HONEYCOMB-LIKE DISK RESONATOR WITH HIGH IMMUNITY TO FABRICATION ERROR FOR GYROSCOPIC APPLICATION

Dingbang Xiao[1], Xin Zhou[1], Qingsong Li[1], Zhanqiang Hou[1], Yulie Wu[1], Wei Li[1], Xinghua Wang[1], Jinying Zhang[2,3], and Xuezhong Wu[1]*
[1]National University of Defense Technology, Changsha, CHINA
[2]Institute of Semiconductors, University of Chinese Academy of Sciences, CAS, Beijing, CHINA
[3]State Key Laboratory of Transducer Technology, Shanghai, CHINA

ABSTRACT

This paper reports a novel honeycomb-like disk resonator for gyroscopic application. Compared with the state of the art nested-rings disk resonator, the honeycomb-like disk resonator can provide more than two-fold higher immunity to the fabrication error, which means that structure imperfection could cause less relative frequency error. The honeycomb-like disk resonator also shows much higher resonant frequency which results in superiorities in robustness to the environment disturbance and mechanical resolution.

INTRODUCTION

Wine-glass mode gyroscopes show their superiority in size, accuracy, shock resistance, and operation life [1-7]. Among them, a kind of disk resonator made by nested rings has been an attractive candidate for making high performance MEMS gyroscope [5-8]. The disk resonator can provide high thermal stability, low anchor loss, large transducer area, and large modal mass. The mode-matched working condition of the wine-glass mode gyroscope is essential for obtaining high signal to noise ratio [8-9]. Though many methods can be utilized to match the driving and sensing modes [8-12], decreasing the dependence of the frequency spit from fabrication error and material defect is still attractive. In this paper, we demonstrate that the structural design could influence the robustness of a structure against fabrication error and material defect. And a novel honeycomb-like disk resonator providing excellent error robustness is proposed. Simulations and Experiments have been used to characterize this honeycomb-like disk resonator.

DESIGN AND FABRICATION

Design

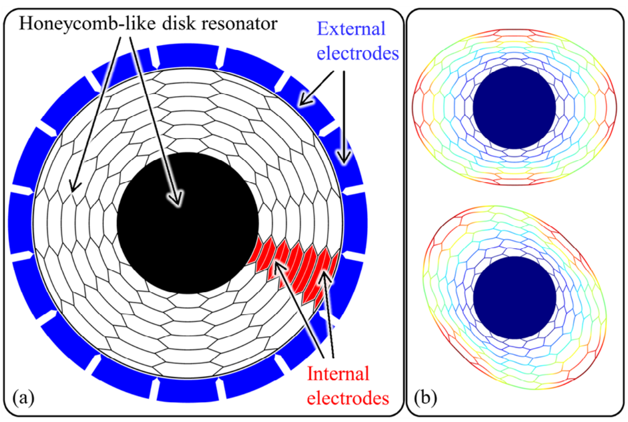

Figure 1: (a) Structural schematic of the honeycomb-like disk resonator, (b) n=2 wine-glass mode shapes.

The topological geometry of the disk resonator is similar to honeycomb, as shown in Figure 1(a). The 30 μm thick outer ring with 8 mm diameter is supported by interleaved hexagon frames with 19 μm thickness. The anchor diameter is 3.68 mm. The height of the resonator is 148 μm. The disk resonator is surrounded by 16 external electrodes, and the hexagon slots are inserted with internal electrodes. The *n*=2 wine-glass modes are used as the working modes, as shown in Figure 1(b). This disk resonator has large proof mass and large capacitance area.

Fabrication

This disk resonator is fabricated with aligned Au-Au thermo-compression bonding and DRIE process, as shown in Figure 2(a). A P-type 150 μm (111) single-crystal silicon wafer is used as the structure wafer. Au bonding pads are patterned, and then some 2 μm pillars are etched on the structure wafer for bonding. Another P-type 350 μm (111) wafer is used as the substrate. A 2 μm SiO_2 layer is grown on the substrate wafer by thermal oxidization. Then the mating Au bonding pads are patterned on the oxide layer. The structure wafer and the substrate wafer are bonded by using aligned Au-Au thermo-compression bonding process. The structure wafer is patterned with Al leading pads. Lastly, the resonator structure and the electrodes are released by a deep reactive ion etching process.

