# Reference SAW Oscillator on Quartz-on-Silicon (QoS) Wafer for PolyLithic Integration of True Single Chip Radio

Yunseong Eo, Seokbong Hyun, Pilsoon Choi, Kwyro Lee, *Gilhwan Oh, and *Joong-Won Lee

Department of Electrical Engineering, Korea Advanced Institute of Science and Technology
Kusong, Yusung, Taejon, KOREA, 305-701
*Devices & Materials Lab, LG Corporate Institute of Technology
16 Woomyeon, Seocho, Seoul, Korea, 137-724

## Abstract

This paper presents an electro-acoustic circuit fabricated on Quartz directly bonded on the processed Silicon wafer (QoS), which allows us to polylithically integrate high precision passives with integrated circuits. We first fabricated a prototype SAW resonator and oscillator on thick QoS. The SAW resonator on QoS shows Q about 10,000 and 11dB insertion loss at 289MHz, and SAW oscillator on QoS shows phase noise of as small as –120dBc at 10kHz offset, demonstrating the feasibility of true single chip radio.

## Introduction

One of the biggest obstacles to realize true single chip radio is how to integrate high precision reference oscillators and high quality passive filters on silicon. Bulk quartz crystal oscillator and dielectric, SAW, ceramic filters have been widely used for these purposes. But these are hard to be integrated on silicon, making it inevitable to connect them as the external off-chip elements. This causes many problems, such as degraded RF system performances, large power consumption due to 50 ohm off-chip matching, large volume, high cost, and so forth. To overcome these bottlenecks, various architectures and technologies such as Silicon-On-Anything (SOA) have been presented (1), where SOI wafer is bonded on glass substrate. However, only VCO using relatively high Q inductors (Q<30@2GHz) on glass were demonstrated (1), and the reference oscillator and high performance filters cannot be integrated in this way, which are major bottlenecks toward single chip integration. In this work, using CMP(Chemical Mechanical Polishing) and wafer bonding techniques, we demonstrate that it is indeed possible to polylithically integrate circuits on high quality dielectric such as quartz on finished silicon integrated circuits. To show the feasibility of PLIC(PolyLithic Integrated Circuit), a SAW oscillator on QoS(Quartz-on-Silicon) is designed and fabricated, which has comparable performance with conventional crystal oscillators.

## PLIC Fabrication on QoS(Quartz-on-Silicon)

Figure 1 shows the cross section of our proposed QoS(Quartz-on-Silicon) process. At first a quartz wafer is bonded to the finished silicon substrate and then mechanically grinded and polished. Wafer bonding is done by the epoxy layer of thickness of approximately 10 μm. Because quartz may be broken by stress at bonded interface, the thickness and curing temperature of epoxy should be optimized. Next, Al metal pattern for SAW resonator is disposed on the QoS by standard lithography process. To make via hole through the quartz wafer, HF solution(HF:DI=1:3) is chosen as etchant. The thermally deposited Cr/Au layer is used for masking layer against HF solution (2). To connect SAW on quartz and active devices on Si electrically, epoxy under via is eliminated by RIE(O2:CF4=9:1). The conditions of RF power and gas composition are important to eliminate the epoxy. Finally SAW on quartz is connected to pad on Si with wire bond. But it is also possible to use thin film technology for this interconnection with proper thinning of quartz by CMP. Figure. 2 and 3 show SEM photograph of via through quartz and the microphotograph of QoS prototype, respectively. Note that our prototype is fabricated on pieces of silicon wafer and quartz wafer, which contains only several MOS transistors and SAW resonator.

## SAW resonator on QoS

The integration of conventional bulk crystal is very difficult or impossible because its thickness should be controlled with error less than several ppm to trim its resonant frequency. Contrary to crystal resonator, the resonant frequency of SAW depends on the periodicity of thin film reflection gratings. It means that SAW is compatible with standard lithographic process, and so we chose SAW resonator as high Q resonator for reference oscillator. Additionally at the frequency above 100MHz, because the thickness of crystal is so thin that we can hardly handle and control bulk crystal. Thus SAW has many advantages over conventional crystal for high

