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High Performance On-Chip Integrable Inductor for RF Applications

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ABSTRACT

The high Q(quality factor) suspended spiral inductors were fabricated on the silicon substrate by 3D surface micromachined process. The integration of 2.4GHz VCO has been performed by fabricating suspended spiral inductor of the top of CMOS VCO circuit. The phase noise of VCO integrated MEMS inductor is 93.5 dBc/Hz at 100kHz of offset frequency.

Key Words : Quality factor, Inductor, Integration, MEMS, VCO

1. Introduction

VCO(Voltage controlled oscillator) is one of key elements in RF communication which was used for frequency modulation. The oscillation voltage of VCO was changed by control voltage of PLL(Phase-Locked Loop).

Even though VCO has been researched in long time, RF designer is actively researching by increase of frequency band for communication and request of integration for miniature. Due to low Q factor of inductor, VCO integrated by silicon CMOS process has not been satisfied the specification of phase noise which is a key characteristic of VCO and shows the purity of frequency[1]. It is difficult to make high Q LC resonator circuit by standard silicon process.

The planar spiral inductors can be integrated on the low cost standard silicon technology and aluminum metal interconnects. These inductors show low Q due to substrate loss of the standard silicon substrate at radio frequencies and the ohmic loss of the aluminum thin film.

Afterwards, it is be introduced for high-Q inductors for the high performance single chip RFICs, while ohmic loss can be reduced by using high conductivity metals such as copper, the reduction of the substrate loss remains the major obstacle for high performance silicon-based inductors. To overcome the substrate loss, several approaches have been fabricated to reduce the substrate loss and noise coupling with limited improvement in Q (~10)[2,3]. Several CMOS-compatible surface micromachined inductors have been researched including solenoid inductor[4], suspended spiral inductor[5,6] and vertical spiral inductor[7].

Suspended inductors with the inductor metal separated from the lossy silicon substrate have offered high Q factors on silicon substrates.

We have fabricated suspended spiral inductor for 2.4 GHz range and integrated this inductor with voltage-controlled oscillator. The characteristics of this integrated VCO shows better performance than VCO

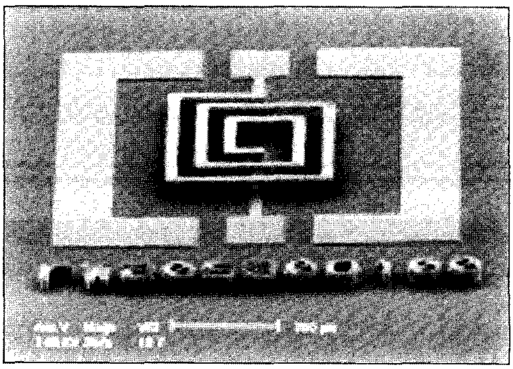

Fig. 1. SEM photography of suspension spiral inductor.

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with conventional CMOS inductor. We measures performance of 2.4 GHz VCO integrated with MEMS inductor. We can measure 2.4 GHz VCO fabricated by SiGe BiCMOS process.

2. The Suspension Spiral Inductor

2.1 Inductor Design and Fabrication

The inductor has been designed to have inductance of 2 to 2.5 nH at 2.4GHz. To optimize the design, the spacing of inductors were varied from 10 um to 50 um. The inductor was fixed to 2.5 turns and the inner diameter was also fixed to 100 um.

The fabrication process of a single inductor is similar to that of inductor integration. The exact process will be explained later. Fig. 1 shows SEM photograph of the fabricated MEMS inductor.

2.2 Inductor Measurement

The measurement of fabricated suspended-spiral inductor was performed from 0.5 GHz to 20 GHz using a HP8410C network analyzer. After the calibration, inductors having different spacing were measured. Fig. 2 shows the Q and the inductance of the inductors. The line spacing of the inductors range from 10 to 50 um with the line width fixed to 40 um. The silicon with 5 um of silicon dioxide insulation layer was used as the substrate. At the low frequency range(<3 GHz), the Q is mainly determined by L/Rs. As the spacing increases, the inductance L increases more rapidly than the series resistance Rs. Thus, the inductor with larger spacing has slightly higher Q. At higher frequencies(>3 GHz) the parasitic capacitors reduce the Q, and therefore the inductor with 10 um spacing has the highest Q. Optimum inductance and Q factor of inductor was existed in various width and spacing of inductor.