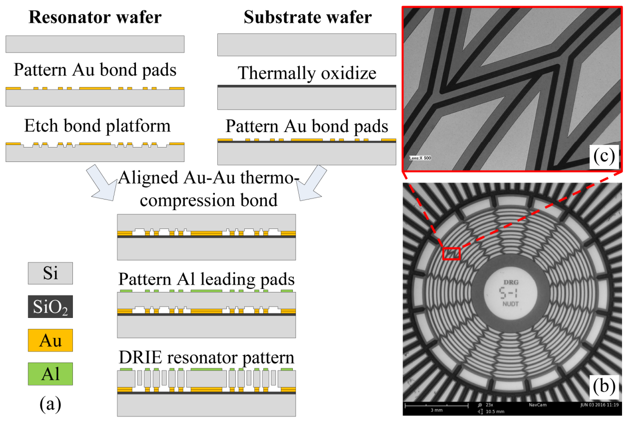

Figure 2: (a) Fabrication process. (b) Overview and (c) zoomed-in view of the fabricated honeycomb-like disk resonator.

One of the fabricated honeycomb-like disk resonators is shown in Figure 2(b), (c). The resonator is surrounded by 16 external capacitive electrodes. The hexagon slots in the disk resonator are inserted with internal capacitive electrodes which can be used for driving, sensing, tuning or parametric exciting. The capacitive gap is 15 μm.

METHODS

For the degenerated mode gyroscopes, reducing the mode mismatch is one of the bases to realize high performance. Relative frequency error (frequency split / resonant frequency) is the main index to evaluate the degree of mode mismatch. Besides, relative quality-factor (Q) error (Q mismatch / Q) is also an important indicator. In this part, simulations and experimental tests will be used to demonstrate that structural design could greatly influence the effect of the mechanical asymmetry to mode mismatch.

Crystal Orientation Error Simulation

The proposed disk resonators are made from (111) wafer. Young's modulus, Poisson's ratio, and shear modulus are transversely and vertically isotropic for (111) silicon [13]. Whereas crystal orientation error of the (111) wafer could cause an asymmetry in the disk resonator. Finite element analyses are implemented to calculate the relative frequency error and relative Q_{TED} error of the honeycomb-like disk resonator caused by crystal orientation error; those of the conventional nested-rings disk resonator are also calculated for comparison. The results are shown in Figure 3.

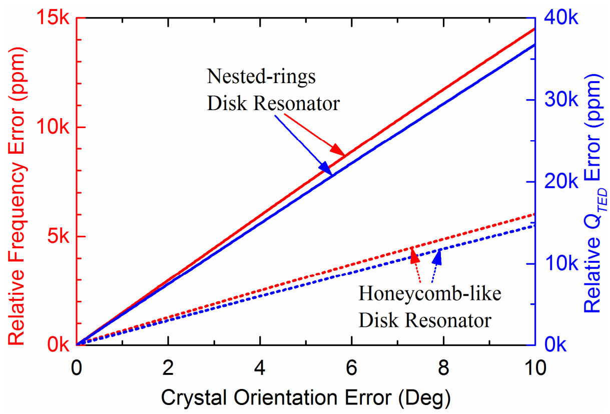

Figure 3: The relative frequency error and the relative Q_{TED} error vs. crystal orientation error of the honeycomb-like disk resonator and those of a nested-rings disk resonator.

The relative frequency error and the relative Q_{TED} error of the honeycomb-like disk resonator are about 2.4 times and 2.5 times smaller than those of the conventional nested-rings disk resonator.

