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Effect of residual stress on the performance of self-packaging piezoresistive pressure sensor in wireless capsule

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ABSTRACT

Piezoresistive pressure sensors with excellent performance are widely used in the field of biomedical engineering for measuring pressure, however, residual stress will be introduced in the process of repackaging and effect the performance of the sensor. The effect of residual stress on the repackaged pressure sensor is often neglected, but it will cause errors in measuring physiological signals. In this paper, effect of residual stress on the performance of a self-packaging pressure sensor (SPS) is analyzed by finite element analysis (FEA) and experiments. Through analysis of simulation results and experimental data, the material and structure of SPS are optimized. A reinforced plate is used in the self-packaging structure, which can solve the problem of stress induced by the self-packaging structure. Compared with the ordinary SPS, the effect of the self-packaging structure proposed in this paper is reduced by more than 80%; measurement accuracy of SPS in weak signal detection is significantly improved.

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1. Introduction

Piezoresistive pressure sensors using microelectromechanical systems (MEMS) fabrication methods are applied in many different industries, which include instrumentation, aerospace, automotive and medical equipment [1–7]. Compared with other types of pressure sensors, piezoresistive sensors have characteristics such as high pressure sensitivity, excellent linearity and easy miniaturization [1,8]. These make piezoresistive pressure sensors very suitable for biomedical devices which are used to implant in human body. For example, it is applied to measure the pressure of cerebrospinal fluid, urinary bladder, gastrointestinal tract and intraocular pressure [9–12].

Most previous work on piezoresistive pressure sensors are concentrated on optimizing and improving the performance of the pressure sensor itself [13–15]. The package is a mechanical structure that has a large influence on the sensor's performance, and research confirms that this influence is caused by the warpage of the package [16]. As an extension of the package, an inappropriate repackaging structure in SPS can strengthen the warpage and affect the performance of the pressure sensor, but this kind of effect has rarely been considered when the pressure sensor is placed in the device [10,11]. Most implantable biomedical devices have specific requirement for its size and shape, thus the commercial pressure sensors cannot be used directly; and they always need to be repackaged by device designers to meet the requirements of biomedical devices. When components of self-packaging structures are assembled together, residual stress will exist in the SPS module due to the mismatched thermodynamic parameter among components.

In this paper, the effect of residual stress on the performance of SPS module is discussed. The SPS module discussed in this paper is applied in a wireless capsule developed by our institute, and this device is used to detect the pressure of human gastrointestinal tract [11,17]. The detection ranges of the SPS module is from 70 to 150 kPa. The effect of the self-packaging structure on the performance of SPS is simulated by FEA and tested in experiments. The structure of the sensor module is optimized by using a reinforced plate, which can reduce the influence of residual stress on the performance of SPS.

2. Piezoresistive sensor and self-packaging

A typical piezoresistive pressure sensor is shown in Fig. 1(a). Four piezoresistors are diffused into the diaphragm and interconnected a Wheatstone bridge, as shown in Fig. 1(b). When pressure acts on the diaphragm, changes in resistance of the piezoresistors caused by bending strains (elongation or compression) yield a change in output voltage from the Wheatstone bridge.

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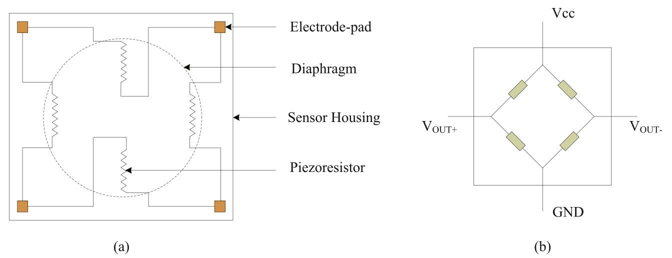

Fig. 1. The structure of pressure sensor and Wheatstone bridge.

The change in pressure is converted to change in voltage output of the Wheatstone bridge. The sensitivity of the sensor can be written as [18]:

$$Sen = \frac{\Delta V}{V_{cc}\Delta P} = \frac{\Delta R}{R_i \Delta P} \quad (1)$$

where Sen, sensitivity of pressure sensor; ΔV, the change of output voltage; V_{cc}, the input voltage; ΔP, the change of pressure; ΔR, the change of piezoresistance; and R_i, the initial value of piezoresistance.

An ordinary SPS module usually consists of a pressure sensor, a printed circuit board (PCB), bonding wires, protective colloid, and a shell. A reinforced plate (RP) is added to the structure of SPS module proposed in this paper, as shown in Fig. 2. The piezoresistive pressure sensor with a shape of 2.2 mm × 2.7 mm is mounted to the PCB. The output of the sensor is connected to the microprocessor via bonding wires (gold) and PCB. Bonding wires and bonding connections are vulnerable and usually adequately protected by covering colloid [19]. The shell of SPS module can protect the pressure sensor from the harsh environment.

