Design and Optimization of Peninsula-island-based Diaphragm with Grooves for MEMS Pressure Sensors

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Abstract: *This paper introduces a piezoresistive pressure sensor, which has an important application value in the pressure measurement of hydraulic system. A novel peninsula-island-based diaphragm with grooves is designed. The proposed diaphragm can ease the contradiction between sensitivity and non-linearity compared with the conventional diaphragm structures. Especially, the elastic potential energy is concentrated above the gap position, which greatly improves the sensitivity. The optimization process for the proposed diaphragm has been presented by the finite element method (FEM). The proposed sensor chip is potentially a better choice for the high sensitive pressure sensor.*

Keywords: *MEMS; pressure sensor; peninsula-island structure with grooves; sensitivity; non-linearity*

1. Introduction

Hydraulic transmission with outstanding advantages such as stable work, large output force, good speed rigidity, and easy comprehensive control is an indispensable part of modern mechanical equipment. In hydraulic systems, dynamic flow feedback is of great significance for achieving high efficiency and high precision control. According to Bernoulli's equation, the flow is related to the pressure drop. At present, a hydraulic gauge is mainly used in the pressure measurement of the hydraulic system, which not only is inaccurate, but also affects the transportation of fluid. So, an embedded micromechanical sensor is needed. With the advantages of high sensitivity, fast frequency response, simple structure, small size, mature technology, and easy integration (Jiang, 2018, p.3), Micro-Electro-Mechanical System (MEMS) piezoresistive sensor can be used in the flow measurement. In this application, the pressure change caused by the oil leakage is small, so high sensitivity and linearity are required. Sensitivity is one of the static characteristics of the sensor, which refers to the output produced by the unit input of the sensor. The chip structure determines the sensitivity and linearity to some extent. For a sensing chip, flat silicon diaphragms are generally modified with additional lump limiting the deformation of the diaphragm to improve the non-linearity (Kanda, Y. & Yasukawa, A. 1997, p.2). However, the lump also makes the diaphragm more constrained, lowering the measuring sensitivity, so there is a contradiction between linearity and sensitivity. Previous studies usually focused on modifying the design of the structures to resolve the contradiction. For example, Hein et al. (1997, p.8) used a diaphragm with four flexible beams to reduce nonlinearity effects. Huang (2014, p.4) introduced a peninsula structured diaphragm, which remarkably lowered the non-linearity, but its sensitivity was low. Xu (2016.p.9) concluded that the contradiction between the measuring sensitivity and dynamic performance could be remarkably solved, for example, "d and a certain optimization range of l1, l2 made the Sy − Sx and f increase at the same time." But he didn't discuss non-linearity.

In this paper, a novel peninsula-island-based diaphragm with grooves is put forward. By optimizing the length of the island and peninsula, the constraint from the silicon pedestal is eased to enhance the sensor sensitivity. Besides, the ridge plays a main role in resisting the diaphragm deformation to improve the non-linearity. To verify the scheme, finite element method (FEM) model and linearity and sensitivity optimization are implemented [1-2].

2. Sensing Chip Design

A novel peninsula-island-based diaphragm combined with grooves is proposed for the sensor chip. In view of the limitation of the high voltage working range, the thickness of the peninsula-island structure is around 300 ± 10 μm. The size of the effective diaphragm is set as 3500 × 3500 μm2. In the back side of the diaphragm, there are four pairs of peninsula-island structures, as shown in Figure 1. In the front side of the diaphragm, there is a bump with four grooves, as shown in Figure 2.

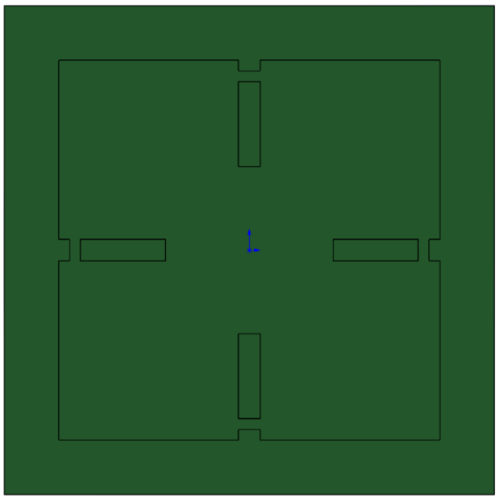

Figure 1: Schematic of the diaphragm in the backside view.