Frequency Response Test and Electrostatic Tuning

The frequency response test is implemented to characterize the basic parameters of the honeycomb-like disk resonator. The frequency response analyzer (NF FRA 5087) is used to actuate the disk resonator. The AC driving signal is modulated into a carrier wave. The capacitance variation is monitored by a charge amplifier and a demodulator. The frequency response of a typical honeycomb-like disk resonator is shown in Figure 4. The as-fabricated frequency split is 3.66 Hz. The frequency split is reduced to less than 0.02 Hz using electrostatic tuning.

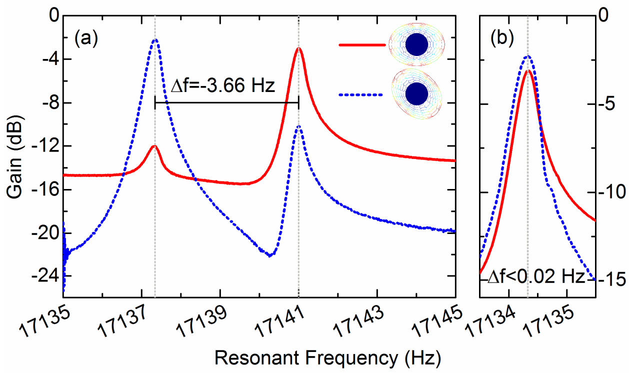

Figure 4: Frequency responses of the honeycomb-like disk resonator's n=2 wine-glass modes. (a) Initial frequency split is 3.66 Hz. (b) Frequency split is reduced to <0.02 Hz using electrostatic tuning.

The frequency split Δf_0 of the disk resonator can be divided into two orthogonal parts Δ_s and Δ_c

$$\Delta f_0 = \sqrt{\Delta_s^2 + \Delta_c^2}\ , \tag{1}$$

where Δ_s=Δf_0sin4ψ, Δ_c=Δf_0cos4ψ, and ψ is the angle between the anti-node orientation and the driving axis, which represents the angular offset of the mode shape. The outer most layers of the internal electrodes are used for tuning. Firstly, Δ_s can be compensated by applying highly stable DC voltage on 22.5° or 67.5° sets of electrodes. It is demonstrated that Δf_0 decreases / increases when a low voltage is applied on 22.5° / 67.5° electrodes. Thus, 22.5° electrodes should be used. We adjust the voltage on 22.5° electrodes, and Δf_0 reaches the lowest when the voltage is 14.7 V. At this point, the mode shape orientation error, or the quadrature is null. Lastly, Δ_c can be compensated by applying highly stable DC voltage on 0° or 45° sets of electrodes. It is demonstrated that Δf_0 decreases / increases when a low voltage is applied on 0° / 45° electrodes. Thus, 0° electrodes should be used. We adjust the voltage on 0° electrodes. Δf_0 is reduced to less than 0.02 Hz when voltage on 0° electrodes is 11.7 V. The precision of tuning is restricted by the stability of the applied DC voltage.

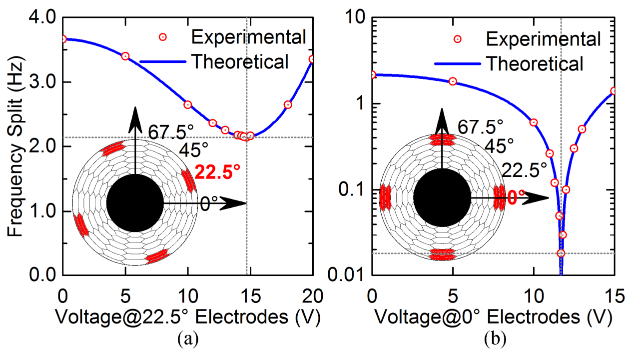

Figure 5: (a) Bias voltage of 14.7 V is applied on the outer two layers of 22.5° internal electrodes to diminish the offset of the mode shape orientation. (b) Frequency split is reduced to < 0.02 Hz by applying bias voltage of 11.7 V on the outer two layers of 0° internal electrodes.

