Improvement of fabrication and characterization methods for micromechanical disk resonators*

Zhao Hui(赵 晖), Luo Wei(骆 伟), Zheng Hai-Yang(郑海洋),
Yang Jin-Ling(杨晋玲)†, and Yang Fu-Hua(杨富华)

Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, *China*

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In this paper we present a novel method to fabricate reliable micro-electro-mechanical system (MEMS) disk resonators with high yield and good performance. The key breakthrough in the fabrication process is a novel approach to effectively restraining electro-chemical corrosion of polycrystalline silicon (polysilicon) electrically coupled with noble metals of MEMS devices by hydrofluoric acid (HF)-based solutions. In addition, a measurement architecture based on a differential readout topology is demonstrated. The differential circuit proposed here can effectively suppress noise and feed-through current by common-mode rejection of the differential amplifier. This differential amplifier circuit configuration is also used to build up a notch filter. The preliminary result about the temperature dependence of the resonance frequency is discussed, and the device failure is analysed.

Keywords: disk resonator, differential readout, electro-chemical corrosion, notch filter

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1. Introduction

Micro-electro-mechanical system (MEMS) resonators with a high resonance frequency and quality factor (Q factor) are considered as a potential substitutes for quartz crystal and ceramic resonators in wireless communication systems due to their small size, low cost, high performance, and "on-chip" integrated circuit (IC) compatible fabrication process. Recently, much effort has been made to develop versatile very high frequency (VHF) disk resonators with a promising Q factor and to explore their applications as competitive oscillator, band-pass filter,[1−4] and high-Q notch filter[5] in future wireless communication systems. However, there are still many open questions demanding reliable and cost-effective fabrication techniques. For example, electro-chemical corrosion of polycrystalline silicon (polysilicon) by hydrofluoric acid (HF)-based solutions is a long-standing issue in polysilicon MEMS field. This corrosion severely reduces fabrication yield and performance of MEMS resonators and makes it impossible to fabricate large resonators. In recent work, we found an effective solution to prevent electro-chemical corrosion of polysilicon.[6] Employing this key technique, a reliable low-cost fabrication process is developed to produce high-end disk resonators with various dimensions in radius (10 μm–80 μm).

Reliable characterization of resonance properties with high accuracy is another challenging technology for VHF resonator due to the effect of feed-through signal. There are three conventional schemes for characterizing resonance spectrum of VHF resonators: one-port, two-port, and mixing measurement.[1,7] One-port measurement has a large feed-through current, which results in the distortion of resonance spectrum, despite its advantages of low bias voltage, low noise, and large output signal. For two-port measurement, a large DC-bias voltage that is needed to drive the device into resonance easily destroys the device. Mixing measurement requires both a large AC input signal power and a high DC-bias voltage. In a word, all of these measurements have their own restrictions. Hence a reliable measurement scheme for characterizing VHF resonators is highly desired.

In this paper we also present a novel measurement architecture according to a differential readout topology. This measurement method can effectively suppress noise and surrounding feed-through current by common-mode rejection of the differential amplifier, and acquires a clean resonance spectrum of VHF

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†Corresponding author. E-mail: jlyang@semi.ac.cn
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resonators. Therefore, this method is suitable for reliable characterization of VHF resonators.