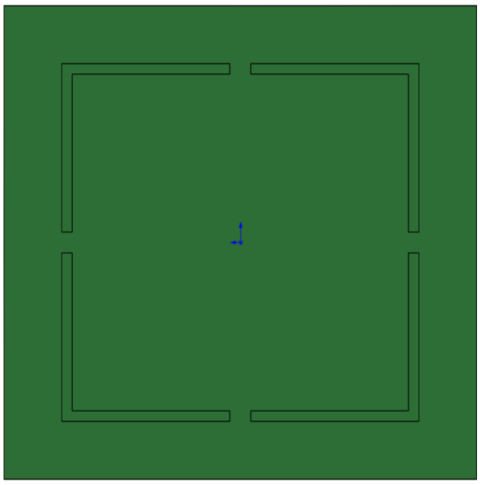

Figure 2: Schematic of the diaphragm in the frontside view.

3. Finite Element Method Analysis

3.1. Finite element method analysis of the stress distribution

The performance of the proposed sensor chip is predicted by the commercially available finite element method (FEM) software (ANSYS15.0). Because of the symmetry of the sensor chip, only one quarter of the finite element model is built. The sensitivity of the sensor chip is actually determined by the stress difference between the longitudinal stress Sy and transversal stress Sx and the non-linearity is related to the displacement of the center of the diaphragm. Compared with flat diaphragm(Figure3), the stress difference of the proposed diaphragm(Figure4) is increased tremendously. Due to the stiffness mutation created by the ridges, the strain energy is strictly confined in a small region known as the SCR(Bashir R , Gupta A , Neudeck G W , et al. 2018, p.9). Besides, the uniform distribution of the grooves not only reduces the constraint of the silicon base, as shown in Figure5, which improves the stress, but also created a stiffness peak along the transversal direction shown in Figure.6, which resists the diaphragm deformation and reduce the non-linearity.

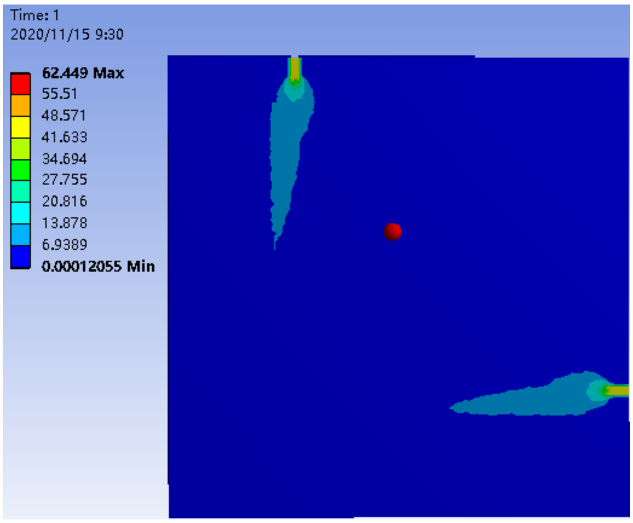

Figure 3: Stress difference distribution for the traditional diaphragm.

