Proceedings of the 2003 IEEE International Frequency Control Symposium and PDA Exhibition Jointly with the 17th European Frequency and Time Forum

MINIATURIZATION OF ANGULAR RATE SENSOR ELEMENT USING BONDED QUARTZ TUNING FORK

Takahiro Inoue, Masahiro Yoshimatsu,
and Masanobu Okazaki
Nihon Dempa Kogyo Co., Ltd., Sayama, Saitama, JAPAN

Abstract **- We developed an extraordinarily miniaturized quartz tuning fork angular rate sensor element(5.3×0.94×0.24mm). In order to miniaturize an element without sensitivity degradation, we introduced composite quartz by bonding two monolithic wafers with reversing x axes. Moreover we applied photolithography which achieved fine patterning and excellent productivity. The sensor using the new element accomplished the specifications of angular rate sensor.**
Keywords **– Angular rate sensor element, quartz crystal tuning fork, composite quartz, photolithography**

I. INTRODUCTION

A piezoelectric vibratory gyroscope has been widely utilized as a angular rate sensor element. In particular, various types of piezoelectric ceramic elements were proposed and some of them have been already put to practical use [1] [2]. However piezoelectric ceramic has poor temperature characteristics and is not suitable for machining. Meanwhile it is known that quartz has excellent temperature characteristics and superior capability for machining. Therefore we investigated a compact angular rate sensor element using quartz crystal tuning fork and presented it 3 years ago [3]. In our paper we reported that we had developed a high quality, reliable and manufacturable angular rate sensor element.

Recently, angular rate sensor application is expanding significantly. For example,

1) To improve accuracy and reliability of automotive navigation system
2) Trigger for an automotive airbag during rollover
3) Vehicle stability control system
4) To detect hand movement during shooting by video and still camera

This situation demands high quality, massproduction and low price for sensor element. So we worked on further miniaturization of quartz crystal sensor element. However, we faced on some subjects for miniaturization [4]. We had to establish micromachining process which enabled manufacturable electrode structure, fine patterning and excellent productivity. We introduced 3 inches composite quartz wafer and photolithography technology as breakthrough.

II. MINIATURIZATION OF QUARTZ CRYSTAL SENSOR ELEMENT

A. 3 inches composite quartz wafer

The first subject for miniaturization is side wall electrode patterning. In conventional element, the sense electrode had to be divided on the side wall as shown in Fig.1. It is not easy to divide sense electrode on narrow side wall. Therefore to divide sense electrode obstructed to miniaturize sensor element. Fig.2 shows a bended single crystal element by coriolis force which is viewed from the top of an element. In case of single crystal, coriolis force bends tuning fork arms so that the dielectric polarization, namely piezoelectric effect, is generated on the side wall. That’s why dielectric polarization generated on the side wall must be detected by divided electrode.

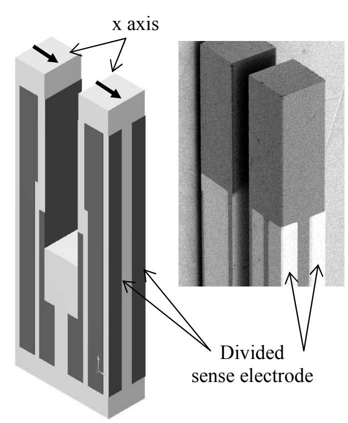


Fig.1. Conventional quartz crystal element for angular rate sensor.

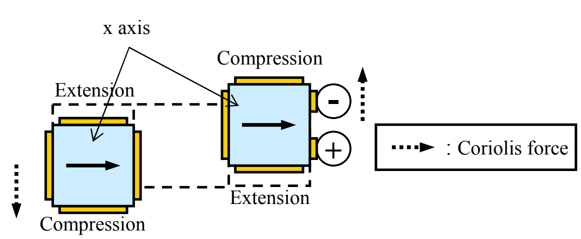


Fig.2. Bended single crystal element (conventional element) by coriolis force (Element top view)

