Design of tunable interdigital capacitor

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Abstract. In this paper, a MetalMUMPs (Multi-User Microelectromechanical System Processes) based tunable interdigitated capacitor is proposed. The tunable interdigitated capacitor consists of thermal actuator, guided beam, and twelve closely coupled parallel fingers lines to produce a nominal capacitance value of about 40.863 fF capable to tune till 326.902 fF. It actuated (tunned) thermally by applying a voltage across the thermal actuator to decreased distance between capacitor rotor and stator then capacitor becomes more capacitive, due to the increase in fringing fields between the fingers. The tunable interdigitated capacitor was fabricated on a standard low-resistivity substrate adopting MetalMUMPs manufacturing process. It was suspended by 25µm from the inner surface of the etched silicon substrate. It typical called microstrip tunable interdigitated capacitor. The capacitor was designed using 2008 CoventorWare software and fabricated based on MetalMUMPs technology. The measured capacitor structure is 494×520 µm². The measured results show good compatible with theoretical one.

1. Introduction
Wireless communication has resulted in a volatile progress of evolving military and consumer applications of microwave, radio frequency (RF), and millimeter wave circuits and systems. The forthcoming trend for ground and personal communication systems is the recognition and application of extremely integrated RF front-end devices having high performance accompanied by low cost, low weight and small size [1]. The filter is among the most imperative applications for Micro-electro-mechanical systems (MEMS). In communications systems, radar and electronic warfare, microwave filters are used as crucial components. However, conventional tunable filters are huge and costly, and at the same time require extensive amounts of power. Currently, there are four kinds of filters: band-stop, low-pass, high-pass and band-pass filters. As compared to other filters, band-pass filters are generally used to attain significant receiver parameters including dynamic range, selectivity and sensitivity [2]. The tunable filter are integral components in radar
and communication system with the capability to substitute switched filter banks [3]. In the elementary single down conversion stage receiver architecture (figure 1), the tunability of RF band-pass filters performs the best. It has the ability to permit desired frequency by eradicating the undesired frequency.

![Figure 1. Architecture of basic single down conversion stage receiver.](image)

In this research study, MetalMUMPs [4] manufacturing process was used to realize a tunable interdigitated capacitor that is a vital component in many filters design. RF-MEMS technology delivers the option of high linearity filtering in volumes and low-loss in comparison to those of integrated circuits [5]. So far, many of the monolithic RF-MEMS tuned filters [6-11] use a tunable capacitor as tuning element. The tuning range of these filters is inadequate due to the any of the two given reasons; 1) frequency range over which the filter elements sustain their coupling relationships and reactances, 2) the tuning range of the MEMS components [8], [9]. Though conventional combline filters with coupled or tapped line exploit capacitor as tuning element and a broad tuning range is provided by the transformer inputs fed from the grounded end of the resonators [12]. Hunter [13] stated that resonators are grounded from one side, and the capacitors are connected to the opposite side of the opposite side of the grounded ends of the resonators, the tuning range can be amplified by feeding the input and output coupled line transformers. In addition, tunable combline filter has fewer RF-MEMS components than other filter designs [7-9] that have capacitors. In this study, the loading capacitance was varied using thermal actuator (chevron) to change capacitor value, rather than using individual fixed capacitors to provide a wider tuning range. For the acceptance of RF-MEMS based components into fielded systems, this type of implementation is indispensable.

### 2. Capacitor design methodology

In this paper, the RF-MEMS tunable interdigitated capacitor is presented as a crucial component for a tunable band-pass filter, formed on the Chebyshev three order circuit [14]. The capacitor is transverse comb-drive device, as shown in figure 2. The set of free fingers move in a direction perpendicular to the longitudinal axis of comb fingers. The direction of finger movement is orthogonal to the direction of fingers. The advantage is ease of fabrication and the use for sensing for the sensitivity time and again. On the other hand, the disadvantage is that due to the physical limit of distance it could not be used as an actuator. For the interdigitated beams model, the values of minimum and maximum capacitance expressions are as follows:
Figure 2. Schematics of a longitudinal comb drive.

\[
C_{\text{min}} = (N-2) \left[ \frac{2\varepsilon_{\text{f}}}{g_{\text{max}}} + 2\varepsilon_0 \right] \left[ \frac{K}{K} \left[ \frac{\sin\left(\frac{\pi w_f}{2} \right)}{2(w_f + g_{\text{max}})} \right] \right] (1)
\]

\[
K(x) = \frac{1}{\sqrt{1 - x^2}} \int_0^\theta d\theta (2)
\]

\[
C_{\text{max}} = N L_0 \left[ \frac{2\varepsilon_{\text{f}}}{g_{\text{min}}} + \frac{2\varepsilon_0}{\pi} \ln \left( \frac{w_f}{g_{\text{min}}} + 1 \right) \left( \frac{1 + \frac{2g_{\text{min}}}{w_f}}{g_{\text{max}}} \right) \right] (3)
\]

Where:

\( N \) is number of interdigitated tunable finger, \( L_0 \) is length of the interdigitated tunable finger, \( w_f \) is width of interdigitated tunable finger, \( g_{\text{max}} \) is the gap (distance) between the rotor and stator.

