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High-Q Continuously Tunable Zipping Varactors with Large Tuning Range

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Introduction

The design, simulation and on-going fabrication of a continuously variable microelectromechanical (MEMS) capacitor is presented in this paper. In recent years, MEMS varactors have emerged as viable alternatives to semiconductor varactors, achieving higher quality factors (*Q*) and larger tuning ranges [1, 2]. *Q* values in the region of 100 and capacitance ratios (C_r, defined as the ratio of maximum capacitance over minimum capacitance) greater than 10 can be obtained in MEMS varactors. Conversely, semiconductor varactor *Q* values are typically at the low tens and their capacitance ratios are around 1.3 or less. However, current MEMS variable capacitor designs often suffer from either poor linearity in capacitance versus actuation voltage, or have not achieved their true potential of having large tuning ranges. By employing a novel zipping design (see Figure 1), it is possible to achieve good tuning control across the capacitance range and at the same time obtain a large capacitance ratio. High *Q* values can be achieved by using gold as the main material for the electrodes, keeping the series resistance low. While relatively large tuning ranges are possible using silicon dioxide (SiO_2) as the dielectric ($C_r > 10$), using a high-permittivity material such as lead zirconate titanate (PZT) allows a very large tuning range ($C_r > 60$) to be obtained within smaller physical dimensions. This is particularly important for mobile handset applications, where increasing functionality such as GPS, wireless LAN, Bluetooth and more recently mobile TV (DVB-H) must be fitted within a finite handset volume. Typically, MEMS varactors with very large tuning ranges are achieved by biasing an array of capacitive switches connected in parallel [3]. While this method is highly scalable, its main disadvantage is the large physical area required for the discrete devices as well as the circuit connections. A high-*Q* zipping varactor incorporating a high-permittivity dielectric has the potential to meet both tunability and size requirements for mobile applications.

Electro-Mechanical Simulation

The proposed varactor has a movable top electrode which is actuated by applying a DC bias voltage between the top and bottom electrodes. Unlike electrostatic switches or actuators, where the well-known pull-in instability is used to pull down movable electrode membranes instantaneously, this zipping varactor can be tuned continuously between the minimum and maximum capacitance. Electrostatic pull-in instability is eliminated by shaping the top electrode such that its local stiffness increases axially, and hence increasingly greater voltages are required to zip the capacitor further. It is possible to engineer the shape of the top electrode in order to alter the zipping behaviour. At present, the varactors which are being fabricated have linear top electrode shapes such that the width of the electrode increases linearly from the anchor towards the free end.

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The static electro-mechanical response of several zipping varactor variations has been modelled in ANSYS. Figure 2(a) shows the capacitance versus bias voltage for a device with 300 nm thick SiO_2 dielectric (dielectric constant, $\varepsilon_r = 4.5$). The capacitance can be tuned continuously between 0.2 and 2.3 pF giving a C_r of 11.5. Figure 2(b) shows the modelled results for devices with 500 nm thick $PbZr_{0.3}Ti_{0.7}0_3$ (i.e. PZT 30/70, $\varepsilon_r = 380$) [4]. Two electrode beam thicknesses were modelled and the results indicate that the thinner electrode (0.88 μm) gives lower zipping voltages than the thicker electrode (1.65 μm) due to its lower bending stiffness. In both cases, the capacitance can be tuned continuously between 0.2 and 13.4 pF giving a C_r of 67. The dimensions of the varactor with the SiO_2 dielectric are 300 μm long by 168 μm while the dimensions of the varactors with the PZT dielectric are 200 μm long by 46 μm. Hence, using a high-permittivity dielectric allows a very large capacitance range to be achieved in the varactor within a more compact size.

HFSS Simulation

HFSS simulation results for the varactor with SiO_2 dielectric have been obtained between 1 and 10 GHz. Three varactor states were modelled corresponding to different applied bias voltages, hence different capacitance values. States A, B and C correspond to the varactor being totally unzipped, half-zipped and fully-zipped respectively. The capacitance of the varactor is at its minimum in state A since the dielectric properties are dominated by the relatively large air gap between the varactor electrodes. As the bias voltage is increased, the air gap between the electrodes gradually decreases and the area of contact of the top electrode with the dielectric increases, therefore capacitance increases (states B and C). Figure 3 shows the capacitance and Q factor plots for the modelled frequency range. For states B and C, capacitance increases with frequency while for state A the capacitance remains approximately constant with frequency. The simulation results also indicate that the minimum Q of the varactor at 1 GHz is 94. In the HFSS model, the bottom electrode of the varactor and the coplanar waveguide (CPW) transmission line are 3.5 μm thick gold. The curved top electrode is 1.65 μm thick gold.