On the other hand, we applied composite quartz to a new element. We introduced composite quartz by bonding two monolithic wafers with reversing x axes each other. Fig.3 shows a composite quartz wafer. Fig.4 is a picture of a new element which was made from composite quartz. The tuning fork is bonded and the sense electrode is not divided as shown in this picture. Moreover x axes are reversed because of composite quartz. Fig.5 shows a bended composite crystal element by coriolis force which is viewed from the top of an element. In case of composite crystal, coriolis force bends tuning fork arms as well as single crystal. However, due to reversed x axes of quartz crystal, dielectric polarization is generated, not on the same side wall, but between the opposite side walls. A composite crystal element enables to detect dielectric polarization without divided electrode and all side walls are available for sense electrodes in composite crystal. Consequently, no need to divide side wall electrode enabled to decrease the thickness of an element and increase of sense electrode area prevented sensitivity degradation by using composite quartz crystal. Fig.6 shows transition of quartz crystal elements. Quartz crystal elements were miniaturized by introducing composite crystal.

Quartz wafer bonding is shown symbolically in Fig.7. Quartz surface becomes hydrophilic after wet cleaning. Dehydration process proceeds during heat treatment so that Si-O-Si bonds are formed. They are so-called siloxiane. Fig.8 shows a cross sectional view of a composite quartz wafer by TEM. It is confirmed that two wafers are bonded through crystal boundary in the middle of the picture. Fig.9 shows summary of quartz wafer bonding process flow. Polished 3 inches monolithic wafers are processed cleaning, bonding and heat treatment. After that composite wafers are accomplished.

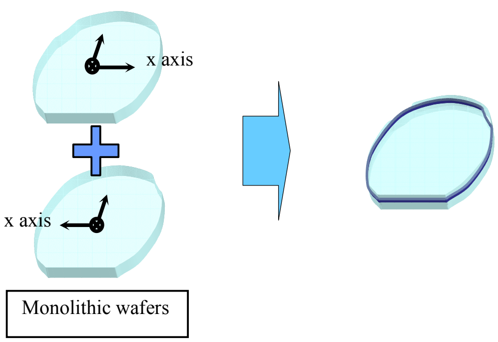


Fig.3. Composite quartz wafer

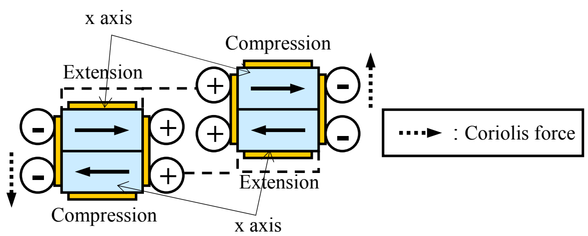


Fig.5. Bended composite crystal element (new element) by coriolis force (Element top view)

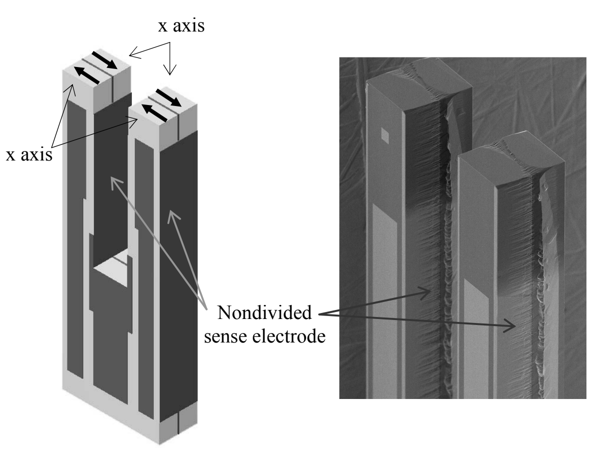
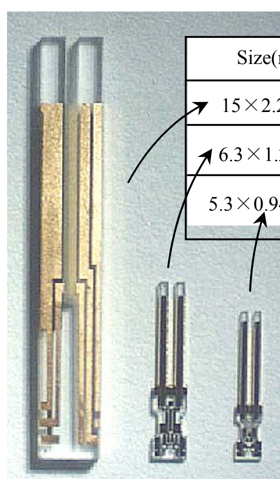


Fig.4. New quartz crystal element for angular rate sensor.