Five honeycomb-like disk resonators and seven nested-rings disk resonators which are co-fabricated in one wafer is characterized by the frequency response test. The frequency splits with the resonant frequencies of those disk resonators are shown in Figure 6. The relative frequency error of the honeycomb-like disk resonators (175-229 ppm) is more than 2.3 times smaller than that of the nested-rings disk resonators (546-1381 ppm).

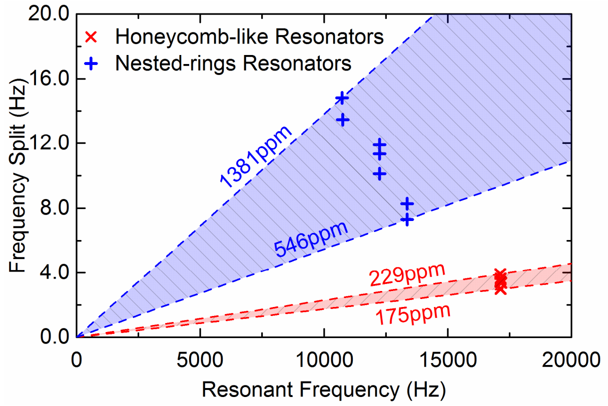

Figure 6: Frequency splits vs. resonant frequencies of the honeycomb-like disk resonators and the nested-rings disk resonators that are co-fabricated in one wafer.

Ring-down Test

The ring-down test is implemented to precisely characterize Q of the honeycomb-like disk resonators. First actuate the disk resonator at resonance using FRA 5087. Then stop the actuation and record the decaying signal by using a NI-DAQ card in Labview. The recorded decaying signal is then filtered and the enveloped using MATLAB. The decaying time constant τ is calculated by fitting the envelope with inverse exponential function $A_0\exp(-t/\tau)$. Q can be estimated based on $Q=\tau\pi f_0$.

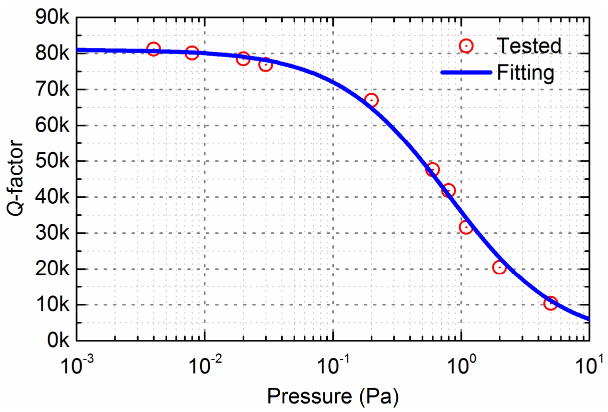

Figure 7: Qs measured at different pressure levels using ring-down test.

Qs of the honeycomb-like disk resonator under different pressure levels are measured using ring-down test. The result is shown in Figure 7. Q stops increasing when the pressure is below 0.01 Pa. The pressure-Q curve is fitted by an air damping model [14]. Q_{air} of the honeycomb-like disk resonator at 0.004 Pa is estimated to be about 16 million.

The ring-down signals of a honeycomb-like disk resonator's two wine-glass modes are shown in Figure 8. The Q mismatch is 252, and relative Q error is about 3000 ppm.

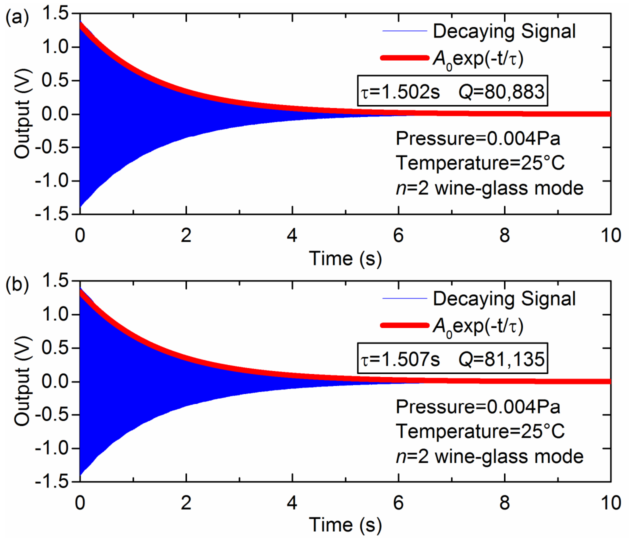

Figure 8: Ring-down signals of the honeycomb-like disk resonator's (a) first and (b) second n=2 wine-glass modes in 0.004 Pa vacuum and at temperature of 25°C.

