A Novel Wireless Thermal Convection Type Angular Accelerometer with Xenon Gas Filled in Hemispherical Chamber of Floating and Non-Floating Structures

Jium-Ming Lin
Dept. of Communication Engineering, Chung-Hua University, Hsin-Chu 30012, Taiwan, ROC.
Email: jmlin@chu.edu.tw

Cheng-Hung Lin
Ph. D. Program in Engineering Science, College of Engineering, Chung-Hua University, Taiwan, ROC
Email: b09306014@chu.edu.tw

Abstract—Five novel ideas are proposed in this paper to integrate an active RFID tag with thermal convection angular accelerometer on a flexible substrate, thus the device is a wireless sensor. The first idea is that this device is without any movable parts, so it is very reliable. The second one is that it is made on a flexible substrate, such as plastic or polyimide, the thermal conductivity of the flexible substrate of which is much lower than silicon, and thus it can save more power and very useful for mobile operation. The third idea is to apply xenon gas is in the chambers with floating and non-floating structures instead of CO2 used in the traditional thermal convection accelerometer for heat conduction. Carbon dioxide may oxidize the heater and thermal sensors, while the inert gas xenon does not. So the heater reliability and life cycle can be increased. Besides, the Xe molecular weight (131.29 g/mol) is three times of CO2 (44.01 g/mol), so the inertia is larger and can yield quicker time response. The fourth new idea is to apply a hemispherical chamber; it is more streamlined in nature with less drag effect. Thus it can ease the fluid flow and yield quicker response. The fifth idea is to integrate the angular accelerometer with an active RFID tag on the same substrate, thus the device becomes a more useful wireless sensor. From the results if one considers sensitivity as the first priority, then the non-floating structure is the choice (258°C/(rad/s²) in average). However, if the response speed is the top requirement, then the floating structure is better (60μs).

Index Terms—angular accelerometer, RFID tag, flexible substrate, thermal convection, hemispherical chamber, xenon gas, E-bean evaporation, non-floating structure

I. INTRODUCTION

Conventional accelerometers are made on silicon wafers [1-21], some of them used the thermal convection technologies, and the chamber is filled with air, CO2, liquid, or others. As shown in Fig. 1 five novel ideas are proposed in this paper to integrate an active RFID tag with thermal convection angular accelerometers on a flexible substrate, thus the device is a wireless sensor. The first innovative idea is that the new device is without any movable parts, so the reliability is very good. The second new idea is that it is made on a flexible substrate, such as plastic or polyimide, since the thermal conductivity of the flexible substrate such as polyimide (0.06-0.0017 W/(cm-K)) is about twenty-fifth of the silicon (1.48 W/(cm-K)) thus it can save more power leakage through the flexible substrate. The third new idea is to use xenon inert gas in the chambers with floating and non-floating structures for heat conduction instead of the previous CO2, which can produce oxidation effect to the heater and thermal sensors [1-21], while the xenon gas will not. So the heater reliability and life cycle can be increased. Besides, the Xe molecular weight (131.29 g/mol) is three times of CO2 (44.01 g/mol), so the inertia is larger and can yield quicker time response. The fourth new idea is to apply a hemispherical chamber; it is more streamlined in nature with less drag effect. Thus it can ease the fluid flow and yield quicker response. The fifth new idea is the most powerful one to integrate an active RFID tag with the angular accelerometer on the same flexible substrate, thus the device becomes a more useful wireless sensor, which can be applied in the fields of hospital monitoring, game, etc., so the new device is very easy for usage and fabrication. The heater is made by E-bean evaporation of powders of chromium (Cr) and nickel (Ni), and its operating temperature is 127°C (400K) without melting the polyimide substrate. We can see if one considers sensitivity as the first priority, then the non-floating structure is the choice (258°C / (rad/s²) in average). On the other hand, if the response speed is the top requirement, then the floating structure is better (60μs).

The paper organization is as follows: the first section is the introduction. The next concerns fabrication and packaging steps. The third one is simulation and discussion. Finally, a summary is given.

Corresponding author: jmlin@chu.edu.tw.
II. FABRICATION AND PACKAGING STEPS

Step 1: Deposit SiO$_2$ on both surfaces of substrate for thermal, electrical and humidity isolation. Then cover the layers of SiO$_2$ with layers of Photo Resist (PR). The result is shown in Fig. 2.

Step 2: Spray SU-8 PR on the front surface, use mask #1 and Photolithography And Etching Processes (PAEP) to make a cavity on the substrate front surface. The result is shown in Fig. 3.