The assembly process of SPS is shown as the following steps:

(1) Pressure sensor is fixed on the PCB with resin adhesive.
(2) Pressure sensor and PCB pads are connected by bonding wires.
(3) Bonding wires and bonding connections are protected with resin adhesive.
(4) In our SPS module, a RP is added.
(5) All components are fixed to a self-made shell.

3. Experimental details

The main content of this work is to better understand the factors which affect the performance of SPS and minimize these impacts by taking effective measures.

The residual stress primarily comes from two factors. One is the resin adhesive used to fix the pressure sensor to the PCB. The residual stresses which were generated in the curing process will exist in pressure sensor module and affect the performance of the pressure sensor. The other factor is the warpage caused by thermal stress between the packaging components (including resin adhesive). Thermodynamic properties of components used in SPS module are distinct from each other, such as coefficient of thermal expansion (CTE), Young's modulus, thermal conductivity, Poisson's ratio, etc.

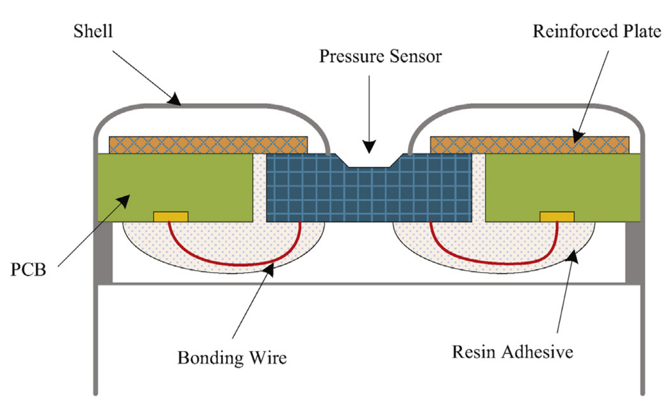

Fig. 2. The structure of SPS module.

3.1. Shrinkage of resin adhesive

Resin adhesive was used for securing the pressure sensor and protecting the bonding wires and bonding connections. During the curing process of resin adhesive, volume contraction and the restriction of molecular motion induced stress at the resin–silicon interface. Stress could also be induced by non-uniform shrinkage as the resin adhesive cooled from the curing temperature to room temperature [20]. Residual stress induced in the curing process would keep acting on the pressure sensor after resin adhesive solidified. In order to assess the effect, outputs of the pressure sensor before and after gluing were tested in the experiment. Furthermore, three kinds of resin adhesives were used to analyze the effect of different resin adhesives on the pressure sensor's performance.

3.2. Effect of thermal stress

As shown in Fig. 2, SPS module consisted of pressure sensor, PCB, resin adhesive and so on. These components were made of different materials whose thermodynamic properties were varied. In general, thermal stress could be expressed as

$$S = K \int E(T)\alpha(T)dT \quad (2)$$

where, S, stress; K, constant; E, Young's modulus; α, coefficient of thermal expansion; and T, temperature.

From Eq. (2), we knew that the thermal stress of different material was closely related to its CTE and Young's modulus. Although change of the temperature was the same, the thermal stress was different in different materials. When these thermal stresses acted on the pressure sensor together, it would cause warpage of the pressure sensor module and the bending strains of the diaphragm was also impacted. This warpage would have a lasting effect on the output of the pressure sensor.

In order to suppress the warpage caused by thermal stress, a RP was added in the SPS structure. Because there were several bonding pads at the underside of the sensor and PCB, as shown in Fig. 2, the RP had to be assembled upon the pressure sensor and PCB and fixed on the PCB by resin adhesive. Then the shell of SPS module would be fixed on the RP at four symmetric points with a small amount of resin adhesive. Because the shell of SPS module was not directly contact with the pressure sensor, and only four points were contact with the RP, so this structure had little impact on the performance of the pressure sensor. The material of the RP determined its function. Through the comparison of different materials, the test results showed that the material having similar thermal stress with the pressure sensor shell could better suppress the warpage. Considering the malleability and cost, metal material was a good choice to fabricate RP. The CTE and Young's modulus of the materials were primarily considered.

As shown in Fig. 3, there are four states during assembly process of SPS module which is designed by us: state A, a single pressure sensor (commercial sensor); state B, the pressure sensor is fixed to the PCB with resin adhesive and bonded; state C, a RP is assembled upon pressure sensor and PCB; state D, all components are assembled into a SPS module. In order to analyze the effect of the self-packaging structure on the performance of SPS and

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