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Wafer-level Vacuum Packaged X and Y axis Gyroscope Using the Extended SBM Process for Ubiquitous Robot applications

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Abstract: A wafer-level vacuum packaged x and y axis gyroscope is fabricated on a (111) SOI wafer using the extended SBM (sacrificial bulk micromachining) process. The gyroscope uses vertically offset combs to resonate the proof mass in the vertical plane, and lateral combs to sense the Coriolis force in the horizontal plane. The extended SBM process is a simple two-mask process, and because all structural parts and combs are defined in one mask level, there is no misalignment in any structural parts or comb fingers. The silicon-to-glass anodic bonding carried out in low vacuum is used for the encapsulation of the fabricated gyroscope. The fabricated x and y axis gyroscope resolves 0.7 deg/sec angular rate, and the measured bandwidth is 22 Hz. The input range and the output linearity are over ± 80 deg/sec and 1.03 %FSO, respectively. The fabricated vacuum packaged x and y axis gyroscope without align error is important component at the high performance multiple-axis gyroscopes. The multiple-axis gyroscopes are used in many applications such as recently interested ubiquitous robot, car navigation, game controller, vehicle safety system, and so on.

1. INTRODUCTION

A planar x and y axis MEMS gyroscope has received much attention for multiple-axis inertial sensing applications. Multiple-axis gyroscopes are used in a myriad of application areas such as ubiquitous robot application, mobile device, car navigation, rollover detection, vehicle dynamic control, computer mouse, and game controller. More recently ubiquitous robot application has been investigated because it allows small volume, low-cost, and high performance sensors. Multiple-axis gyroscopes in ubiquitous robot application are utilized by sensing and controlling precise motion and position. For the realization of multiple-axis gyroscopes, one method is to assemble 3 one-axis gyroscopes orthogonal to each other. However, this method doesn't allow small volume, low-cost, and high performance. Another method is integrating x, y and z-axis gyroscopes in one planar substrate, which is very difficult to realize the combination of vertical and horizontal motions on the same plane. A z-axis gyroscope with lateral motion is easily implemented while an x or y-axis gyroscope with vertical and lateral motions is hardly achieved. There have been previous works on x-axis gyroscopes using silicon to silicon wafer bonding techniques (Robert A. C. et al., 2000, Jin-Ho L. et al., 2002). Although vertically offset combs can be fabricated by defining upper and lower electrodes on different wafer and then bonding them together, there are inevitable misalignment error of upper and lower electrodes leading to a significant secondary motion, which is undesirable for any sensor.

This paper presents the vacuum packaged x and y axis gyroscope using the extended SBM process on one silicon wafer. The extended SBM process can fabricate vertically offset combs in single-crystalline silicon with no alignment error, by defining all combs and structural parts in the same mask (Jongpal K. et al., 2002, Jongpal K. et al., 2005). The vertical actuation method of the x and y-axis gyroscope is referred to the previous literature. The obtained gyroscope using ESBM process shows better performance than gyroscopes previously mentioned two methods. And the wafer-level packaging

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process provide rather than the chip-level packaging process to achieve mass-production and lower packaging cost.

2. DESIGN AND FABRICATION

2.1 Design of the x and y axis gyroscope

The x-axis gyroscope is designed to detect the x-axis input angular rate which is parallel to the device substrate, as shown in Figure 1. The FEA (Finite Element Analysis) results are given in figure 2. The outer and inner masses are actuated together in the z-direction, using the vertically offset combs fabricated by the extended SBM process. When an angular rate is applied in the x-direction, the Coriolis force is generated in the y-direction. The movement of the outer mass in the y-direction is restricted because of the high stiffness of the vertical actuation spring in the y-direction. Only the inner mass can move in the y-direction by the Coriolis force. The capacitance change of the sensing combs connected to the inner mass is converted into the voltage using the C/V converter, and then the C/V converter's output is modulated using the AM modulator. The x-axis angular rate is measured. The y-axis gyroscope is easily fabricated by rotating the x-axis gyroscope by 90 degrees in the mask layout.

