Design, Simulation and Measurement of a Flexible Voltage-controlled Oscillator (VCO) Chip with Bending Radius

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***Abstract*—In this paper, we designed, simulated and measured an extremely thin flexible LC voltage-controlled oscillator (VCO) with bending radius for flexible electronics. An LC VCO chip is fabricated using a SK Hynix 0.18 µm process. A silicon substrate of the fabricated VCO chip is grinded to 50 µm to achieve the flexibility. The flexible VCO chip is bent with a bending device to check voltage output and phase with bending radius. The bending radius is applied from infinite to 20 mm. The results showed that the designed flexible VCO chip is operating properly with the bent structure.**

Keywords— flexible chip, flexible interconnects, flexible PCB, signal integrity, S-parameter, thin silicon substrate, voltage-controlled oscillator.

I. INTRODUCTION

Flexible electronic devices have been in the spotlight in recent years [1]-[4]. Those electronics are useful when the devices are applied to a human body for monitoring human health conditions. Since there are no rigid parts in the devices, they can be worn without discomfort. The flexible electronics use flexible substrates such as Polyimide, Polyethylene terephthalate (PET), and Urethane. Moreover, the attached silicon (Si) chips must flexible to avoid the failure between the flexible substrate and Si chip.

Firstly, electrical characteristics of flexible PCBs have been studied [5]. Through these studies, the results showed that the electrical characteristics of flexible PCB coils are not significantly affected by the variation of bending radius. Moreover, passive interconnection lines on a Si chip is studied [6], [7]. In these studies, the electrical characteristics of the passive interconnection lines using extremely thin Si substrate are analyzed with bending. However, not only the passive interconnection lines, study on active circuits with the extremely thin Si substrate are important the check the feasibility of the flexible electronics implementation.

In this paper, an active chip, including CMOS is designed, fabricated, and measured to see the flexibility of the flexible system operation with mechanical bending. For an active circuit, a voltage-controlled oscillator (VCO) is designed using the SK Hynix 0.18 µm process. The VCO is the sensitive circuit and output electrical characteristics can be changed with bending which might cause system malfunctions as illustrated is Figure 1. Therefore, we need to prove that the flexible chip operates properly with the bending to realize the flexible electronics.

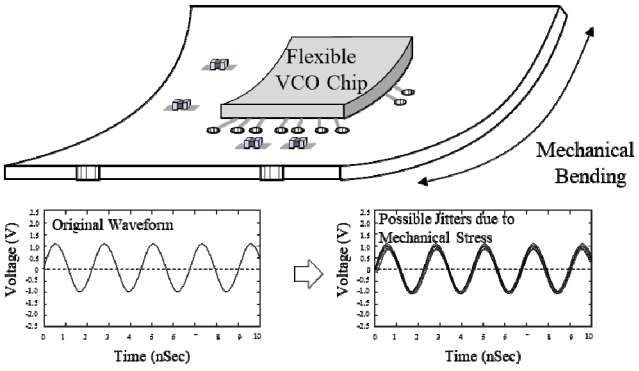

Fig. 1. Flexible voltage-controlled oscillator (VCO) chip with bending radius that may cause time-domain jitter at the output.

Firstly, we have designed the LC VCO that operates at 433.42 MHz considering industry science medical (ISM) and telecommunication frequency bands. The ISM bands are radio frequency (RF) bands allocated internationally for the use of RF energy for industrial, scientific and medical applications. Therefore, by using the ISM bands as the communication frequency, lower power wireless devices are frequently used without the permission.