Size(mm)	Crystal	Status
15×2.2×0.9	Single	Withdrawal
6.3×1.2×0.3	Composite	Production
5.3×0.94×0.24	Composite	Developed

Fig.6. Transition of quartz crystal elements.

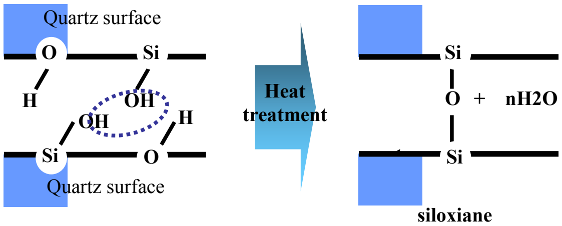


Fig.7. Quartz wafer bonding.

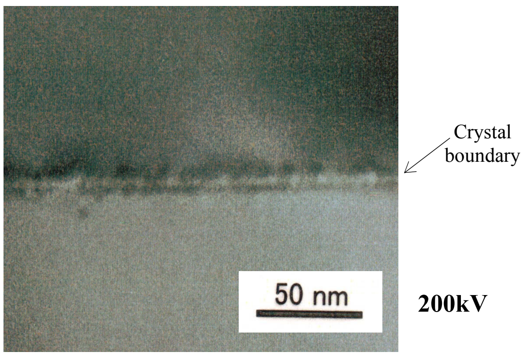


Fig.8. Cross sectional view of composite quartz wafer by TEM.

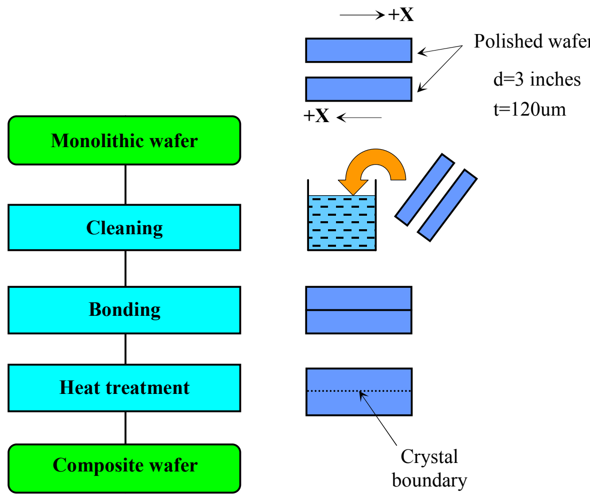
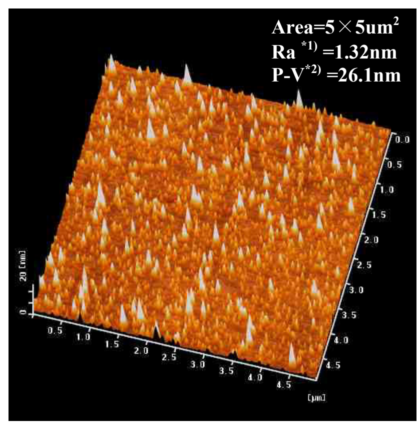
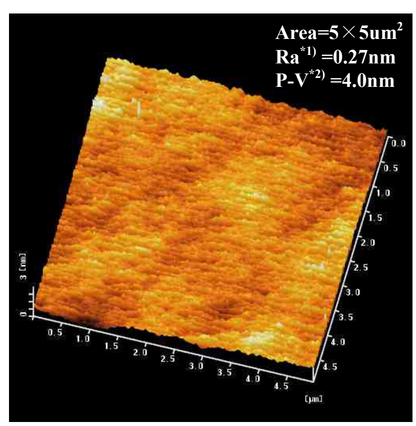


Fig.9. Summary of quartz wafer bonding process flow.



(a) Not optimized



(b) Optimized

Fig.10. Quartz wafer surface morphology by AFM.

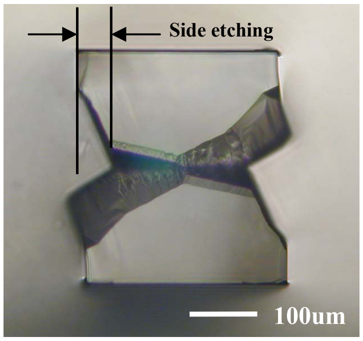
*1) Ra : Mean roughness
*2) P-V : Peak to valley

We optimized polishing, cleaning and heat treatment so that we established quartz wafer bonding process. The optimization results of polishing, cleaning and heat treatment are shown as following.