The Q mismatches and Qs of the five honeycomb-like disk resonators and seven nested-rings disk resonators are shown in Figure 9. The relative Q error of the honeycomb-like disk resonators (2050-3169 ppm) is more than 1.7 times smaller than that of the nested-rings disk resonators (5562-7408 ppm).

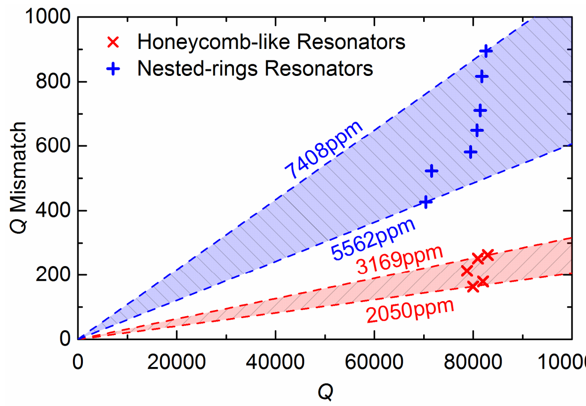

Figure 9: Q mismatches vs. Qs of the honeycomb-like disk resonators and the nested-rings disk resonators that are co-fabricated in one wafer.

RESULTS AND DISCUSSION

It is demonstrated that for a given material error or fabrication error, the honeycomb-like disk resonator shows less relative frequency and Q error compared with the conventional nested-rings disk resonator. The honeycomb-like disk resonator can provide much higher immunity to fabrication or material error.

The effective mass m_{eff} and the angular gain A_g of the honeycomb-like disk resonator is estimated using finite element analysis [15,16]. Mechanical resolution ARW_{mech} of the honeycomb-like disk resonator is estimated based on [17]

$$ARW_{mech} = \frac{1}{4A_g x_0}\sqrt{\frac{4k_B T_0}{2\pi f_0 m_{eff} Q}}\left(\frac{180}{\pi}\times 60\right)^{\circ}/\sqrt{h}\,, \quad (2)$$

where x_0 is the driving amplitude (assumed to be 1.5 μm).

k_B and T_0 are the Boltzmann's constant and the absolute temperature, respectively. The basic parameters of the honeycomb-like disk resonator are shown in Table 1. The basic parameters of a typical nested-rings disk resonator are also shown. The honeycomb-like disk resonator is superior to the nested-rings disk resonator in ARW_{mech}. The resonant frequency of the honeycomb-like disk resonator is about 60% higher than that of the nested-rings disk resonator. This means that the honeycomb-like disk resonator is also more robust to the environmental vibration or shock.

Table 1: Character comparison between the honeycomb-like disk resonator and the nested-rings disk resonator.

Disk Resonator type	Honeycomb-like	Nested-rings
f_0 (Tested)	17.1 kHz	10.7 kHz
Q	81.1 k	82.6 k
m_{eff}	0.36 mg	0.37 mg
A_g	0.414	0.396
ARW_{mech}	0.0031°/√h	0.0041°/√h

CONCLUSION

This study demonstrates that the geometric design of the micro resonators could greatly influence the immunity to fabrication error. A disk resonator with honeycomb-like design is presented. Compared with the conventional nested-rings disk resonator, this honeycomb-like disk resonator shows much higher immunity to the fabrication error, lower ARW_{mech}, and much higher robustness to the environmental vibration or shock.

Our future work will focus on characterizing the gyroscopic performance of this honeycomb-like disk resonator.

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CONTACT

*X. Wu, tel: +86-0731-84574958; xzwu@nudt.edu.cn