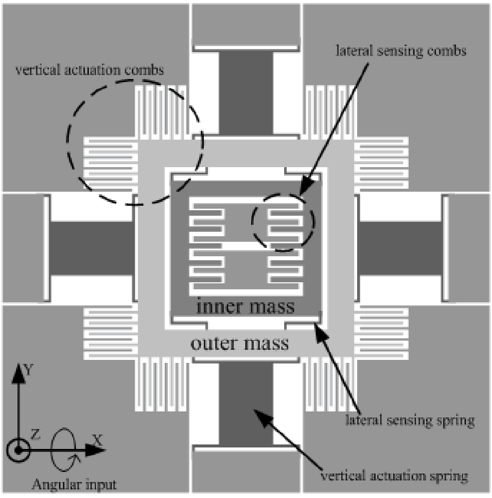
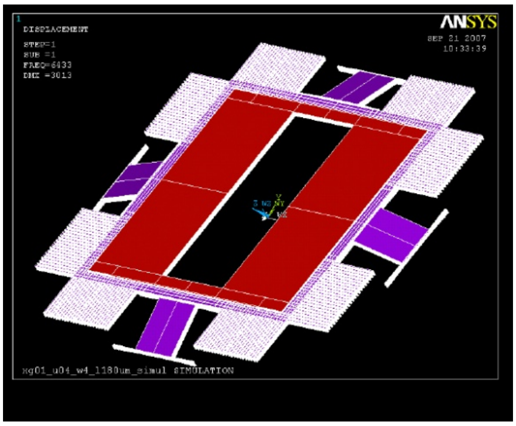
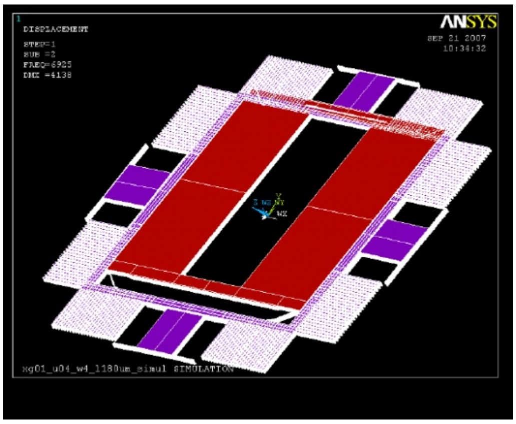


Fig. 1 Scheme of the fabricated x and y axis gyroscope



(a) Driving mode



(b) Sensing mode

Fig. 2 X and y axis gyroscope FEA results

***2.2** Fabrication*

Figure 3 shows the schematic of vacuum packaged gyroscope. The silicon structure is fabricated on a (111) SOI wafer by extended SBM process and the fabrication steps, in order, are shown in Figure 4 (Jongpal K. et al., 2002, Jongpal K. et al., 2005). Initially, the first oxide etch mask is deposited and patterned. Subsequently, a second etch mask is deposited, and patterned to cover the upper comb pattern generated by the first mask (Figure 4(a)). In order to create a thickness difference between upper and lower comb patterns, the first etch mask is slightly etched. After this, silicon is etched by deep RIE (Reactive Ion Etch) (Figure 4(b)). Then the second etch mask is removed and the second silicon etching by deep RIE technique is performed to define the silicon structure (Figure 4(c)). Sidewall passivation film is then deposited, and the bottom film is etched (Figure 4(d)). Silicon is again etched by deep RIE for the third time and then sacrificial etch is performed in an alkaline solution (Figure 4(e)). Now, the first etch mask is etched until the top surface of lower silicon combs are exposed and the fourth deep silicon RIE is performed. By controlling the depth of deep silicon etch in the fourth step, the vertical offset between upper and lower combs can be adjusted (Figure (4f)). Finally, the etch mask and sidewall passivation film is stripped (Figure 4(g)). In the extended SBM process, although two photo masks are used, all the in-plane dimensions of structures are determined to the first photo mask. Therefore, there is no horizontal alignment error between the upper and lower electrodes. Through four steps of deep silicon etch, the thickness of upper electrode and lower electrode, the vertical overlap or offset between the upper and lower electrodes, and the sacrificial depth can be defined arbitrary.

A Pyrex 7740 glass wafer, which is used for the wafer-level vacuum package, has cavities for protection of silicon structures and via-holes for interconnections. Process steps are shown in Figure 5. The glass wafer is deposited by poly-silicon (figure 5(a)). Then poly-silicon is patterned, and the glass wafer is etched by HF (Hydrofluoric acid) solution for the 1st cavities. The glass wafer, has the 1st cavities, is again deposited by poly-silicon (figure 5(b)). The glass wafer is etched by sandblast for making via-holes (figure 5(c)). Then, the glass wafer is etched for the 2nd cavities. Then, the glass wafer is wet etched to make the 2nd cavities. The 2nd cavity prevents stiction between silicon structure and glass during anodic bonding process. Finally, poly-silicon is removed by alkaline solution (figure 5(d)), and Ti getter material is deposited in the glass wafer (figure 5(e)). Ti getter enhances the vacuum level in cavities.

