Two Movable Plate Nitride Loaded MEMS Variable Capacitor

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***Abstract* – A MEMS variable capacitor having two movable plates loaded with a Nitride layer is proposed. A trench in the silicon substrate underneath the capacitor is used to decrease the parasitic capacitance. The use of an insulation dielectric layer on the bottom plate of the MEMS capacitor increases the capacitor's tuning range and eliminates sticktion. The tuning range was measured and found to be 280% at 1 GHz. The achievable tuning range far exceeds that of the traditional parallel plate MEMS variable capacitors. The proposed MEMS variable capacitor is built using the MetalMUMPs process.**

I- Introduction

MEMS variable capacitors have the potential to replace conventional varactor diodes in many applications such as phase shifters, oscillators and tunable filters. While there are various configurations to realize MEMS variable capacitors, the parallel plate configuration exhibits a relatively high Q value and is very convenient to build due to simplicity of fabrication [1]-[2]. Such type of MEMS capacitors, however have a maximum theoretical tuning range of 50% due to the collapse of the capacitor structure as the voltage is increased beyond the pull-in voltage [1].

A MEMS parallel plate capacitor with a wider tuning range was proposed in [2] by making the actuation electrodes spaced differently from the capacitor plates. Such approach has yielded a theoretical 100% tuning range. However in practice, the capacitor demonstrated a tuning range of only 69.8%. There has been therefore a need to develop MEMS variable capacitors with a much wider tuning range.

In this paper, we introduce the Two Movable Plate Nitride Loaded MEMS Variable Capacitor. The proposed configuration has three unique features that made it possible to achieve a superior performance in comparison with traditional parallel plate MEMS capacitors. These features are: the use of two movable plates, the use of a nitride layer between the two plates and the use of a trench underneath the capacitor's bottom plate. The capacitor is built using the MetalMUMPs process, which has been recently released by Cronos JDS [3]-[4] for commercial use. We present in this paper theoretical and measured results that verify the validity of the proposed approach.

II- Proposed MEMS Capacitor Design

Fig. 1 illustrates a schematic diagram of the proposed capacitor. It consists of two movable plates with an insulation dielectric layer on top of the bottom plate. With the two plates being flexible, makes it possible for the two plates to attract each other and decrease the maximum distance before the pull-in voltage occurs. Moreover, the capacitor demonstrated an extended tuning range even after the two plates touched each other.

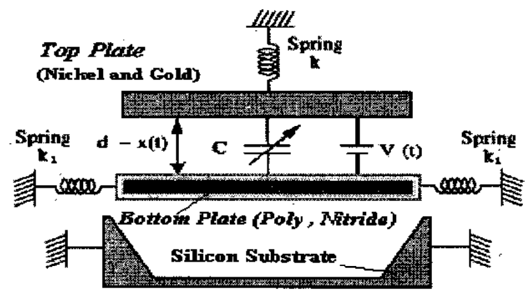

Fig. 1. A schematic diagram of the proposed capacitor

The capacitor is constructed using two structural layers, three sacrificial layers, and two insulating layers of Nitride. The top plate is fabricated from nickel with a thickness of 26 μm covered by a gold layer of thickness 2 μm, while the bottom plate is made of polysilicon covered by a Nitride layer of a thickness of 0.35 μm.

Fig. 2 illustrates the different layers used to construct the capacitor using the MetalMUMPs process [3]. The 2D layers given in this figure are generated using CoventorWare [5]. First, a layer of 0.5-micron oxide is deposited and patterned as illustrated in Figs 2(a)-2(b). This oxide layer outlines the area that will be used to etch a trench in the silicon substrate. The first Nitride layer of 0.35-micron thickness is deposited and pattered as illustrated in Fig 2(c). This Nitride layer forms the bottom cover of the polysilicon layer and is used as a part of the capacitor's bottom plate. On top of the first Nitride layer, a 0.7-micron layer of polysilicon is deposited and patterned

0-7803-7695-1/03/$17.00 © 2003 IEEE

to form the bottom conductive plate of the variable capacitor as shown in Fig. 2(d). The last step in building the bottom plate of the variable capacitor is to deposit the second Nitride layer on top of the polysilicon layer to form the isolating area that prevents any electrical contact between the two plates. Thus, eliminating the sticktion problem.

A 1.1-micron layer of second oxide is then deposited as illustrated in Fig. 2(f). The second oxide layer is etched so that the metal layer is anchored on the Nitride and a physical contact between the bottom electrode (Polysilicon) and the two outer pads is ensured. The last layer is the metal layer, which is formed of a 25μm of Nickel with 2μm of gold on top of the Nickel layer.