2. Fabrication of disk resonators

Figure 1 shows cross-sectional diagrams of the process flow for fabricating the disk resonators. The process starts with (100)-oriented Si wafer. Firstly, heavy boron implantation is done to form the p^+-doped substrate ground. Subsequently, a 2-μm-thick SiO_2 film is deposited by plasma enhanced chemical vapour deposition (PECVD), followed by the growth of a 500-nm-thick low-stress Si_3N_4 film with low pressure chemical vapour deposition (LPCVD). The SiO_2/Si_3N_4 layers electrically isolate the devices and interconnects from the conductive silicon substrate, and are patterned by inductively coupled plasma (ICP) dry etching to form substrate contact trenches (step (a)).[8] Secondly, a 500-nm thick *in-situ* boron-doped polysilicon (poly 1) is deposited by LPCVD to serve as interconnecting layer and substrate contact pads. In step (b), a sacrificial SiO_2 layer is deposited by PECVD. The second *in-situ* boron-doped polysilicon film (poly 2) with nearly zero-stress and relatively low resistivity is produced by LPCVD depositing amorphous silicon with large compressive stress and high resistivity at 520 °C then annealed at 750 °C.[9] Subsequently, a 1-μm thick PECVD SiO_2 layer is deposited to serve as a mask for dry etching poly 2 and as a spacer to separate the disk from overhanging electrode portions. The SiO_2/poly 2 is patterned after one lithography step to define the disk and a mini-opening (3-μm) for the disk stem. Thirdly, thermal oxidation is done to produce 70-nm thick sacrificial SiO_2 and to define the eventual capacitive gap spacing (step (c)). The small capacitive gap spacing is crucial for reducing the driving voltage. Then a 1.5-μm thick *in-situ* boron-doped LPCVD polysilicon (poly 3) with low-stress is deposited into an electrode layer and to create very rigid, self-aligned stems by refilling the anchor via. In step (d), the poly 3 layer is etched to define stem tops and electrodes with a 7-μm thick photoresist mask. Then the Au/Cr electrode pads are produced by e-beam evaporation and the lift-off process.

Finally, the structures are released in 49% concentrated HF solution. The concentrated HF-based solution has a high etch-rate of SiO_2 and a good etching selectivity of SiO_2/polysilicon as well as SiO_2/Si_3N_4. However, when the polysilicon devices containing noble metals are etched in HF-based solutions, polysilicon is subjected to electro-chemical corrosion due to its lower electro-chemical potential than that of the noble metal. This corrosion seriously degrades the mechanical and electrical performance of MEMS devices, e.g., increasing the resistivity of structural layer, reducing its Young's modulus, changing the stress gradient, etc., in the end the device reliabilities are deteriorated.[10,11]

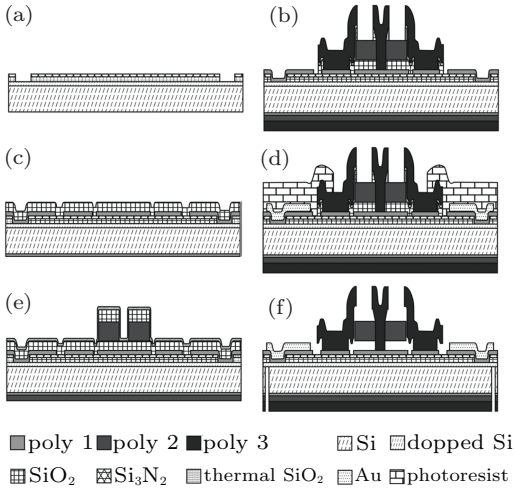


Fig. 1. Cross-sectional diagrams of fabrication process flow for disk resonators.

The key fabrication breakthrough presented here is a reliable and simple release process, in which a photoresist layer to cut off electrical current of electro-chemical corrosion and protect the polysilicon layer intact is used.[6] In the present work, an AZ6130 PR film of 3-μm thick is spin-coated and patterned to cover the whole surface of the test device except the release hole, and hard-baked at 70 °C, 90 °C, and 110 °C for 20 min, respectively (step (e)). By baking the PR film at step-up temperatures instead of at one targeting temperature, the porosity of the PR can be minimized. Thus the HF-based etchant can neither penetrate the PR layer nor contact the noble metal, the electrical current of the galvanic cell is cut off, and the electro-chemical corrosion of polysilicon is effectively restrained.

After releasing in HF solution, the devices are rinsed in deionized water, acetone, and isopropanol each for 5 min, sequentially, and dried on hot plate at 120 °C to avoid stiction (Fig. 1(f)). This fabrication method is simple, low-cost, IC-compatible, thus is suitable for batch fabrication of high quality disk resonators. Two types of disk resonators are fabricated

with this process: one-port disk and two-port disk as shown in Fig. 2.

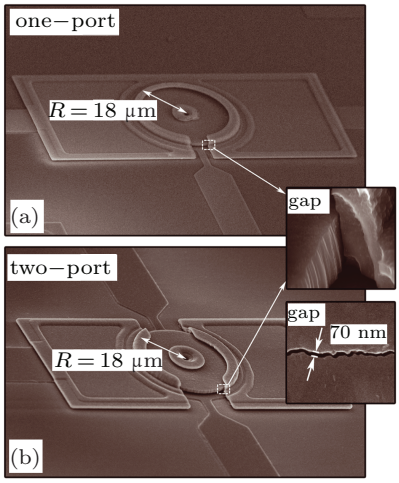


Fig. 2. SEM images of (a) one-port and (b) two-port disk resonator with 70-nm capacitive gap spacing.