The Anodic bonding of the structure wafer and the fabricated glass wafer is carried out in low vacuum. Then, the getter is activated in high temperature. Next, a metal interconnection layer is deposited and patterned for the wire bonding process. Then, the bonded wafer with metal interconnection layer is annealed in order to have low contact resistance. It has been observed that the contact resistance of metal-silicon, without annealing, is more than hundred kilo-ohms, and it is less than hundreds ohms after the annealing treatment.

Figure 6 shows the fabricated x-axis gyroscope with 3.5 mm × 2.86 mm size, and 40 ㎛ thickness using the extended SBM process. Figure 7 shows the magnified view of vertically offset actuation combs. The actuation combs have vertically offset 11 μm between upper and lower combs. The lateral spring and sensing combs for sensing the Coriolis motion is shown in Figure 8. The cross section of the wafer-level vacuum packaged x- / y- axis gyroscope is shown in Figure 9(a). Figure 9(b) shows the cross section of sensing electrodes. Figure 9(c), 9(d) show metal electrodes patterned on the glass wafer and silicon electrodes are interconnected by metal.

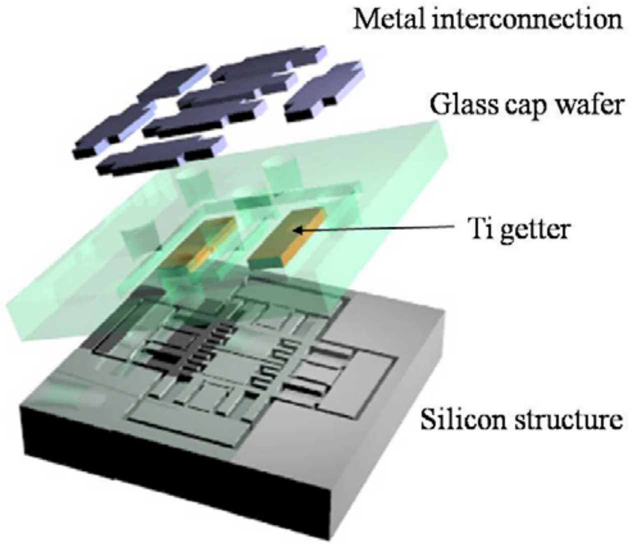
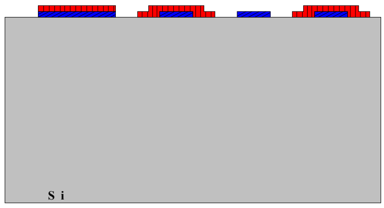
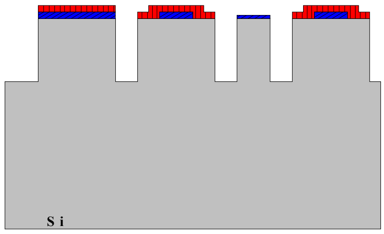


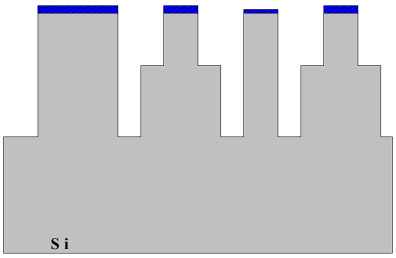
Fig. 3 Schematic diagram of vacuum packaged gyroscope



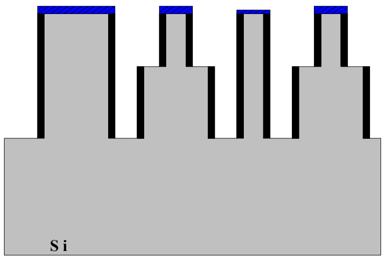
(a) The 1st etch mask and the 2nd etch mask are patterned