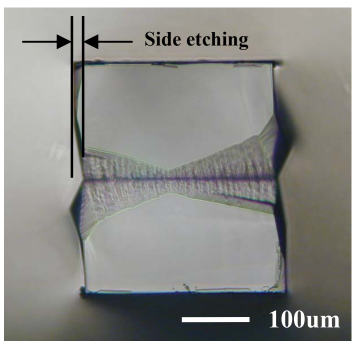
At first, the optimization result of polishing and cleaning is shown in Fig.10. Flat and clean surface enabled to wafer bonding process. Fig.10 shows surface morphology of quartz wafer by AFM. In "not optimized" condition, a lot of projections were observed on the wafer and this kind of wafers could not be bonded. Meanwhile smooth surface was observed in "optimized" condition and could be bonded successfully. Fig.11 shows the optimization result of heat treatment. These pictures show elements top view by microscope after tuning fork shape etching. Lower anneal temperature caused side etching along the crystal boundary during tuning fork shape etching as shown in this picture. This kind of elements didn't work as a sensor element because of output noise. On the other hand, optimized anneal temperature minimized side etching. So we could prevent to increase of output noise.

B. Photolithography technology

Another subject for miniaturization is fine patterning and productivity. In a conventional element, the tuning fork shape was made by machining. And electrode was patterned by evaporation with metal mask. However, these technologies are unsuitable for miniaturization and micromachining. So we applied photolithography technology to a new element as solution.



(a) Lower temp.



(b) Optimized temp.

Fig.11. Element top view by microscope.

Fig.12 shows the summary of process flow that was applied to a new element. The cross sectional views of elements are also shown by process. Process flow is composed of wafer bonding, tuning fork shape etching, electrode patterning, inspection and assembly. We introduced photolithography technology to tuning fork shape etching process and electrode patterning process. Fig.13 shows a 3 inches composite wafer before assembly process and a miniaturized quartz crystal sensor element This chip is arrayed continuously on the wafer like matrix. After all we developed the smallest quartz crystal sensor element in the world.

C. Summary

The comparison between a conventional element and a new element is listed in TABLE I. As regards a quartz wafer, a monolithic wafer was changed to a composite wafer. Besides photolithography technology was introduced instead of machining and metal mask technique. As a result chip size is miniaturized and volume ratio was reduced to about 4%. The output

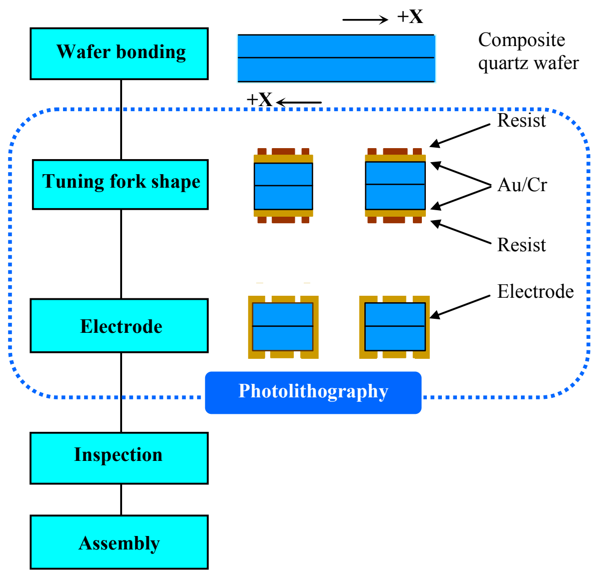
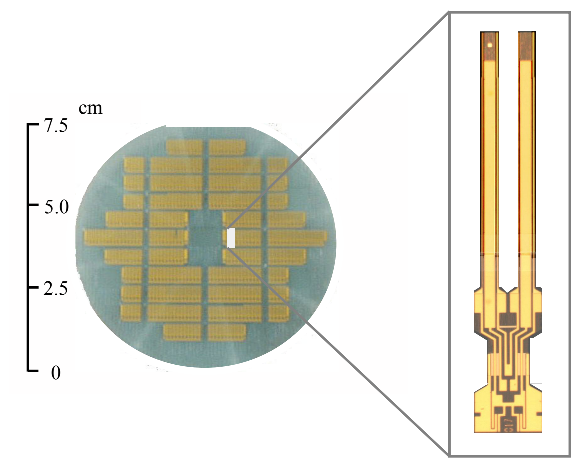


Fig.12. Summary of process flow with the element cross sectional views by process.