II. DESIGN OF FLEXIBLE VOLTAGE-CONTROLLED OSCILLATOR CHIP ON SI SUBSTRATE

Figure 2 depicts the designed LC VCO using CMOS technology. Two PMOS and two NMOS are used to create negative resistance for an output oscillation. On-chip inductor and varactor circuit are used as a resonant tank for the oscillation. For the LC VCO, the design of the inductor for oscillation is the most important design consideration. For the

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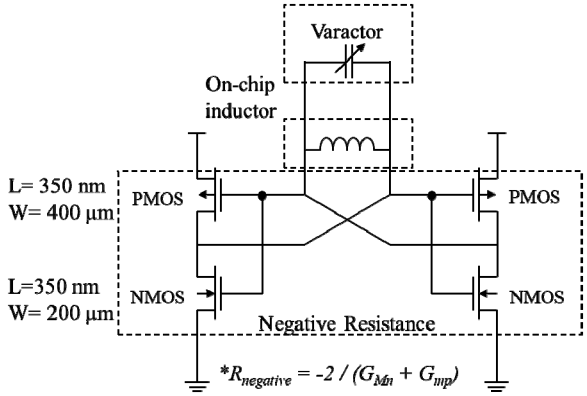


Fig. 2. Designed LC VCO using the SK Hynix 180 nm process. Negative resistance circuit, on-chip inductor, and varactor are designed.

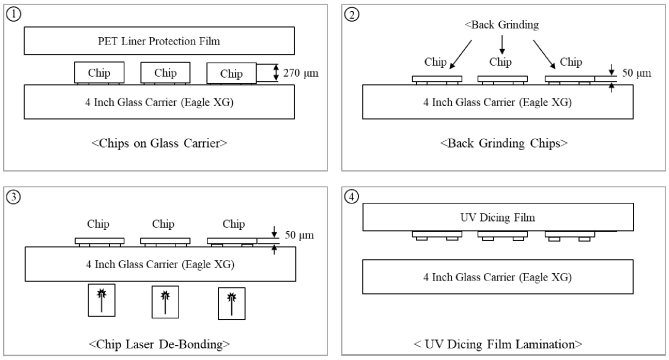


Fig. 3. Chip-level backgrinding process of the fabricated VCO chips to obtained the flexibility.

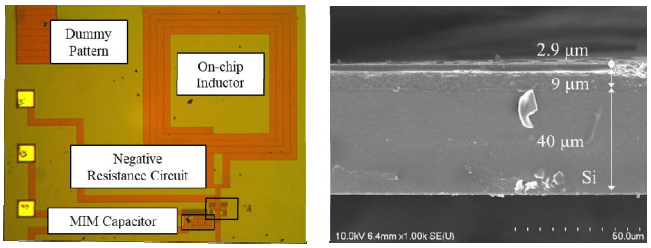
inductor design, on-chip inductor and off-chip inductor can be considered. In our design, we have designed the on-chip inductor by using a thick metal process.

To achieve a higher Q-factor. The on-chip inductor is optimized using an HFSS 3D EM simulation with the higher Q-factor within the area of 700 µm^2. The line width is designed to be 30 µm and the line to line space is set to 1 µm that is the minimum line to line space set by the manufacturing process. The coil turns are designed to be 4 turns and finally the metal thickness is set to 2 µm using the top thick metal process where the conductor thickness of inner design layers is 0.7 µm.

The designed VCO is fabricated using the SK Hynix 0.18 µm process through multi-wafer project (MPW). In this project, the fabricated chip is only available in chip level. To achieve the flexibility of the Si chip, the Si substrate is grinded to less than 50 µm. However, backgrinding process in the chip level is difficulty in comparison to the back-grinding of the wafer level since the dimension is relatively small and it is hard to handle the flexible chip after the backgrinding process.

TABLE I. DESIGN PARAMETERS OF THE ON-CHIP INDUCTOR

Dimension	Line Width	Line Space	Metal Thickness	Coil Turn
700 µm^2	30 µm	1 µm	2 µm	4 turns



(a) (b)

Fig. 4. (a) The top-view of the fabricated flexible VCO chip. (b) The cross-sectional view of the flexible VCO chip after backgrinding.