0–7803–5410–9/99/$10.00 © 1999 IEEE

frequency reference applications. Fig. 4 shows the top schematic view of 2-port SAW resonator. The more the number of reflection gratings is, the higher Q of SAW resonator is. But because the number of reflection gratings determines the size of SAW resonator, there should be a compromise between Q and size. Increasing thickness of Al metal also improves Q of SAW resonator. However, it may cause too large shift of frequency to compensate the frequency error, because thickness variation affects center frequency more when it is thick. The electrically equivalent model of 2 port SAW resonator is shown in Fig. 5. Cm and Lm determines resonance frequency and Ct are unwanted parasitic capacitances caused by interdigital transducers. Fig. 6 compares the simulated and measured insertion loss and phase characteristics of two port resonator. The simulation results is calculated using Coupling of Mode model (3). The measured data agree well with the simulated ones. The designed geometric parameters and material constants of ST-cut SAW resonator are given in Table I and II, respectively. And the extracted electrical parameters using Equivalent Circuit model (4) are also given in Table III. The measured insertion loss is about 11dB and $Q \approx 10,000$ at 289MHz, which is high enough to replace crystal oscillator with proper tuning.

## SAW oscillator on QoS

Using above SAW resonator on QoS, a preliminary reference oscillator is fabricated. We design and fabricate a Pierce type oscillator because it is the most desirable configuration in stability, parasitic, and noise points of view. Fig.7 shows the schematic of our designed oscillator. SAW resonator is connected between base and collector. By trimming C1 and C2, the oscillation condition and frequency can be adjusted slightly. As for active device, BJT or PMOS are preferable because of their low 1/f noise than NMOS. But in this work, the experimental results include only that of BJT oscillator. Fig. 8 shows output spectrum of SAW oscillator. The output power is about –6dBm and reference frequency is 289MHz. The supply voltage is 3.3V and consumed current is 3mA. Fig. 9 shows the measured phase noise of SAW oscillator. The measured phase noise at 10kHz offset is –120dBc, which is comparable to that of conventional crystal oscillator and can be reduced further by optimizing oscillator circuit.

The resonance frequency may be shifted by temperature and process variation. To compensate for the change of temperature and process, the oscillator should be tuned by varying the capacitances C1 or C2 in Fig. 7. This is rather easy in QoS, because, with additive circuits on Si for compensation such as unit capacitor array, switch, sensor, and memory, a PLIC TCSO(Temperature Compensated SAW Oscillator) on QoS can be cheaply obtained (5).

## Conclusion

PLIC using QoS are proposed for realizing true single chip radio. A prototype SAW oscillator on QoS has been obtained with comparable performance as bulk crystal oscillator, demonstrating this feasibility. Even though SAW has lower Q than conventional bulk crystal, its Q is sufficient enough to replace bulk crystal resonator for reference oscillator. Our presented data shows that high precision reference clock as well as filters can indeed be integrated on silicon using QoS.

## References

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Table I. Design parameters of SAW resonator on QoS

| Parameter | Design Specification |
|---|---|
| Wavelength ($\lambda_0$) | 10.85 μm |
| Aperture width | 160 $\lambda_0$ |
| Number of strips in reflector | 300 |
| Number of finger pairs | 70 |
| Al-electrode thickness | 2000 Å |
| Transducer / reflector linewidth | 0.225 $\lambda_0$ |

Table II. Material constants for ST-cut Quartz

| | |
|---|---|
| Rayleigh mode wave velocity ($\upsilon_0$) | 3158 m/s |
| Piezoelectric coupling constant ($K^2$) | 0.0011 |
| Characteristic capacitance ($C_s$) | 0.5 pF/cm |
| Temperature coefficient of delay at 25 °C | 0.0 ppm/ °C |

Table III. Equivalent circuit parameters for the SAW resonator, extracted using Equivalent circuit model.

| | |
|---|---|
| Motional resistance ($R_m$) | 120 $\Omega$ |
| Motional inductance ($L_m$) | $6.7679 \times 10^{-1}$ mH |
| Motional capacitance ($C_m$) | $4.5 \times 10^{-1}$ fF |
| Shunt capacitance ($C_T$) | 1.4 pF |
| Unloaded quality factor ($Q_u$) | 10233 |