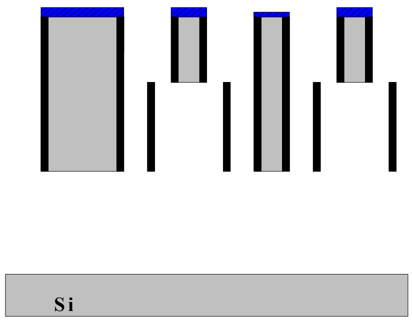
(b) The 1st etch mask is slightly etched and the 1st deep silicon etch is performed



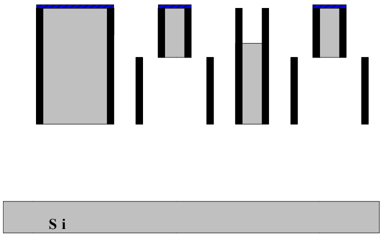
(c) The 2nd etch mask is removed and the 2nd deep silicon etch is performed



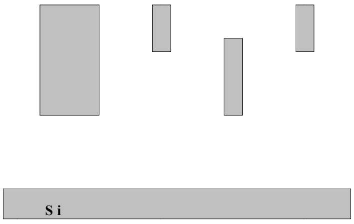
(d) The sidewallpassivation film is deposited and the bottom film is etched



(e) The 3rd deep silicon etch by deep RIE followed by sacrificial etched in an alkaline solution



(f) The 1st etch mask of the lower comb pattern is etched and the 4th deep silicon etch is performed



(g) The etch mask and sidewallpassivation film is removed

▢ Si 🟦 The 1st etch mask 🟥 The 2nd etch mask ⬛ Sidewall passivat on film

Fig. 4 the process flow of the ESBM process-

(a) Poly-silicon is deposited.

(b) The 1st cavity is etched by HF solution, and poly-silicon is deposited.

(c) Via-holes etched by sandblast.

(d) The 2nd cavities are etched by HF solution, and poly-silicon is removed by alkaline solution.

(e) Ti getter is deposited by thermal evaporator.

🟧 Poly-Silicon 🟦 glass 🟧 Ti getter

Fig. 5 Process flow of the glass wafer used for the wafer-level vacuum package.

