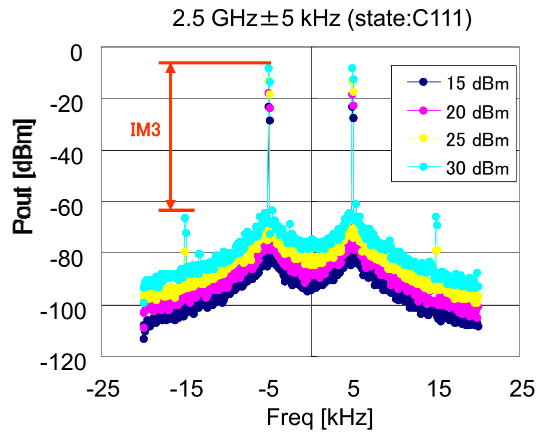

Fig. 13. RF power-proof performance of the fabricated variable capacitor in IM3 method.

V. Conclusion

We proposed a novel design of a MEMS variable capacitor with plenty of Metal-Insulator-Metal (MIM) dots between a fixed electrode and a movable electrode. The fabricated MEMS capacitor achieved a high-quality factor of 200 at 0.5 pF. Moreover, it achieved a high reliability of one billion or more operations without sticking. It was confirmed that MIM dots effectively achieve a high-performance and sticking-free MEMS capacitor.

Acknowledgements

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