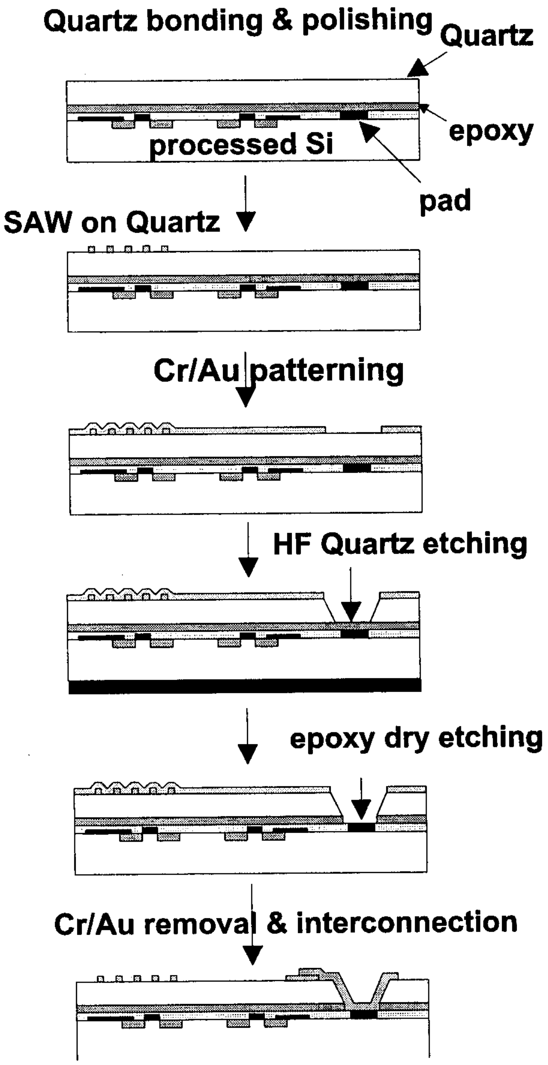

Fig. 1 Schematic cross-section of the QoS process

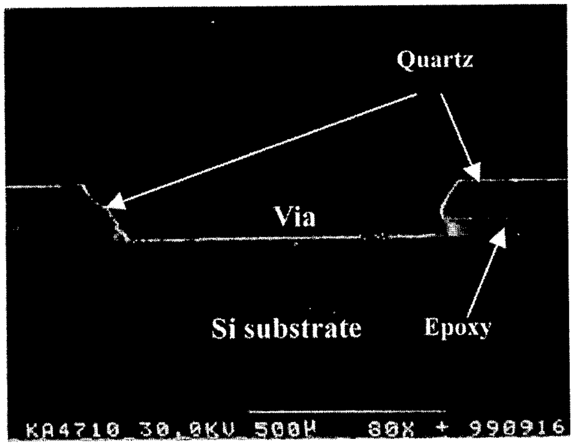

Fig. 2 SEM cross section of via hole in QoS

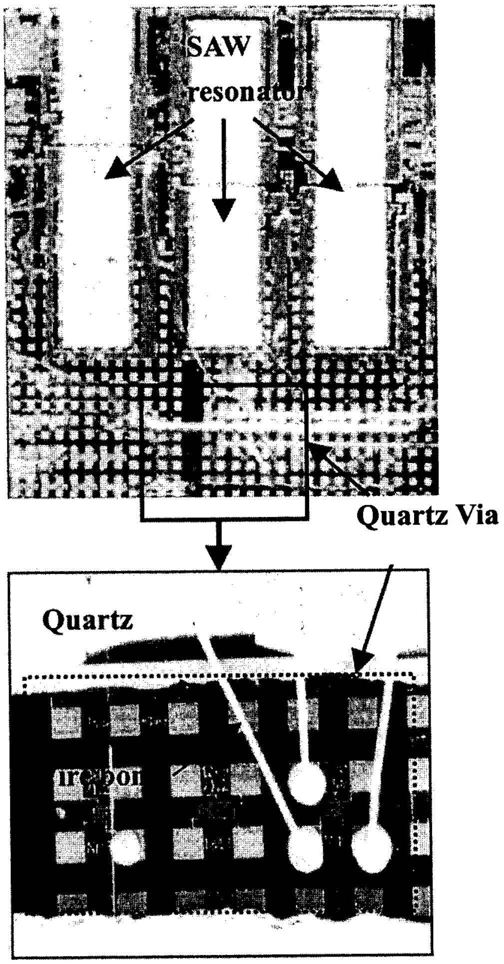

Fig. 3 Top photograph of prototype QoS interconnected by wire bond.