3. Frequency characterization

3.1. One-port and two-port measurement using microwave probe station

Reliable characterization of resonance properties with high accuracy is another challenging technology for VHF resonator due to the effect of surrounding feed-through signal. The resonance spectra of one-port and two-port disk resonator each with a radius of 18 μm are obtained respectively by one-port and two-port measurement scheme as depicted in Fig. 3. The one-port measurement has a large feed-through current, which results in the distortion of resonance spectrum, despite its advantages of low bias voltage (8 V) and large output signal (Fig. 3(a)). However, the presence of a large feed-through current results in a small peak height, less than 1 dB above the base feed-through level. The parallel-resonance is evident at the sharp notch near the series resonance peak. For two-port measurement, the peak height increases to more than 4 dB above the base noise level due to the reduction of the feed-through current, and the parallel-resonance has been eliminated, but a large DC-bias voltage (20 V) is needed to drive the device into resonance as shown in Fig. 3(b).

A microwave probe station can dramatically suppress feed-through signal and is suitable for wafer-level measurement. When the microwave probe station is employed in the two-port measurement scheme, the peak height for a disk resonator with a radius of 10 μm is more than 10 dB above the base noise level and the Q factor reaches 2120 at atmosphere as shown in Fig. 4.

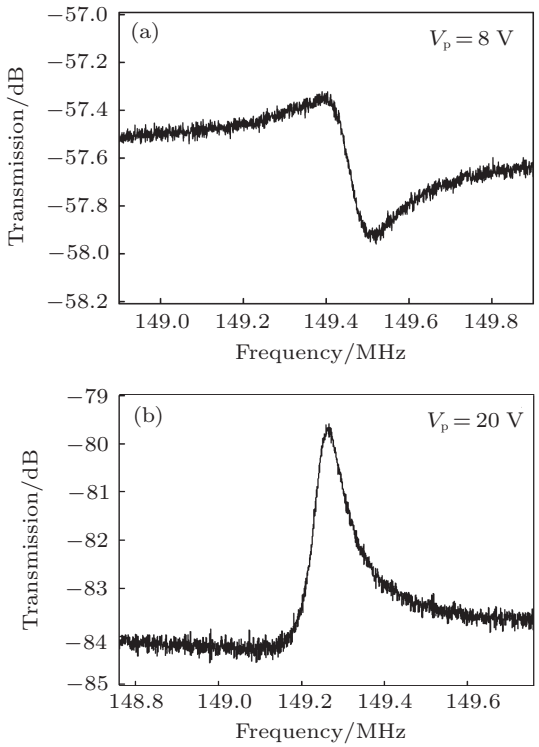


Fig. 3. Comparison between frequency characteristics of (a) one-port and (b) two-port disk resonator each with a radius of 18 μm.

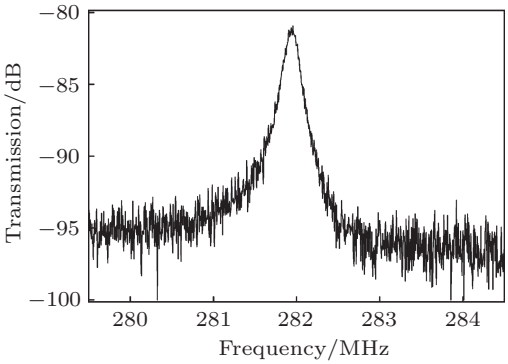


Fig. 4. S21 parameter of a two-port disk resonator with a radius of 10 μm.

3.2. Differential readout measurement scheme

In this paper we present a novel measurement architecture according to a differential readout topology as shown in Fig. 5. Two one-port disks (D1 and D2) with identical sizes are used in the circuit. The SiO_2 sacrificial layer underneath D1 is not removed, thus

D1 is not in normal operation; while D2 properly functions. When the input currents I_{AC1} and I_{AC2} pass through D1 and D2 respectively, the generated feed-through currents I_{fd1} and I_{fd2} are identical. In the time domain of the differential circuit, by subtracting two output signals from D1 and D2, the feed-through signal can be reduced to a minimum. In a corresponding frequency domain, the sharp notch caused by parallel resonance vanishes, and the output signal is clean resonance output as given in Fig. 6.