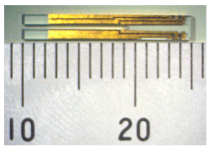
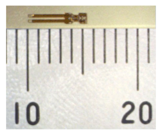
(a) 3 inches composite wafer

(b) Sensor element
5.3×0.94×0.24mm

Fig.13. Miniaturized quartz crystal sensor element manufactured from 3 inches composite wafer.

characteristic of angular rate sensor is shown in Fig.14. It is found that output voltage was linearly changed according to angular rate. It appears that the new element showed no degradation against the conventional element. At last the characteristics of the angular rate sensor is listed in TABLE II. The angular rate sensor using composite quartz accomplished these specifications.

TABLE I. The comparison between conventional element and new element.

Item	Conventional	New
Quartz wafer	Monolithic	Composite
Tuning fork shape	Machining	Photolithography
Electrode pattern	Metal mask	
Chip size(mm)	15×2.2×0.9	5.3×0.94×0.24
Volume ratio	1.0	0.040
Chip externals		

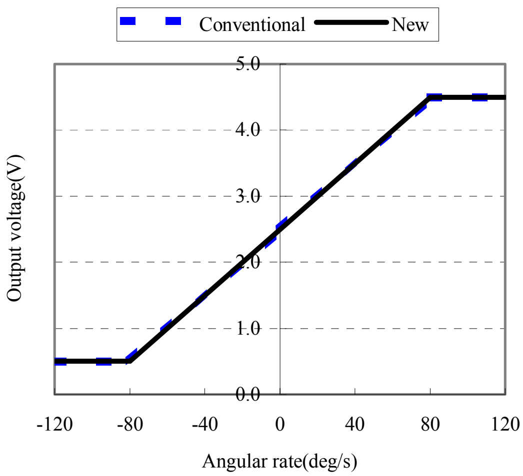


Fig.14. Output characteristic of angular rate sensor using miniaturized quartz crystal sensor element.

TABLE II. The characteristics of the angular rate sensor using miniaturized quartz crystal sensor element.

Parameter	Specification	Experimental
Nominal frequency	17.1±0.2kHz	16.980kHz
Sensitivity	25mV/deg/sec	25mV/deg/sec
Output voltage	0.3 to 4.7V	0.30 to 4.70V
Output noise	<10mVp-p	4mVp-p
Zero point voltage	2.5±0.4V	2.40V

III. CONCLUSION

We established 3 inches quartz wafer bonding process which enabled composite quartz crystal. Composite quartz crystal eliminated the divided sense electrode structure so that a miniaturized manufacturable sensor element was developed. Photolithography technology achieved fine patterning and excellent productivity. Finally we developed an extraordinarily miniaturized angular rate sensor element.

REFERENCES

[1] T. Nakamura, “Vibration gyroscope employs piezoelectric vibration”, *JEE,* September, pp99-104(1990).

[2] H. Abe, T. Yoshida, and K. Turuga, “Piezoelectric-ceramic cylinder vibratory gyroscope”, *Jpn. J. Appl. Phys.,* **31**, pp.3061-3063(1992)

[3] H. Matsudo, M. Ishihara, S. Kawasaki, J. Yukawa, and M. Hatanaka, “Quartz crystal element for angular rate sensor”, *Proc. IEEE/EIA International Frequency Control Symposium,* pp.115(2000)

[4] M. Okazaki, et al., “Miniaturized quartz tuning fork angular rate sensor”, *Proc. 2000 Eng. Sciences Society Conf. IEICE*, pp.321-322(2000)[in Japanese].