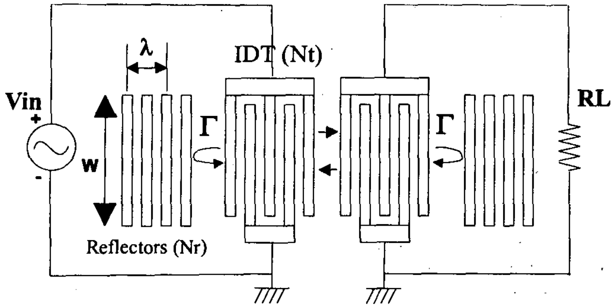

Fig. 4 Schematic top view of 2-port SAW resonator

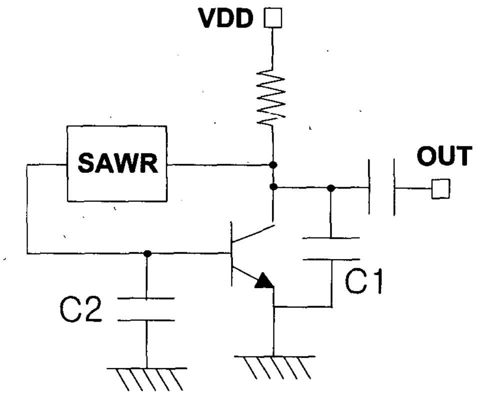

Fig. 7 Circuit schematic of designed SAW oscillator

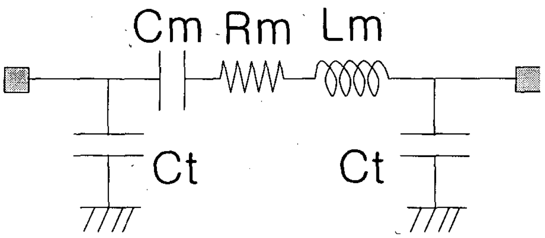

Fig. 5 equivalent model of 2 port SAW resonator

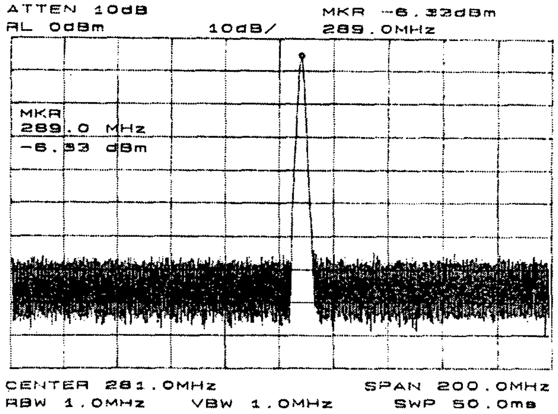

Fig. 8 Measured output spectrum of fabricated SAW reference oscillator

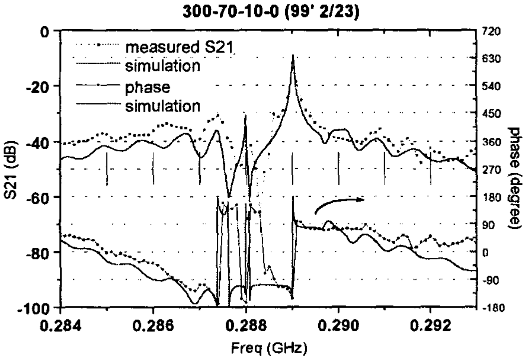

Fig. 6 Measured and simulated insertion loss and phase of SAW resonator.
(The measured Q is as high as 10,000.)

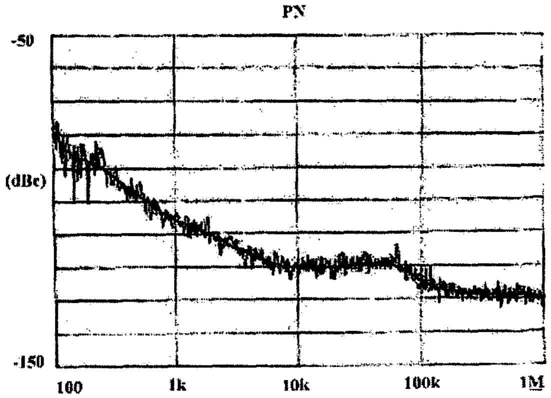

Fig. 9 Measured phase noise of fabricated SAW reference oscillator