Fabrication

At present we are working on the fabrication of the zipping varactors. Figure 4 shows early prototypes of series- and shunt-mounted varactors fabricated on CPW transmission lines. The top electrode is fabricated on carrier dies with a sacrificial layer. Subsequently, the top electrode is aligned with the bottom electrode and CPW transmission line, and then thermosonically bonded. Curvature in the top electrode is achieved using a bi-layered design where the top layer is a sputtered film with residual tension. The thicker bottom layer is electroplated gold and is relatively stress-free. When the sacrificial layer is removed, the stress in the top layer curves the top electrode upwards.

Conclusion

The design, simulation and fabrication of high-Q zipping MEMS varactors have been presented. A novel, stable zipping design allows continuous tuning as well as a large tuning range. High quality factors can be obtained using gold electrodes in order to minimise series resistance. A minimum Q of 94 at 1 GHz has been obtained from HFSS simulations in a varactor with SiO_2 dielectric, and this is much higher than semiconductor varactor Q values which are typically in the low tens [1, 5]. By incorporating a high-permittivity dielectric in the varactor, the tuning range can be greatly increased and at the same time, the device size can be reduced. This is a particularly important advantage for applications where size reductions or maintaining the same system size while increasing functionality is required (e.g. mobile handsets). A fabrication process has been developed, including pre-stressed layers to provide the initial curvature, and this has been demonstrated up to and including transfer and bonding of the top electrodes from a carrier wafer. Suitable applications for the zipping varactors include tunable filters, phase shifters, oscillators and tunable matching networks for mobile antennas.

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References

[1] J.J. Yao, "RF MEMS from a device perspective," *Journal of Micromechanics and Microengineering*, vol. 10, no. 4, pp. R9-R38, December 2000.

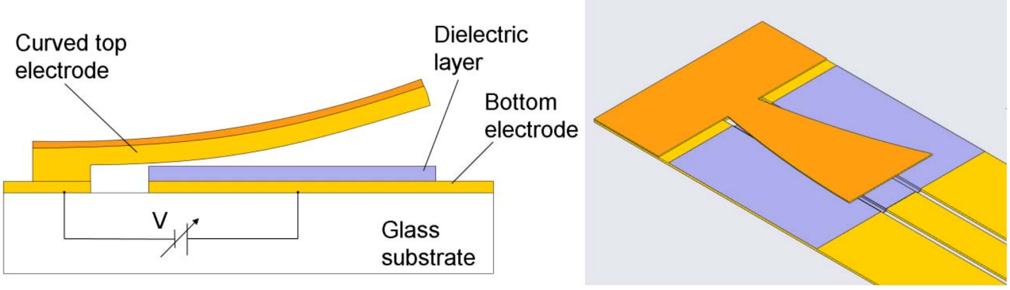
[2] S. Lucyszyn, "Review of radio frequency microelectromechanical systems technology", *IEE proceedings – Science, Measurement and Technology*, vol. 151, pp. 93-103, 2004.

[3] C.L. Goldsmith, A. Malczewski, Z. Yao, S. Chen, J. Ehmke, and D.H. Hinzel. "RF MEMS variable capacitors for tunable filters", *International Journal of RF and Microwave Computer-Aided Engineering*, vol. 9, pp. 362-374, 1999.

[4] R.W. Whatmore, P. Kirby, A. Patel, N.M. Shorrocks, T. Bland and M. Walker, "Ferroelectric thin films for capacitor and sensor applications", *Proc. NATO Advanced Research Workshop on Science and Technology of Electroceramic Thin Films, Villa del Mare, Italy, 20–24 June 1994*, pp 383–397, 1994.