Step 3: Evaporate SiO$_2$ as sacrificial layer (1mm) to make both heater and thermal sensors floated in the chamber as in Step 9 and Fig. 10 later. Cover a layer of PR. Use mask #1 and PAEP, only remain the PR on the cavity to protect the under lying SiO$_2$. After etching SiO$_2$ and removing PR on the cavity the result is as shown in Fig. 4.
**Step 4:** Evaporate a layer of alumina oxide to support the heater and temperature sensors. Cover the surface with SU-8 PR, and use mask #2 and PAEP to left the PR on the cavity to protect alumina oxide. The result is as shown in Fig. 5.

**Step 5:** Etch alumina oxide without PR covering. Remove the PR; the result is as shown in Fig. 6.

**Step 6:** E-beam evaporation powders of silicon and p-type material (such as boron) to make the thermistors. The next is to use mask #3 and PAEP to reserve the PR on the amorphous-Si. Finally, use KOH solution to remove the amorphous-Si layers without PR protection. After removing the PR, use an Nd-YAG laser to anneal the amorphous-Si to be poly-Si without melting the polyimide substrate, the result is as in Fig. 7.

**Step 7:** E-beam evaporation of powders of chromium (Cr) and nickel (Ni) to make the alloys for heater, and the supporting layers of RFID antenna, and conductors connected to the power supply. The next is to use mask #4 and PAEP to reserve PR on the heater, and the supporting layers of RFID antenna, and the conductors connected to the power supply. Finally, use sulfuric acid solution to remove the layers of Cr and Ni without PR protection. Remove the PR, the result is shown in Fig. 8.

Figure 5. The result of Step 4.

Figure 6. The result of Step 5.

Figure 7. The result of Step 6.
Step 8: Cover PR on the substrate and use mask #2 and PAEP to protect heater and the thermistors. After using the buffered solution to remove the sacrificial dioxide layer at the chamber uncovered by the PR, then the heater and the thermistors can be released; the result is in Fig. 9.

Step 9: Remove the PR and screen printing plastic or polymer materials around the angular accelerometer as dam bar, put a cap with a hemispherical chamber on the dam bar, then cure and fill the chamber with Xe before sealing. Finally, flip-chip bonding the chip with metal bumps to the RFID antenna feed terminals by thermal and vibration compression method, and then makes the underfill to increase the adherence of chip; the result is as in Fig. 10. Note the outer shape of the package is in the square flat one [18].

Step 10: To increase the sensitivity, reduce the bias effects due to fabrication and layout errors, and compensate the common-mode-rejection-ratio (CMRR), make four angular accelerometers in a full differential Wheatstone bridge. Finally, put both a socket and a spring to fix the battery on the substrate, the result is shown in Fig. 11. If one need a non-floating chamber structure, then skip Steps 2 and 8, and the result is as in Fig. 12.
III. SIMULATION AND DISCUSSION

In this paper the ESI-CFD+ software package is applied for simulation with floating and non-floating chamber structures. Firstly, the geometric definitions of heaters, thermistors and chamber dimensions are defined as in Fig. 13. The temperatures of the package boundaries and the heaters are set as 300K and 400K, respectively. As in Fig. 13 the thermal sensors can be put at either one of the three points to be trade-off later by simulation. The governing equations of mass, momentum, and energy are respectively as follows:

![Figure 11. The result of Step 10. Fig. 11.](image1)

![Figure 12. The non-floating chamber structure.](image2)

![Figure 13. Geometric dimensions of floating and non-floating chamber structures.](image3)
\[ \nabla \cdot \vec{u} = 0 \quad (1) \]

\[ \frac{\partial \rho}{\partial t} + \nabla \rho \vec{u} = 0 \quad (2) \]

\[ \frac{\partial \rho \vec{u}}{\partial t} + \nabla (\rho \vec{u}^2) = \rho \beta(T - T_{\text{heater}}) \alpha \quad (3) \]

\[ \rho \alpha \vec{u} \nabla T = k \nabla^2 T \quad (4) \]

\[ \rho = \frac{p}{RT} \quad (5) \]

In equations (1)-(5), \( \vec{u} \) is the velocity vector, \( t \) is the time, and \( \nabla \) is nabla. \( \rho \), \( p \), and \( \alpha \) are density, pressure, and acceleration, respectively, and \( c_p \), \( T \), \( R \), and \( k \) are the fluid specific heat, temperature, ideal gas constant, and thermal conductivity, respectively.

