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An wide-range tunable on-chip radio-frequency LC-tank formed with a post-CMOS-compatible MEMS fabrication technique

Lei Gu, Zhengzheng Wu, Xinxin Li *

State Key Laboratory of Transducer Technology, Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, 865 Changning Road, Shanghai 200050, China

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ABSTRACT

An on-chip-micromachined tunable LC-tank, which consists of a metal inter-digitated variable capacitor and a metal solenoid inductor, is developed for wide-range radio-frequency (RF) tuning in multi-GHz band. A low-temperature metal MEMS process is developed to on-chip fabricate the passives. The process can be used for post-CMOS-compatible integration with RF ICs. Both the varactor and the inductor are suspended with a gap from the low-resistivity silicon wafer (i.e. standard CMOS wafer) for effectively depressing RF loss. The fabricated variable capacitor part, the inductor part and the whole tunable LC resonator are sequentially tested, finally resulting in a wide resonance-frequency tuning range of 72% (between about 3.5 and 6.0 GHz) under a low tuning voltage range of 0–4 V, while the *Q*-factor ranged within 23 and 8.

1. Introduction

On-chip tunable radio-frequency (RF) passives and circuits are in great demand in wide-band RF ICs and multi-mode telecommunication. Formed with microelectromechanical system (MEMS) techniques, micromachined tunable RF passives feature wide tuning range, low power consumption, linear RF characters and high RF performances, thereby, showing promise for RF-IC applications [1,2]. Some researchers have tune the resonance frequencies of LC-tanks by using RF switches to vary either the inductance values or the capacitance values of the tunable tanks [3–6]. With the switch-tuning method, the frequency can be varied only in a discontinuous way. In addition, the reported actuating voltage values for the switches are, more often than not, much higher than the voltage for CMOS IC operation. Alternatively, the present research develops an integrated LC-tank, which comprises a low-voltage-driven variable capacitor and a solenoidal inductor to realize continuous wide-range tuning of the resonant frequency. On the other hand, the MEMS tunable passives are expected to be fabricated in a CMOS-compatible or a post-CMOS-compatible way, by which they can be monolithically integrated into RF ICs.

In a tunable resonator that comprises a MEMS variable capacitor and an inductor, the variable capacitor needs an electrostatic actuating capacitor to tune the RF capacitor. Most of the developed MEMS tunable LC resonators have a common electrode that is shared by both the actuating voltage and the LC-tank to be electrically connected into a circuit [7]. Sharing the common electrode with the MEMS actuator, the LC-tank shows its weakness in flexibility of circuit design. In the present research, we try to build a tunable LC-tank with actuating electrodes electrically isolated from the tunable LC part for flexible RF-IC design. Fig. 1 shows a schematic of the present tunable LC-tank with an isolator that is put between the actuator and the capacitor. The LC-tank is composed of a comb-drive, area-tuning capacitor and a solenoid inductor, which are both embedded in a single silicon chip. A post-CMOS-compatible low-temperature micromachining process is developed to fabricate the tunable LC-tanks in standard CMOS silicon wafers (i.e. low-resistivity wafers). Metal micro-electroplating and XeF_2 dry etching are used in the fabrication. By electroplating the metal MEMS structures and dry excavating the silicon substrate under the RF components, both the resistive and the substrate losses can be effectively depressed. For wide-band tuning under a low voltage, a single-sided electrostatic driving structure is optimally designed, and high-aspect-ratio metal comb fingers are formed by electroplating.

2. Design

Shown in Fig. 2(a) is the photo-mask layout of the on-chip tunable LC-tank, which consists of a comb-driven/inter-digitated nickel variable capacitor and a concave-suspended copper high-Q solenoid inductor. The area occupation of the LC-tank, including

* Corresponding author. Tel.: +86 21 62131794; fax: +86 21 62513510.
E-mail address: xxli@mail.sim.ac.cn (X. Li).

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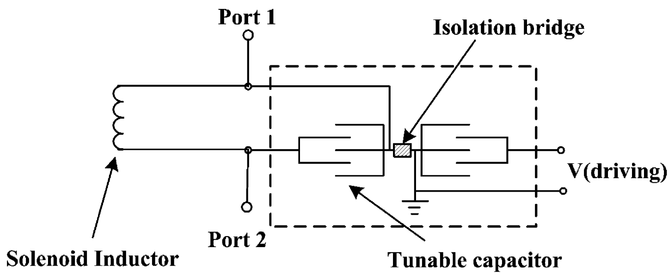

Fig. 1. Schematic equivalent circuit of the MEMS tunable LC-tank. For flexible circuit and system applications, insulating joints are designed to electrically isolate the actuator part and the RF capacitor part.