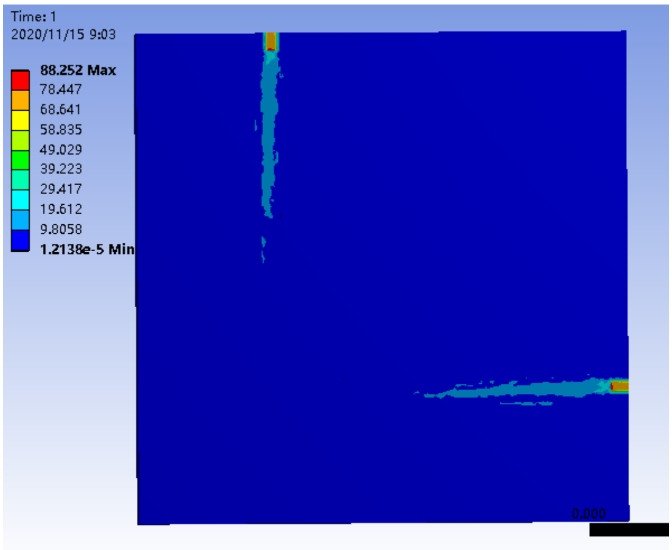

Figure 4: Stress difference distribution for the proposed diaphragm

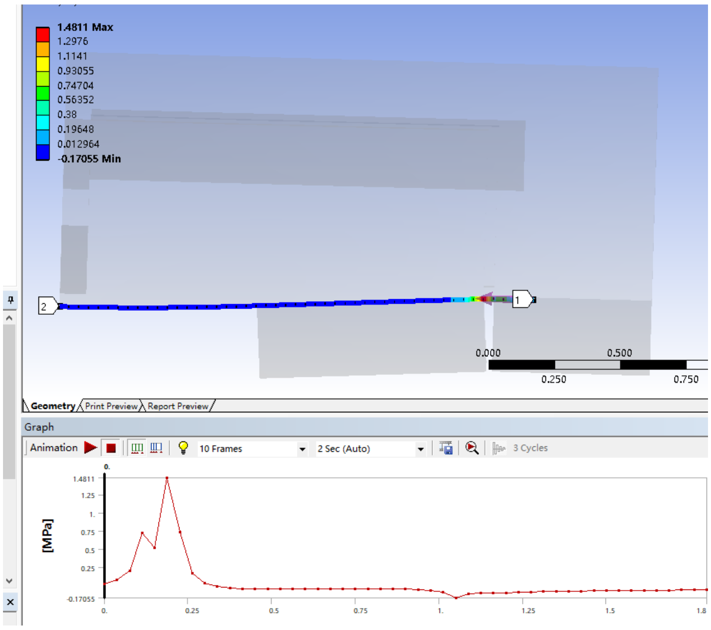

Figure 5: Stress distribution along the longitudinal direction

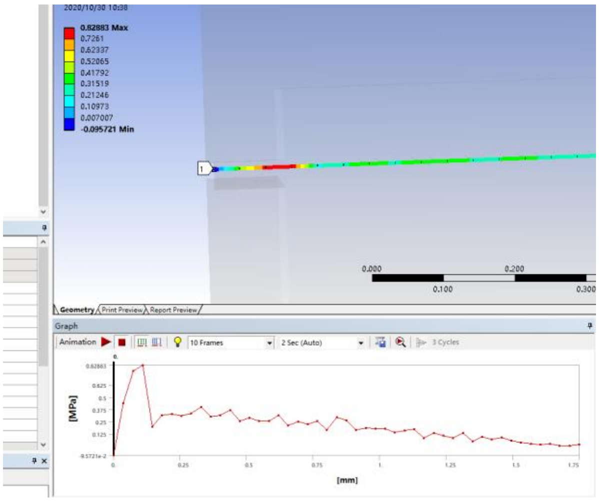

Figure 6: Stress distribution along the transversal direction.

3.2. Geometrical Optimization Process for the Diaphragm

3.2.1. The Effect of Various Geometrical Parameters on Stress and Non-linearity

As shown in Figure7 and Figure8, the increasing thickness of the whole diaphragm resulted in a decrease in Sy-Sx and non-linearity, it's the same when we increase the width of the peninsula-island structure and width of groove. The results mentioned above shown that the contradiction between stress difference and non-linearity can't be solved by optimizing the diaphragm thickness and the width of peninsula-island and groove. As shown in Figure9 and Figure10, as the length of the peninsula decreases, non-linearity decreases and Sy-Sx increases at the same time. Also, this effect can also be achieved when changing the length of the island. The diaphragm thickness is set as 10 μm determined by the fabrication capacity. The SCR area is set as a region of 160 × 35 μm2 to spare enough space for arranging the piezoresistors. The length of the island and peninsula are critical to improve the sensitivity and non-linearity of the sensing chip, as discussed below.