Figure 3 shows a top schematic view of three tunable interdigitated capacitors which consists of four parts chevron actuator, guidance beam, capacitor rotor, and capacitor stator, but figure 4 shows the three dimensions of the three tunable interdigitated capacitors that’s generated from Coventorware simulation.
To demonstrate the working principle of this MEMS tunable interdigitated capacitor in figure 3, firstly it is important to know thoroughly about how voltage signals are eradicated through the chevron construct. When DC voltage is applied from power supply via chevron actuator pads, then the chevron tip expands due to the heat then the guided beam pushes the rotor beam which causes decrease in the distance between the rotor and stator, as a result, the interdigitated capacitor value varies and the change can be observed.

3. FABRICATION PROCESS
A low resistivity substrate, 1–2 Ωm, was used to fabricate the tunable interdigitated capacitor; the suspended tunable interdigitated capacitor was obtained by etching 25 µm deep trench. The MetalMUMP technology was exploited to manufacture the device that is currently obtainable multi project wafer
(MPW) process in the market [5]. Figure 5 depicts the vertical process flow for the capacitor. Involving following steps:

1- On the outer most layer of the starting silicon wafer that was the surface, a 2 µm thick Isolation oxide was developed.

2- The next step was the deposition of a 0.5 µm thick sacrificial phosphosilicate glass (PSG) layer (Oxide 1) that was patterned and the unwanted sacrificial PSG was taken out using wet chemical etching.

3- Then there was deposition of separate and connected 0.7 µm layer of doped polysilicon and a 0.35 µm layer of silicon nitride (Nitride 1). At this point, the polysilicon could be used for cross-over electrical routing, resistors and additional mechanical structures.

4- In the fourth step, the deposition of a second silicon nitride (Nitride 2) layer (0.35 µm thick) was done and the two layers of Nitride (Nitride 1, Nitride 2) were patterned.

5- Then a second sacrificial layer (Oxide 2) of PSG (1.1 mm thick), was deposited and annealed for an hour at the temperature of 1050°C.

6- Subsequently, the patterned resist stencil was developed by the electroplated Nickel of 20 µm nominal thickness and the dense photoresist was used to pattern the wafer followed by the Sidewall Metal electroplating with 1-3 µm gold layer.

7- Before the final step, using the wet etching, the sacrificial oxide layer and PSG layer were taken out.

8- Lastly, as depicted in figure 5, a 25 µm deep trench was formed using a KOH silicon etch.

![Figure 5. Cross-sectional view of a RF-MEMS tunable interdigitated capacitor.](image)

The SEM (scanning electron micrograph) image in figure 6 is an optical image showing the RF-MEMS tunable interdigitated capacitor composed of three parts i.e., comb interdigitated capacitor, guided beam, and electro-thermal actuator. The MetalMUMP die size was 10×10 mm but the tunable interdigitated capacitor occupied only 494 × 520 µm², the guided beam occupied 1.76 × 0.20 mm², and the electro-thermal actuator (Chevron) occupied 1.76 × 0.154 mm². The DC biasing for controlling the capacitor value was used for the pads that were connected with the chevron actuator at the higher edge of the die. The MetalMUMP's tunable interdigitated capacitor design illustrates that there is neither metal bloating nor polymer thickness on the sidewalls of the beams corroborated with the promising fabrication technique.
4. MEASUREMENT RESULTS

The tunable interdigitated capacitor die was glued on a PCB using silver epoxy then it is wire bonded to the PCB pads. Wire bonding is important for establishing electrical connection between the device and the external leads in the PCB. Bond wires usually consist of one of the following materials: aluminum (Al), copper (Cu) or gold (Au). In UTP laboratory, WEST BOND gold wires bonder Model 7700E used to bond the device by gold wire bonding to make the electrical interconnections between the device pads and the PCB. It consists of a microscope, device holder, manipulator arm to control the bonding, capillary and control unit as shown in figure 7. After that the PCB pads was soldered using long wire to use in capacitance measurement.

Then the PCB that hold the tunable interdigitated capacitor put under the RF Prob-station microscope (RE-4RF) then thermal actuator (Chevron) was connected to DC power supply to change capacitance value. The DC value changed from 0 Volt to 2.4 Volt, then the change in capacitance was recorded. The
measured result given in figure 9 shows the relationship between distances in µm, and calculated and measured capacitance value in fF.

![Figure 8. Photograph of the RF Probe Station (RE-4RF).](image)

![Figure 9. Measured and calculated capacitance vs distance.](image)

### 5. Conclusion
This paper has demonstrated design, modeling and fabrication of RF-MEMS tunable interdigitated capacitors on a standard low-resistivity substrate. Its working concept based on moving capacitors rotors in same time using thermal actuator. The control voltage in the 0-2.4 volt rang, with tuning rang from 40.863 to 326.902 fF. The device enabled multiple tuning position continuously. The prominent aspect of
This research study was the use of MetalMUMPs technology to fabricate the device which minimizes the device cost. The designed capacitors has the good ability for the applications needing large tuning range because of its huge number of RF-MEMS devices, RF-MEMS filters, and far-reaching tuning range and compact size. The measured capacitance value of the capacitor led to a very fine resolution. The results evidence that the MetalMUMPs technology is a good solution to RF-MEMS device. This tunable interdigitated capacitor is viable because of its uncomplicated fabrication and low fringing capacitance.

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