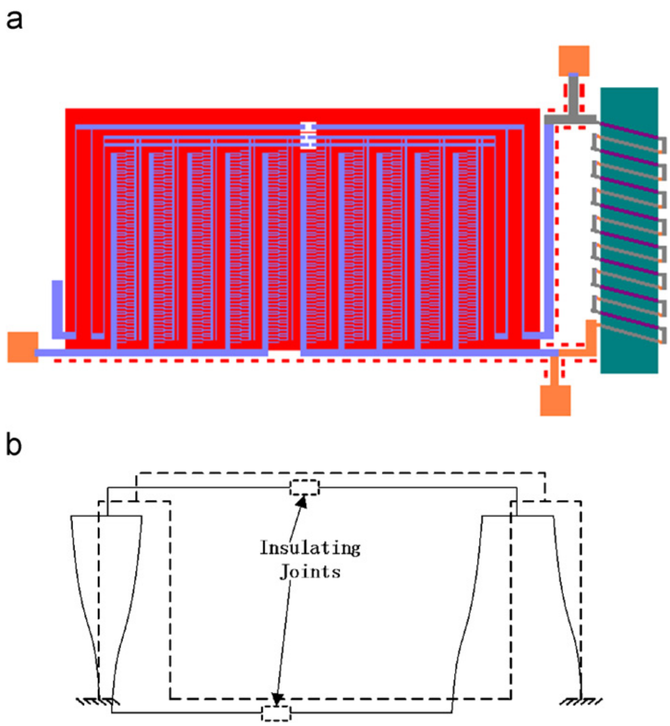

Fig. 2. (a) Process photo-mask layout of the on-chip tunable LC-tank, which is composed of a comb-drive actuator, an inter-digitated variable capacitor and a solenoidal inductor. (b) Schematic of the insulating joints located at the middle points of the linking bars for electric isolation between the actuator and the RF capacitor. The linking bars are used to transfer the electrostatic tuning force from the actuating part to the capacitor part.

the testing pads, is $810 \times 1740\,\mu m^2$. If the LC-tank is connected into a circuit, the testing pads would be of no use and, therefore, could be ignored. In that case the tank area would shrink to $650 \times 1740\,\mu m^2$. The 8.5-turn solenoidal inductor used in this research generally features a high Q-factor within multi-GHz. As detailed in [8], the Q-factor values of the on-chip inductor are generally in the range of 20–30 within 3–6 GHz, while the inductance is about 2.7–2.8 nH. About 7 μm-thick copper lines are used here to form the conductive strips of the solenoid inductor.

On the other hand, the variable capacitance is designed with a high tuning ratio of about 3:1 under a low driving voltage of 4 V. In the nickel-micromachined tunable capacitor, five columns of comb-driven structures are constructed, and there are 55 finger couples in each comb column. The inter-digitated area-tuning style capacitor is designed with the same comb-finger structure as the actuator. The height of the nickel capacitor structure is 9 μm, and the aspect ratio of the finger gap is about 9:1, i.e. the capacitive gap distance, d, is about 1 μm. According to Ref. [9], the spring constant of the folded beams can be calculated as $k = (2Ehb^3/3L^3) = 0.112\,\mathrm{N/m}$, where $h = 9\,\mu m$, $b = 2.5$, $L = 550\,\mu m$ and $E = 2.0 \times 10^{11}$ GPa are the height, width, length of the folded beams and elastic modulus of nickel, respectively. Under a driving voltage of V, the electrostatic force can be calculated as $F = (n\varepsilon_0 h/d)V^2 = 0.0548V^2\,\mu N$, where the comb-finger number is $n = 55 \times 5$. Therefore, the voltage-tuned capacitance value can be expressed as $C = C_0 + (n\varepsilon_0 hF/kd) = (0.19 + 0.027V)^2$ pF, where C_0 is the initial capacitance. Under 4 V driving voltage, the displacement of the comb fingers is designed as about 8 μm. Therefore, the area-tuning inter-digitated capacitance is expected to be varied up to about 200%, and the resonance frequency of the LC-tank can be tuned by about 100%, e.g. from 6 GHz down to 3 GHz.

As aforementioned in the last section, the actuating part and the LC-tank part are electrically isolated from each other for flexible RF circuit design and application. Shown in Fig. 2(a), single-sided folded beams are designed to minimize the area occupation and facilitate electric isolation between the driving part and the capacitor part. Shown in the schematic of Fig. 2(b), the insulating joints are designed and formed at the middle points of the linking bars to realize the electric isolation. Via the insulating joints, the electrostatic driving force can be transferred from the actuating part to the capacitor part. Shown in the close-up SEM image of Fig. 4(a), the SiO_2-film bridging pattern is used as the insulating joints to link the linking bars and electrically isolate the actuator and the capacitor.

3. Fabrication

The processes start form CMOS-compatible p-type (1 0 0) silicon wafers with 3–8 Ω cm resistivity. The low-temperature (maximum 120 °C for photoresist hard baking) fabrication can be post-CMOS implemented and on-chip integrated with an active RF IC. The tunable-capacitor part is constructed mainly with nickel since it features good mechanical properties, while the solenoid inductor is formed with copper due to the satisfactory electric conductivity. Since the precision of lithography is quite critical for the comb fingers of the tunable capacitor, the capacitive part of the LC-tank is fabricated prior to the formation of the inductor. The detailed process steps are shown in Fig. 3 and described as follows:

(a) With plasma-enhanced chemical vapor deposition (PECVD) technique, 3 μm-thick SiO_2 is deposited to simulate the insulating layer formed during a standard CMOS process for active ICs. Then the SiO_2 at the tunable-capacitor regions is patterned and removed with buffered HF. After a 50 nm/100 nm-thick TiW/Cu seed layer is sputtered, 11 μm-thick photoresist is spin coated and patterned; 7 μm/2 μm/0.2 μm-thick Ni/Cu/sold (Au) is sequentially electroplated to form the tunable-capacitor structure. Nickel sulfamate solution is made of nickel sulfamate, boric acid, nickel chloride, butyne diol, sodium saccharin and a commercial wetting agent. By optimally varying the components percentage of the solution, the stress of electroplating nickel can be controlled down to 10 MPa and below. Electroplated nickel is selected as the structure material due to its excellent mechanical properties and much superior electric-conductive properties to silicon [5]. The copper middle layer is utilized here to lower the series resistivity and to serve as an adhesion layer between nickel and the external thin Au film. The thin Au layer is electroplated on the surface of the Cu conductor for long-term anti-oxidation in ambient air. Then, the photoresist and TiW/Cu seed layer are sequentially removed by acetone,