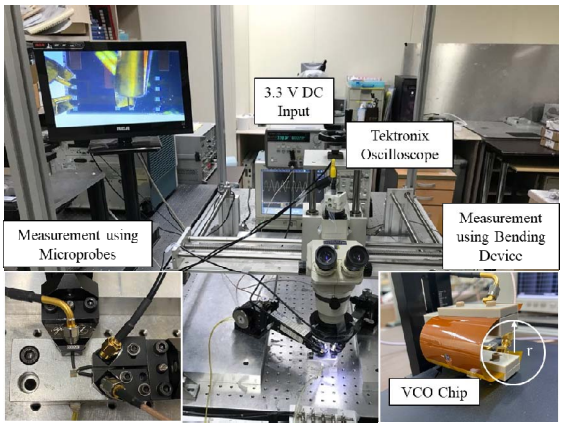


Fig. 5. Measurement setup of the flexible VCO chip using microprobes without bending and with bending using SMA connectors and bending device.

Figure 3 illustrates the backgrinding process of the VCO chip. Firstly, the fabricated VCO chips are attached on the glass carriers because the conventional films for the backgrinding process is not suitable to achieve the equal thickness of the flexible chips after the backgrinding process. Secondly, the VCO chips are grinded to 50 µm to achieve the flexibility. In the wafer level backgrinding process, it is possible to achieve the thickness less than 20 µm [7]. However, since it is the chip level grinding, we decide to have the total thickness of 50 µm. After the grinding process of the chip, the attached flexible VCO chips are detached from the glass wafer using the laser de-bonding process. Finally, the flexible chips are attached to the UV dicing film for the measurement. Figure 4 (a) shows the top view of the fabricated VCO chip and Figure 4 (b) shows the cross-sectional view of the flexible chip after the backgrinding process. The cross-sectional view shows the top metal thickness of 2.9 µm and the total thickness of the design layers as 9 µm. Finally, the Si substrate is grinded to 40 µm to have the flexibility.

III. MEASUREMENT OF THE FLEXIBLE VCO WITH BENDING RADIUS

To measure the flexible chip with the bending radius, the bending device is needed to apply the bending radius the flexible chip. Also, the flexible PCB is designed to measure the

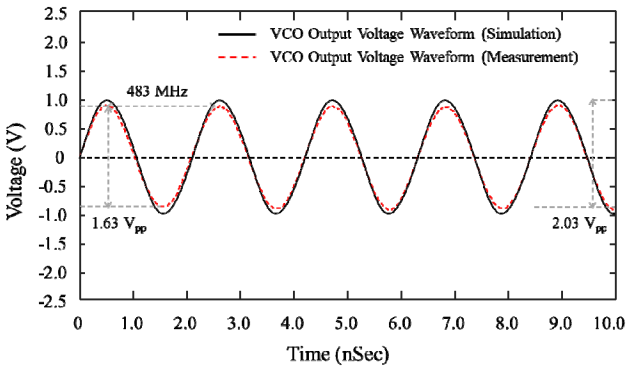


Fig. 6. Comparison of the output voltage waveform simulation and measurement results of the designed VCO without bending.

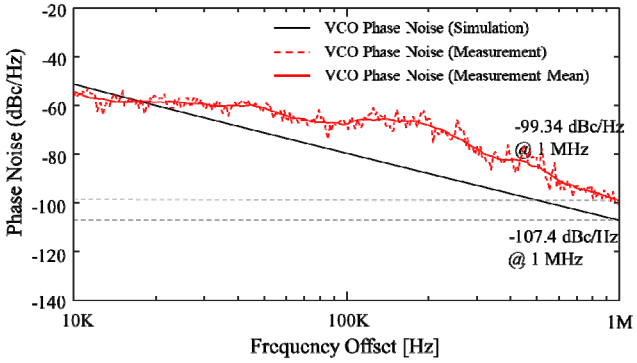


Fig. 7. Comparison of the phase noise simulation and measurement results of the designed VCO without bending.