By using the chamber with floating and non-floating structures, the sensitivities for the thermal sensors at points 1, 2 and 3 are as in Figs. 14 and 15. Note for the floating and non-floating structures, the sensitivities are better to put the thermal sensors located at point 2. Besides, the sensitivity of non-floating structure is better (258°C/(rad/s²) in average). Fig.16 shows the gas flow distributions in both vertical and horizontal planes at point 2 for several angular accelerations. On the other hand, the step-input angular acceleration responses of gas velocity, static pressure and total enthalpy of floating and non-floating structures are also shown in Figs. 17-20, respectively. The detailed response times of step-input angular accelerations are also listed in Table I. Note if one considers sensitivity as the first priority, then the non-floating structure is the choice (258°C/(rad/s²) in average). However, if the response speed is the top requirement, then the floating structure is better (70μs).

![Figure 14](image1.png)

**Figure 14.** Sensitivity with floating structure for the thermal sensors located at points 1, 2 and 3.

![Figure 15](image2.png)

**Figure 15.** Sensitivity with non-floating structure for the thermal sensors located at points 1, 2 and 3.
TABLE I.
RESPONSE TIMES OF STEP-INPUT ANGULAR ACCELERATIONS FOR FLOATING AND NON-FLOATING STRUCTURES.

<table>
<thead>
<tr>
<th></th>
<th>Floating Structure</th>
<th>Non-Floating Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static Pressure</td>
<td>60 μs</td>
<td>81 μs</td>
</tr>
<tr>
<td>Total Enthalpy</td>
<td>40 μs</td>
<td>55 μs</td>
</tr>
</tbody>
</table>

Figure 16. Gas flow distributions in both vertical and horizontal planes for the thermal sensors located at points 2.

Figure 17. By using floating chamber structure, the step input angular acceleration responses of gas velocity.

Figure 18. By using floating chamber structure, the step input angular acceleration responses of static pressure and total enthalpy.
IV. SUMMARY

The contributions of this paper are summarized as follows:

(1) This is a brand new idea to make both heater and temperature sensors of a thermal convection type angular accelerometer on a flexible substrate, it is not proposed before.

(2) By using the plastic substrate one can integrate the RFID tag with the angular accelerometer to make it be a more powerful wireless angular acceleration sensor.

(3) This is a new idea to use flexible substrate, the thermal isolation capability of which is better than silicon, thus the cost of power dissipation for long time operation is lower for the new design. Besides, the inert Xe gas is more reliable without oxidation and aging effects.

(4) If one considers sensitivity as the first priority, then the non-floating structure is the choice (258°C/(rad/s^2) in average). Moreover, if the response speed is the top requirement, then the floating structure is better (70μs).

ACKNOWLEDGMENT

This research was supported by National Science Council with the grants: NSC 101-2622-E-216-001-CC3, 101-2221-E-216-006-MY2, 101-2221-E-216-019-., and National Center for High-performance Computing (NCHC) for computer time and facilities of ESI-CFD+ software package.

REFERENCES


Jium Ming Lin was born at Taipei, Taiwan in 1952. Prof. Lin was graduated from the Department of Electronic Engineering, National Chiao-Tung University at Hsin-Chu, Taiwan in 1974. He had also achieved the Master and Ph. D. Degrees from the same school of Institute of Electronics in 1976 and 1985, respectively. Dr. Lin was a researcher at Chung-Shan Institute of Science and Technology in Taiwan from 1978 to 1992. His major field was in surface-to-air missile navigation, guidance and control. He has been an adjunct professor and full professor since 1992 and 1996 at Dept. of Mechanical Engineering, Chung-Hua University, Taiwan. He was the director of Dept. of Mechanical Engineering from 1996 to 1997; Prof. Lin was also the director of R&D of Chung-Hua University. He has been at Dept. of Communication Engineering from 2009. Prof. Lin majors in the fields of RFID, wireless accelerometer, angular accelerometer, multi-variable control, optimal control, stochastic control, fuzzy-neural control, avionics, MEMS sensors, semiconductor fabrication and packaging, measurement and mechatronics. He also has several patents in RFID-based wireless acupuncture impedance monitors accelerometers and angular accelerometers, speakers.

Cheng-Hung Lin was born at Taipei, Taiwan in 1985. Mr. Lin was graduated from the Department of Mechanical Engineering, Chung-Hua University at Hsin-Chu, Taiwan in 2009. He had also achieved the Master Degree from the same school in 2012. His major field was in missile navigation, guidance and control. The other interests are as RFID, wireless accelerometer, angular accelerometer, multi-variable control, optimal control, stochastic control, fuzzy-neural control, avionics, and MEMS design.