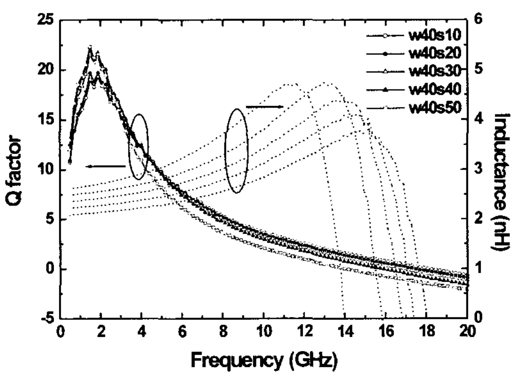

Fig. 2. The measured Q and inductance of the inductor with different line spacing.

3. Integrated VCO with Suspension Spiral Inductor

3.1 Inductor Integration with CMOS VCO

Fig. 3 shows the fabrication flow of integrating MEMS inductor on a VCO circuit. The fabrication process is a simple process using multi-layers of the photoresist. The starting wafer is a silicon wafer with VCO circuit without inductors. First, this wafer is prepared with 1 um of silicon dioxide layer for insulation(Fig. 3a). The top Al pads of VCO circuit are opened through dry etching and Ti/Cu are deposited as seed layer(Fig. 3b). The thick copper bottom electrode is formed by electroplating with thick photoresist, patterned by UV exposure, as a mold(Fig. 3c). After removal of the mold by stripper, thick photoresist is coated again for post patterning(Fig. 3d). After the post patterning, posts copper electroplating of 20 um are formed(Fig. 3e). After hardening of the bottom photoresist, second Cu seed deposition is performed and the photoresist is patterned to make a mold for top spiral inductor(Fig. 3f). The top spiral inductor is electroplated to the height of 10 um to

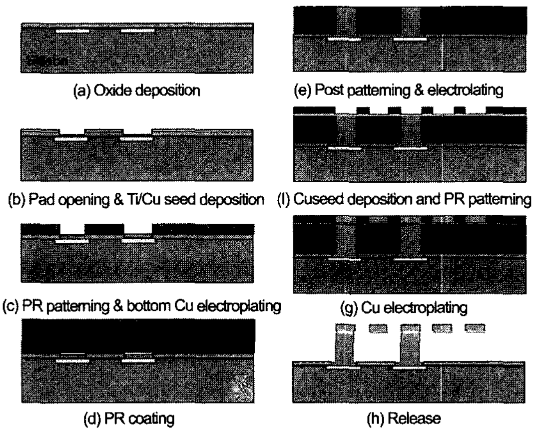

Fig. 3. Process flow of the suspended-spiral inductor integration.

reduce ohmic loss and to gain high Q(Fig. 3g). Finally, the inductor is released by etching photoresist mold and seed metals(Fig. 3h).

Fig. 4 shows the schematic of VCO oscillating at 2.4 GHz. The circuit without MEMS inductor was fabricated by Hynix 0.18 um CMOS process with standard silicon substrate. After CMOS process, the inductor integration process was proceeded by the method to describe above. For performance comparison, another VCO was fabricated using only CMOS process and embedded metal inductor. These two types of VCO are identical except inductor part and were fabricated on the same substrate simultaneously. Fig. 6 shows SEM photography of VCO integrated suspended spiral inductor.

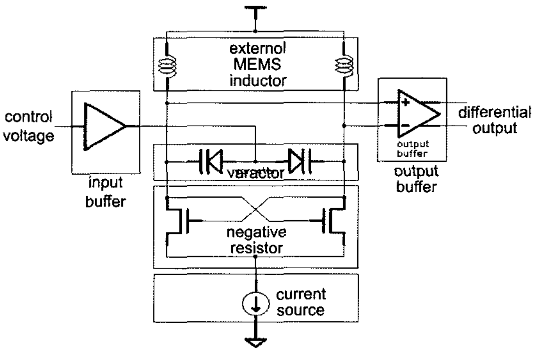

Fig. 4 The schematic of 2.4 GHz VCO design.