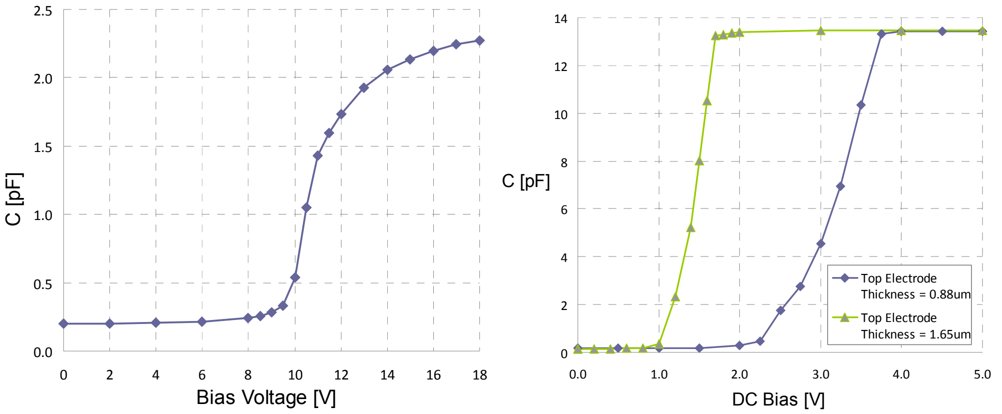
[5] D.J. Young and B.E. Boser, "A micromachine-based RF low-noise voltage-controlled oscillator", *Custom Integrated Circuits Conference, 1997*, Proceedings of the IEEE 1997, pp 431-434, 1997.

Figures



(a) (b)

Figure 1. (a) A schematic of a zipping varactor and (b) a model of a shunt-mounted zipping varactor on coplanar waveguide transmission lines.



(a) (b)

Figure 2. Capacitance versus bias voltage of (a) a varactor with SiO_2 dielectric and (b) varactors with PZT 30/70 dielectric.

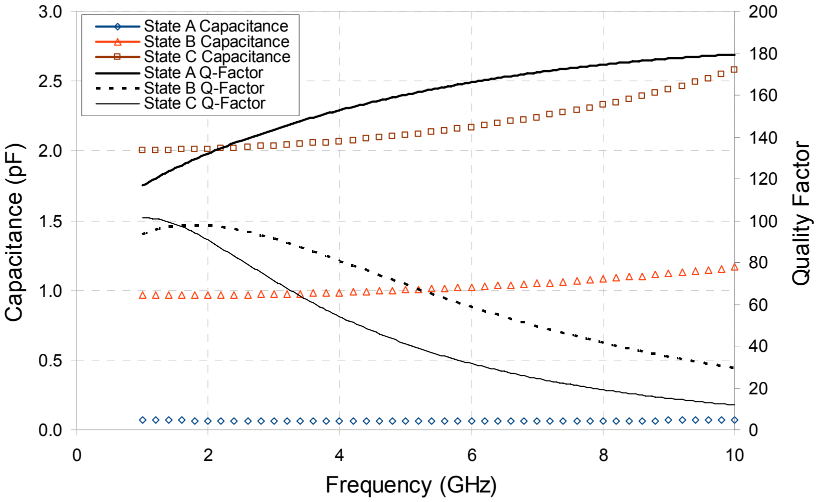
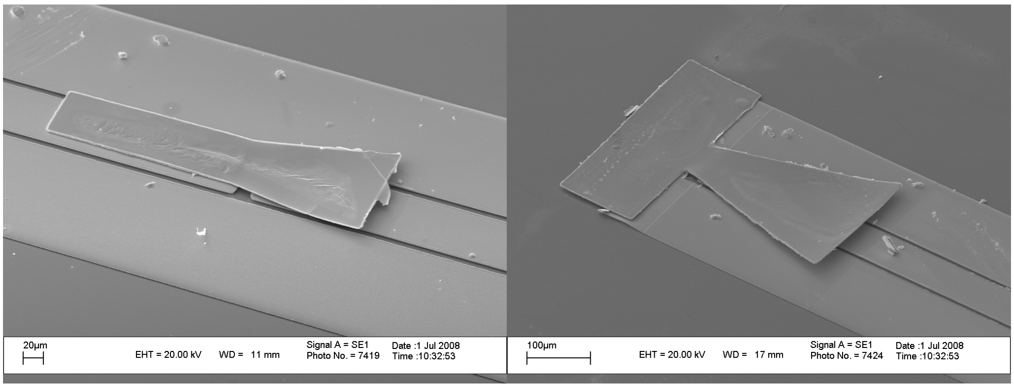


Figure 3. Capacitance and *Q*-factor of a varactor with SiO_2 dielectric from HFSS simulation.



(a) (b)

Figure 4. Early zipping varactor prototypes showing (a) a series-mounted device and (b) a shunt-mounted device.