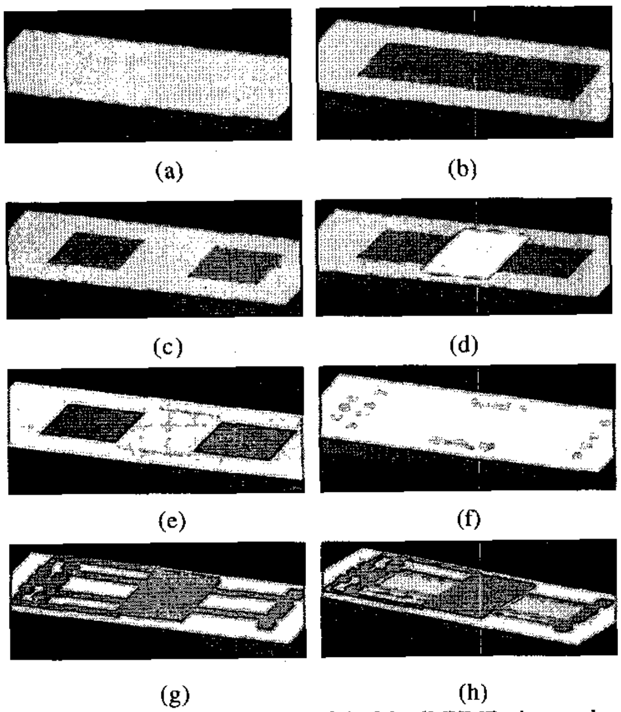

Fig. 2. The fabrication process of the MetalMUMPs that used to build the proposed variable capacitor.

The last step is to etch out the sacrificial layers as well as to etch a trench in the silicon substrate. The trench etch of the substrate is determined by the first oxide layer. Once the first oxide is etched away by opening holes through the Nitride layer, the solvent will etch the isolation layer underneath. The silicon substrate is then etched to form a trench of a depth of 25μm. The total depth from the bottom plate of the variable capacitor is 27.5 μm. Fig. 3 shows the top and cross section views of the proposed MEMS variable capacitor.

In order to get a reasonable value for the beams storing forces (K factor) that suspend the heavy Nickel top plate, the pull in voltage was chosen to be 24 volts. A T-type suspension was used to design the anchors [1]. The calculated K value was found to be 344 N/m for each beam, leading to a beam length of 610 μm. The Young's modulus of Nickel is assumed to be 202 Gpa.

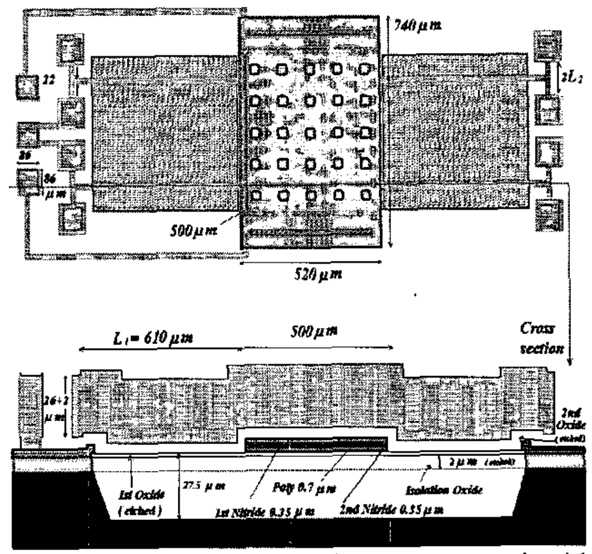

Fig. 3. The top and cross section views of the proposed variable capacitor.

III HFSS© Simulation and Measured Results

The variable capacitor was first built in CoventorWare [5] and then transferred to HFSS for RF simulation.

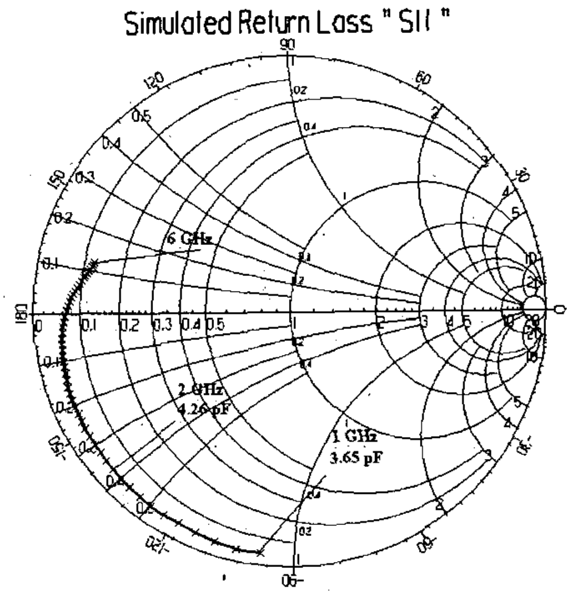

Fig. 4 Simulated Return Loss on Smith chart

The S_{11} response on Smith chart was obtained over a frequency range from 1 GHz up to 6 GHz as illustrated in Fig. 4.