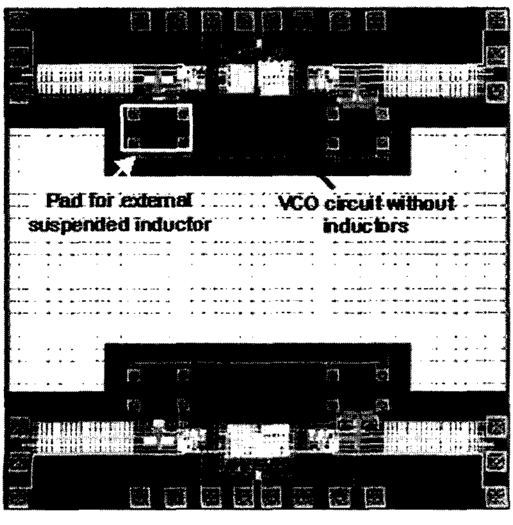

Fig. 5. The layout of CMOS VCO.

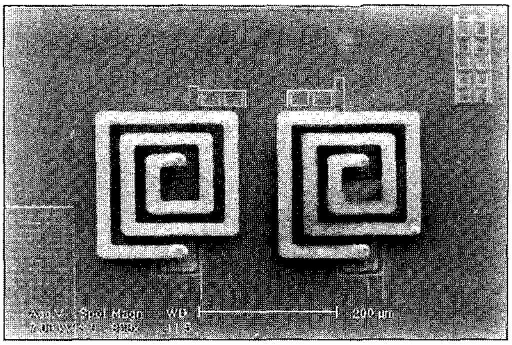

Fig. 6. SEM photography of VCO integrated suspension spiral inductor.

3.2 Measurement

The VCO with CMOS planar inductor and the VCO with MEMS suspended-spiral inductor have been mounted on the PCB for the measurement. The measurement has been performed using HP 8593A spectrum analyzer. The resolution bandwidth is 100 KHz.

The control voltage has been changed from 0.5 V to 2.5 V to see the tunable characteristics of VCO. The center frequency and tuning sensitivity of the MEMS VCO is 2.37 GHz and 80 MHz/V respectively.

Fig. 7 shows phase noise characteristics of each VCO implemented by MEMS inductor and CMOS inductor. The line width of the inductor is 20 um, and the line spacing of that is 14um. Each VCO circuit is identical except for the inductor part. The phase noise of the MEMS VCO is 93.5 dBc/Hz at 100 KHz offset frequency. This value is lower than that of another company product by 10 dB approximately. We think that this result is not due to MEMS inductor but due to the lossy CMOS substrate(1~10) and CMOS proc-

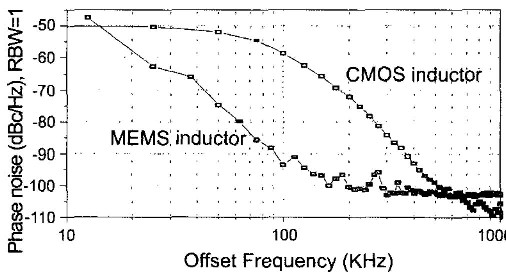

Fig. 7. Phase noise characteristics of eash VCO implemented by MEMS inductor and CMOS inductor.

ess. Other company products were fabricated by Advanced Process(e.g. SiGe process)

In the case of the VCO using MEMS inductor, the phase noise is improved approximately 60% compared to that of CMOS at 100 KHz offset frequency. This result shows that the performance of the VCO can be improved with the MEMS inductor integration.

4. Conclusion

The high Q(quality factor) suspended spiral inductors were fabricated on the silicon substrate for high Q LC resonator. The integration of 2.4 GHz VCO has been performed by fabricating suspended spiral inductor on the top of CMOS VCO circuit. The phase noise of VCO integrated MEMS inductor is -93.5 dBc/Hz at 100 kHz of offset frequency. Now, we are incorporating MEMS suspended inductor with SiGe 2.4 GHz VCO fabricated by SiGe technology. Before long, it will be measured and compared with SiGe VCO without MEMS suspended inductor.

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