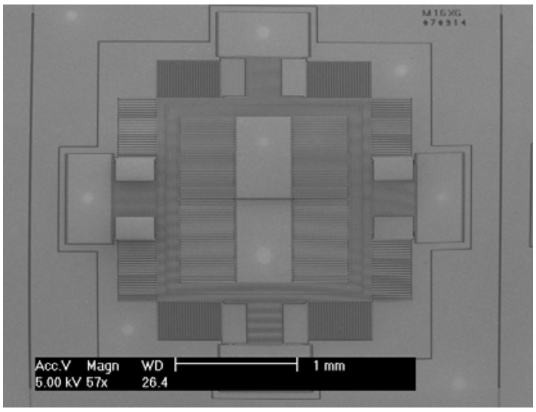


Fig. 6 SEM picture of the fabricated x- / y- axis gyroscope

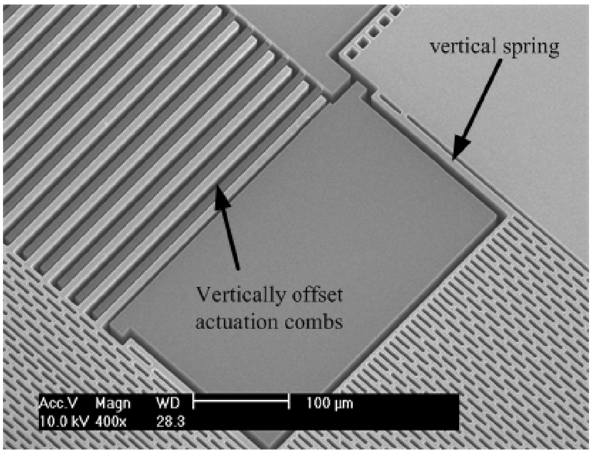


Fig. 7 Close up view of the vertically offset actuation combs

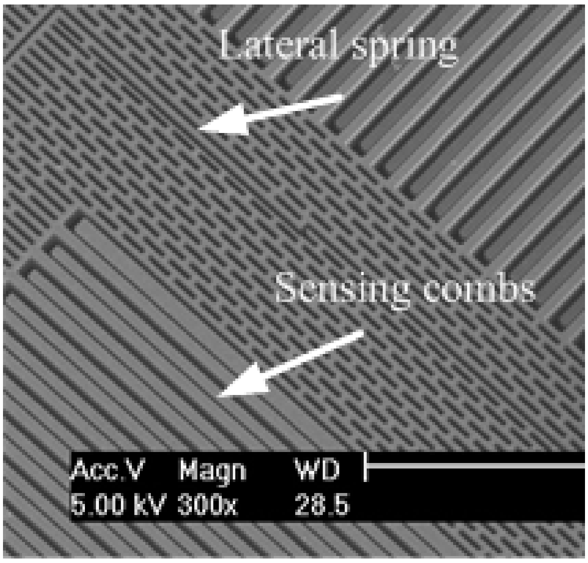
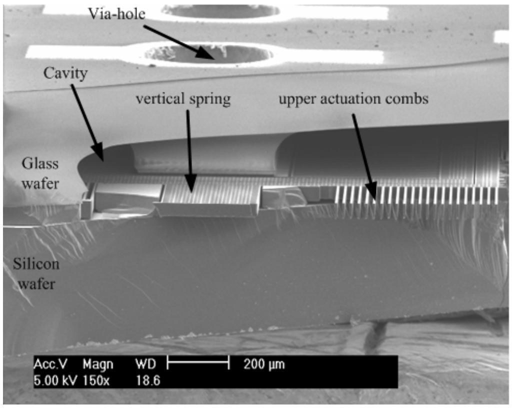
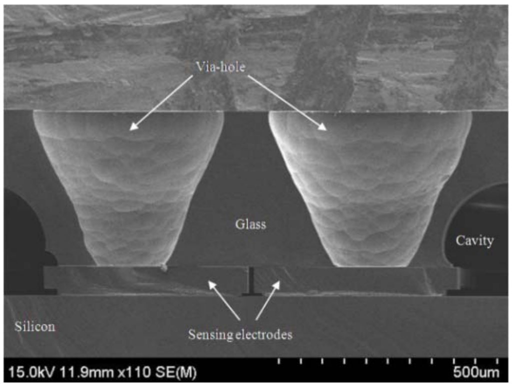


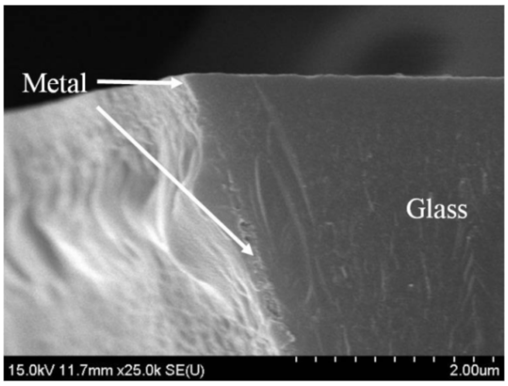
Fig. 8 SEM picture of the lateral spring and sensing combs for sensing the Coriolis motion



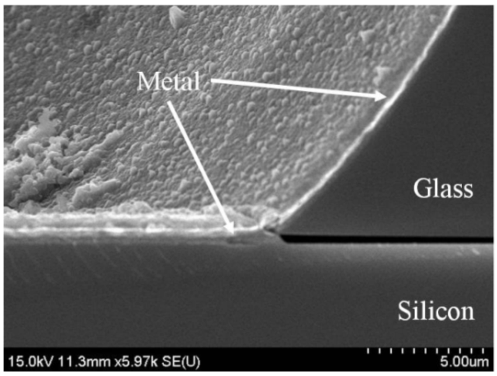
(a) The cross section of vacuum packaged gyroscope



(b) The cross section of sensing electrodes



(c) Close up view of the Via-hole's top



(d) Close up view of the Via-hole's bottom

Fig. 9 The cross section of the wafer-level vacuum packaged gyroscope

3. PERFORMANCE EVALUATIONS

The wafer-level vacuum packaged x and y axis gyroscope is tested using the detection circuit scheme as shown in Figure 9. The gyroscope is electrically modeled as variable capacitors in the dot-lined box. The detection circuit is implemented with two charge amplifiers, two high pass filters and a differential amplifier. When an input angular rate is applied to the gyroscope, the capacitance change of sensing combs is converted into the voltage by the C/V converter. The voltage is produced in the charge amplifier, and then the output signal of the charge amplifier is modulated by AM modulator. The input angular rate is obtained the demodulated output signal of the charge amplifier.