The HFSS simulation results show that the capacitance at 1 GHz is 3.65 pF while the electrostatic theoretical value ($\varepsilon A/x$) is 1.92 pF. The difference between the theoretical capacitance and the simulated RF capacitance, when zero DC voltage is applied, is due to the parasitic capacitances coming from the RF pads and the coupling between the top plate and the silicon substrate. Fig. 5 shows the HFSS simulation of the capcitance assuming different gap values between the two plates. These simulations were conducted using gaps of 1.45, 0.95, 0.79, 0.65 and 0.55 µm including the 0.35 µm Nitride layer.

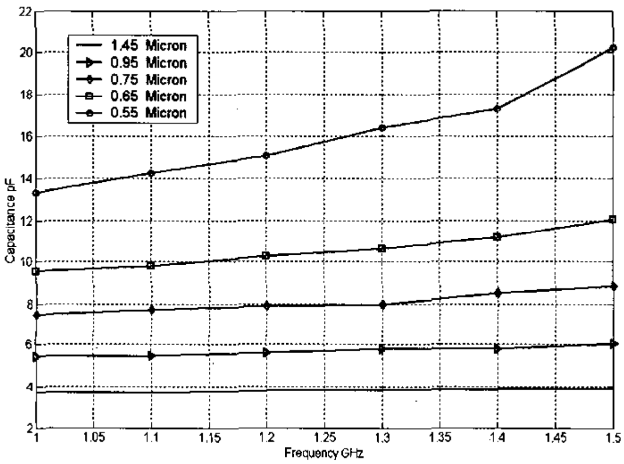

Fig. 5 Simulated capacitance vs. frequency on deferent displacements.

The measurements were done over the same frequency range of 1-6 GHz when a zero DC voltage is applied to the capacitor. The measured S_{11} response on Smith Chart at DC = 0 Volts is given in Fig 6. At 1 GHz the measured capacitance value was found to be 4.6 pF. The difference between the HFSS results and the experimental results is attributed to the deformation of the top plate. Figure 7 shows a SEM picture of the fabricated capacitor. A slight deformation is observed. The gravity effect of the relatively heavy 26 µm thick Nickel top plate, which is 67.6 µg, causes initial deformation. The initial displacement of the top plate can be calculated using the following equation [1]:

$$x_g = \frac{m * g}{k}$$

Where x_g is the initial displacement after releasing the variable capacitor, m is the mass of the plate, and g is the acceleration due to gravity (g = 9.80665 m/s^2). The calculated initial displacement is 0.5 µm. This reduces the spacing between the top and the bottom plate to 0.95 µm including the Nitride layer. By taking such deformation into consideration in the HFSS simulation, the zero dc bias capacitance was found to be 5.4 pF. The difference between the measured and the simulated capacitance, with zero DC bias, is due to the residual stress, which was ignored and the accuracy of the electrical specifications of the materials used in the HFSS simulations.