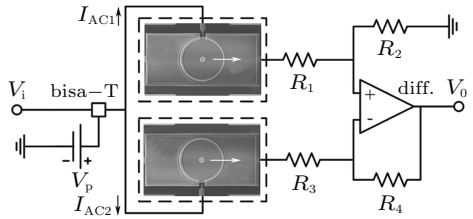


Fig. 5. Differential amplifier measurement scheme for disk resonators.

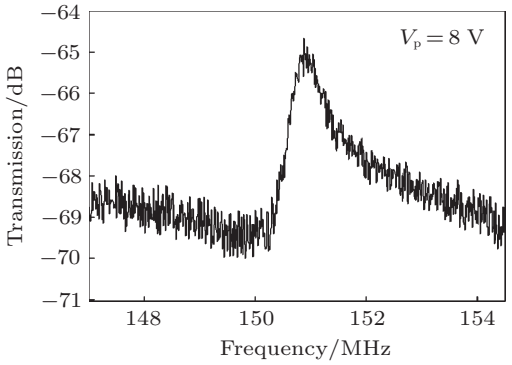


Fig. 6. Spectrum of one-port disk resonator characterized by differential amplifier measurement, setting $R_1 = R_3 = 50\ \Omega$, $R_2 = R_4 = 100\ \Omega$, and $U_o = (R_2/R_1) \times (U_1 - U_2)$.

Overall, the differential circuit proposed here can effectively suppress surrounding noise and feed-through current by common mode rejection of the differential amplifier. Therefore this method is suitable for reliable characterization of VHF resonator. In addition, a low driving voltage is enough for one-port disk resonators due to their large electrodes. However, there are two drawbacks of this method. Firstly, a high common mode rejection ratio (CMRR) amplifier is needed in order to reject the common mode signal generated by the resonator parasitic current.[12] For an amplifier, the CMRR becomes worse with the frequency going up to VHF, so the noise of the output signal increases as shown by comparing Fig. 6 with Fig. 3(b). Secondly, the gain-bandwidth product of an amplifier is approximately a constant. In the differential amplifier measurement scheme used for a VHF resonator, a large bandwidth is needed, thus a high gain is hard to realize, even though it is crucial for increasing output signal. In our experiment, the gain of amplifier is normally lower than 2. Better performance of the differential amplifier measurement scheme is expected by choosing high-end amplifier or designing on-chip amplifier with high (CMMR).

The differential amplifier circuit configuration mentioned above can also be used to build up a notch filter with high Q factor (24800) in air. Figure 7 shows the simulated and measured technical parameters of the notch filter. In the circuit, two one-port disk resonators with identical sizes, but slightly different resonant frequencies, work in normal operation. At a certain point near the resonant frequency, the S21 parameters and phases of the two disk resonators are equal to each other, thus one notch is formed by subtracting the output signals of two resonators.

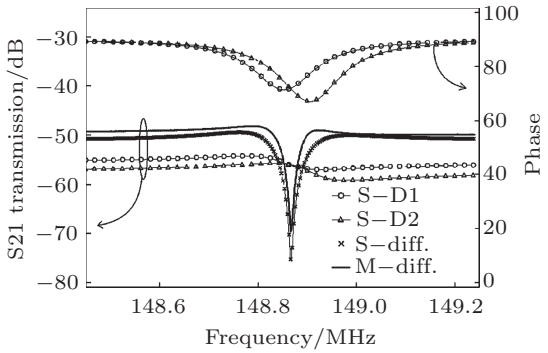


Fig. 7. Simulated (S-) and measured (M-) S21 parameters and phase shifts of the notch filter realized by differential amplifier circuit.

3.3. Stability discussion

During the measurement, when high bias voltage (about 50 V) is applied, the devices become unstable. Figure 8 shows the resonance spectra of the same resonator measured at different times; the resonator is driven by the same bias voltage. The transmission peaks of devices degrade with measurement cycle increasing, meanwhile the resonant frequencies go up. The unstable resonator behavior could be caused by the misalignment of the stem to the disk during fabrication process, which results in the frequency shifting up and the Q values going down.[7]

The poly 2 film for the disk has low stress, while the poly 3 film for the stem has high compressive

stress.[9] The different stress makes the stem fatigue easily. And the disk vibration is coupled to the substrate; this anchor loss degrades the overall resonator Q. However, a detailed study is needed to conclude this.