Figure 11 shows the demodulated output spectrum when 50 deg/sec, 9 Hz input rate is applied. The measured NER (Noise Equivalent Resolution) is 0.7 deg/sec. Figure 12 shows the time domain output when 50 deg/sec, 9 Hz input rate is applied. Figure 13 shows the frequency response of the gyroscope. The measured bandwidth is 22 Hz. Figure 14 shows the measured input-output angular rate characteristic. The range is over ± 80 deg/sec, and the output linearity is 1.03 %FSO.

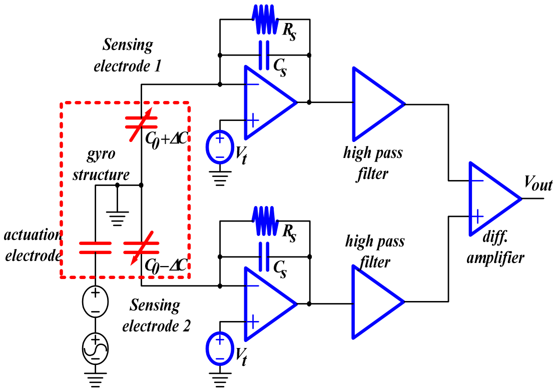


Fig. 10 Detection circuit schematic for the performance test of the fabricated gyroscope

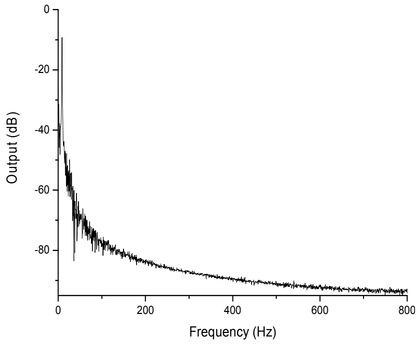


Fig. 11 Output spectrum when 50 deg/sec, 9 Hz angular rate input.

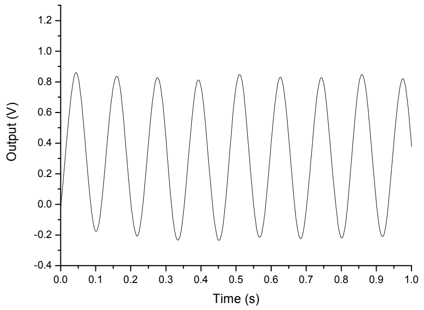


Fig. 12 Time domain output when 50 deg/sec, 9 Hz input rate

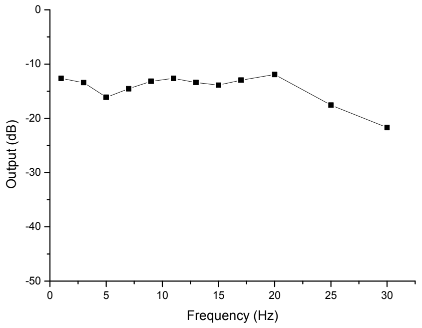


Fig. 13 Measured bandwidth of the fabricated gyroscope

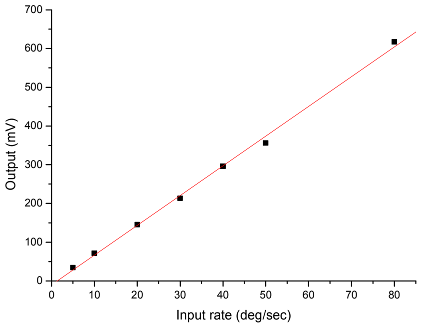


Fig. 14 Output versus angular-rate input

4. CONCLUSION

A wafer-level vacuum packaged single-crystalline silicon x and y axis gyroscope is fabricated using the extended SBM process and wafer-level vacuum packaging process.

The performance of the obtained gyroscope is experimentally evaluated. The measured NER (Noise Equivalent Resolution) is 0.7 deg/sec, when 50 deg/sec, 9 Hz input angular rate. The measured bandwidth is 22 Hz. The range is over ± 80 deg/sec, and the output linearity is 1.03 %FSO.

The fabrication of the vacuum packaged x and y gyroscope allows integrating the x-, y- and z- axis gyroscope on a parallel plane with no misalignment error when implementing a multi-axis gyroscope. This multiple-axis gyroscope is expected to provide advantages of small volume, high performance, and low-cost sensor for URC application.

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[Development of Solutions and Core Technologies for u-Robot HRI Project]

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