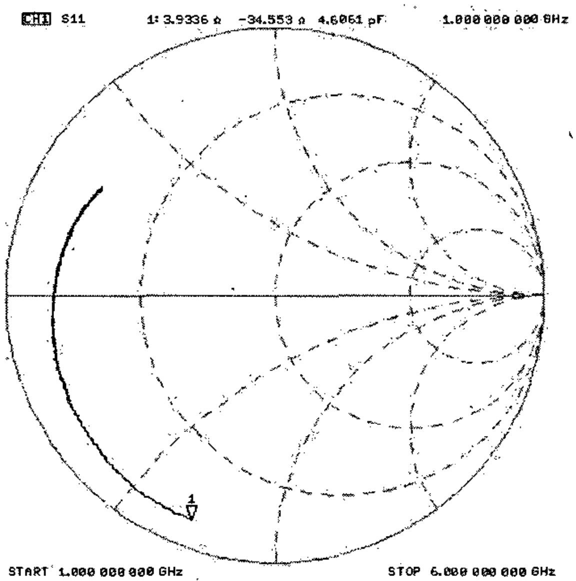

Fig. 6. Measured Return Loss on Smith Chart

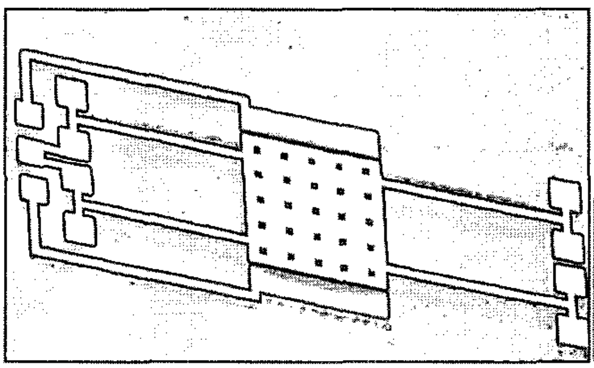

Fig.7. An SEM picture of the fabricated variable capacitor.

A DC voltage sweep from 0 V up to 39 V was applied to the variable capacitor. Figure 8 illustrates the measured capacitance value for DC voltage steps over the frequency range of 1 - 1.5 GHz. At 1 GHz, the achievable tuning of the proposed capacitor is found to be 280% while the variable capacitor reached higher tuning range of 495% at 1.5 GHz. The tuning response at 1 GHz is plotted in Fig. 9. The two plates came in contact with each other (with the Nitride layer in between) at around 21.2 volt. It is observed however, that the capacitance still increases with applied DC voltages beyond 21.2 volt. A zero dc current was observed even at 39 volt. It is worth mentioning that the capacitor demonstrated the same performance when test is repeated several times.

Before the collapse of the capacitor's plates, it is obvious from Fig. 9 that the capacitor demonstrated a tuning range of 117% at 1GHz. The existence of a second movable plate, which is the bottom plate in this case, provided an elastic plate (membrane) that can easily react to the electrostatic forces. Thus, adding a movable bottom plate has extended the 50% tuning range limit of the traditional parallel plate MEMS capacitor [1]. Above 21.2 volt the top plate and the bottom plate relaxed on each other due to the increase of the electrostatic force, which was induced by increasing the DC bias voltage. The tuning range of the proposed variable capacitor increased till it reached 280% at 1GHz for a DC bias voltage of 39 volt.

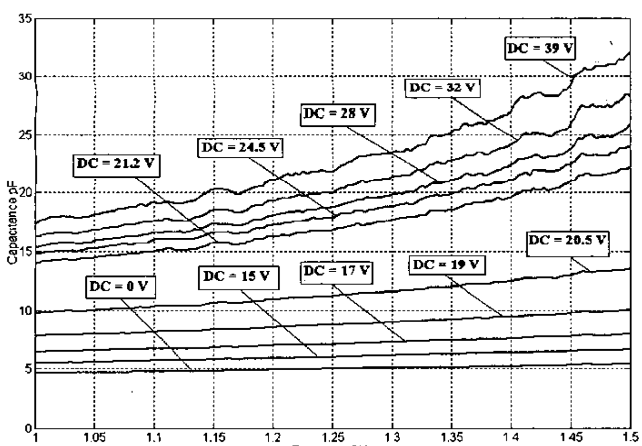

Figure 8. Measured capacitance vs. frequency at different DC voltages:

VI. Conclusion

A Two Movable Plate Nitride Loaded MEMS Variable Capacitor has been introduced in this paper. In comparison with conventional parallel MEMS capacitors, the proposed capacitor exhibits three unique features, namely: the movable two plates, the Nitride layer between the two plates and the trench underneath the capacitor. While the tuning range of traditional parallel plate MEMS capacitors is limited to 50%, the measured tuning range of the proposed MEMS capacitor has been found to be 280%, i.e. more than 5 times improvement in tuning range has been achieved by the proposed capacitor.

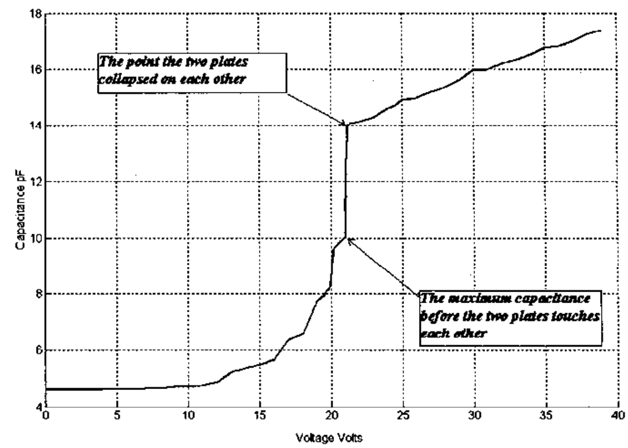

Figure 9. Measured tuning characteristics of the proposed capacitor at 1 GHz.

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