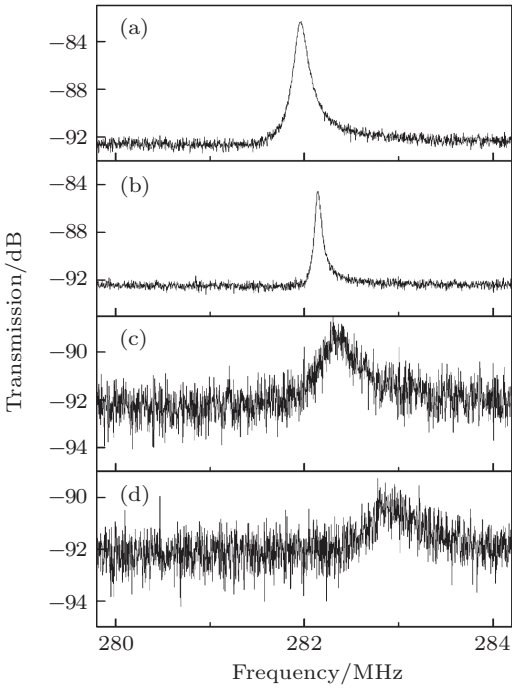


Fig. 8. Degradation of the resonator properties, from (a) to (d) the transmission of the device became worse.

3.4. Temperature dependence

Figure 9 gives the temperature dependence of frequency for a disk resonator of 10 μm in radius operated in fundamental mode, showing that the frequency decreases with temperature going up. The uncompensated temperature coefficient of frequency (TCf)

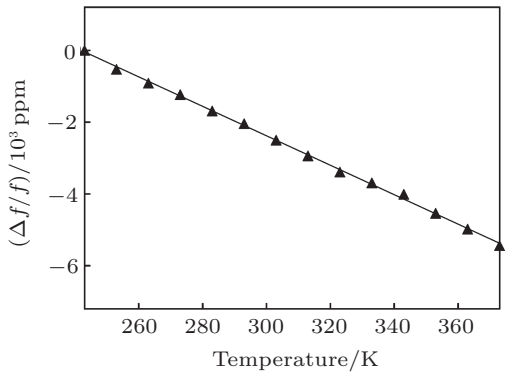


Fig. 9. Temperature dependence of frequency for a disk resonator with a 10-μm radius.

is –41.7 ppm/°C, which is larger than the reported result in Ref. [7]. This variation probably results from the different deposition conditions that determine the elastic properties of the films. In this work, the *in-situ* boron-doped polysilicon film is produced by LPCVD depositing amorphous silicon at 520 °C, then annealed at 750 °C.[9] Its Young's modulus has a negative temperature coefficient.[13] Temperature compensation is required for oscillator applications. In the future work, the temperature coefficient could be further improved by several different methods, including the use of electrostatic forces, alternative materials, stresses, or variable gaps, and so on.

4. Conclusions

A simple fabrication process is successfully developed to manufacture high quality resonators. This approach is not only simple, effective, IC technology compatible, and suitable for batch fabrication, but also able to significantly improve the performances of MEMS resonators with various dimensions (10 μm–80 μm). These advantages mainly benefit from exploiting an effective solution to prevent the polysilicon from electro-chemically corroding, thus dramatically improving the fabrication yield and resonance properties of the resonators.

In addition, in this paper we present a novel resonance characterization method for VHF resonators. This method is based on a differential readout topology, which can be used to effectively suppress surrounding feed-through current by common-mode rejection of the differential amplifier. This measurement scheme is simple, reliable, can work at low bias voltage, and has promising potential in precise characterization of VHF MEMS resonators, provided that an amplifier with high CMMR can be integrated in the future. This differential amplifier circuit configuration is also used to set up a notch filter with a high Q factor (24800). The microwave probe station can dramatically suppress the feed-through signal and is suitable for the wafer-level characterization of the real resonance properties.

This work also addresses the temperature coefficient of the frequency and the failure mechanism of the resonators actuated by a large voltage. The systematic study on these issues is in progress.

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