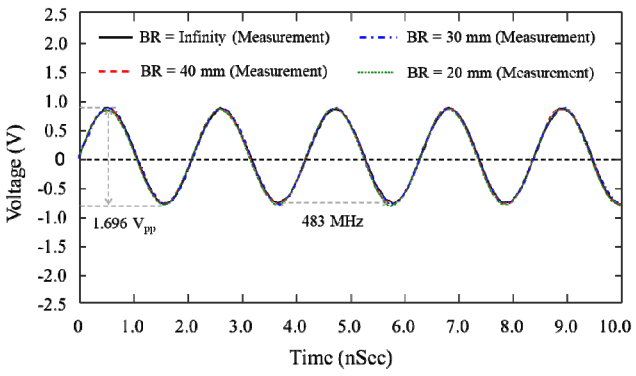


Fig. 8. VCO output voltage waveform measurement results of the flexible VCO chip with bending radius.

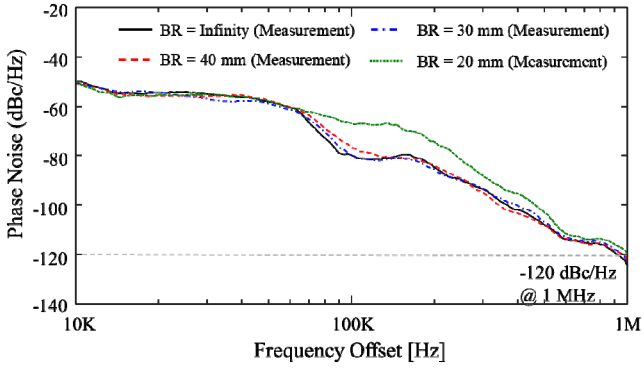


Fig. 9. Phase noise measurement results of the flexible VCO chip with bending radius.

flexible chip as shown in Figure 5. To measure the VCO output with the bending radius, the input voltage of 3.3 V is applied. To measure the output voltage, Tektronix oscilloscope is used.

Firstly, we have tested the flexible chip without bending by using microprobes to compare with the simulation results. Figure 6 shows the comparison between Cadence Virtuoso simulation and measurement results of the flexible chip without bending. The voltage amplitude difference between simulation and measurement is occurred by the higher equivalent series resistance (ESR) value of the on-chip inductor. The oscillation frequency of 483 MHz is occurred with the identical simulation and measurement conditions. Figure 7 shows the comparison of the phase noise simulation and measurement results of the designed VCO from 10 kHz to 1 MHz away from the center frequency. The simulation results showed -99.34 dBc/Hz at 1 MHz and the measurement results showed -107.4 dBc/Hz at 1 MHz. There is a difference in the phase noise results in the middle frequency region, however, the results showed the similar trends.

Figure 8 shows the measurement results of the flexible VCO chip on the PCB with bending radius. The bending radius of the flexible PCB is varied from infinity to 20 mm. The infinity value of the bending radius means the flexible PCB is in the flat structure. The results showed the designed VCO is properly operating until the bending radius of 20 mm is applied without the voltage waveform distortions. Finally, Figure 9 shows the phase noise measurement results with the bending radius. The results showed that the similar trends until the bending radius is 30 mm and showed the small difference when the bending radius is 20 mm. The difference in the phase noise when the bending radius is 20 mm occurs by the mechanical bending of the cables and SMA connectors during the measurement of the flexible PCB.

IV. Future Work

For the future work, the flexible chip with the thickness less than 50 μm can be analyzed with the bending radius. The Si substrate has relatively higher Young's modulus than the flexible PCB. Therefore, the flexible chip is not bent perfectly when we apply the bending radius. This problem can be solved by further reducing the Si substrate thickness.

V. Coclusions

In this paper, we have designed the flexible VCO chip to see the feasibility of the flexible electronics. The designed VCO chip is fabricated for the measurement of the flexible chip with the bending. The measured voltage waveforms and phase noise results were compared with the virtuoso simulation

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results without bending radius. The results showed the correlation between the simulation and the measurement. Finally, the VCO chip is measured with the bending radius on the flexible PCB. The bending radius is applied from infinity to 20 mm. The results showed the proper VCO chip operation without the voltage waveform and the phase noise distortions. Finally, we can conclude that the flexible chip with the bending radius is realizable for the flexible electronics.

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