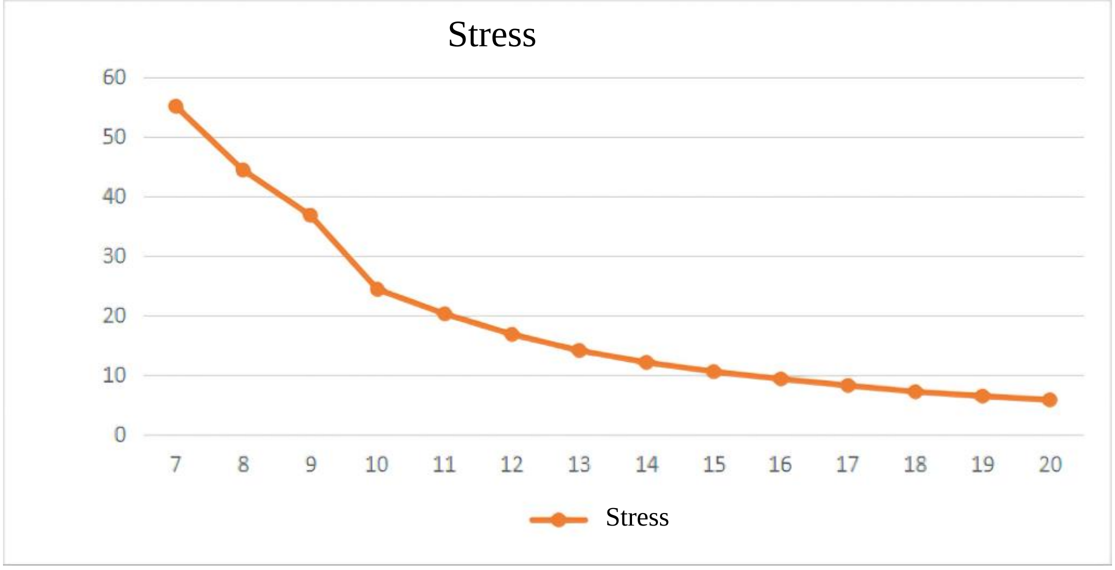

Figure 7: Effect of thickness on stress difference

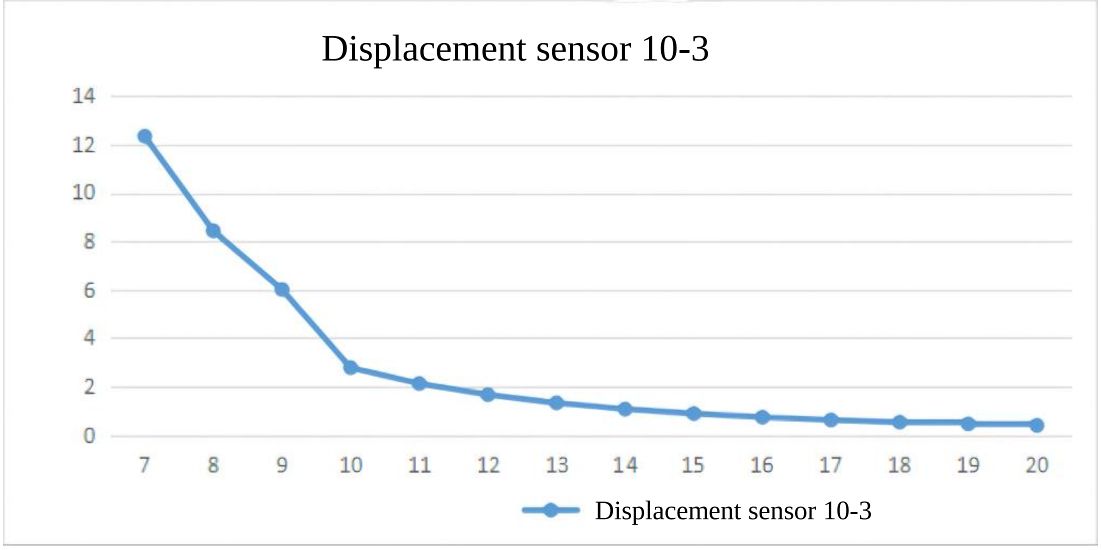

Figure 8: Effect of thickness on non-linearity

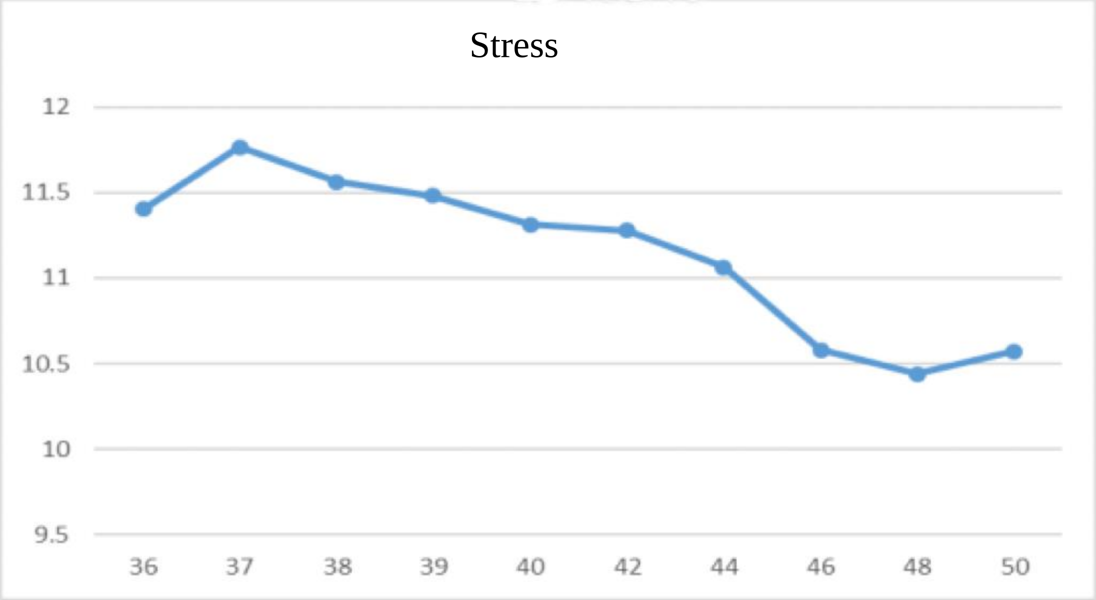

Figure 9: Effect of length of the peninsula on stress difference

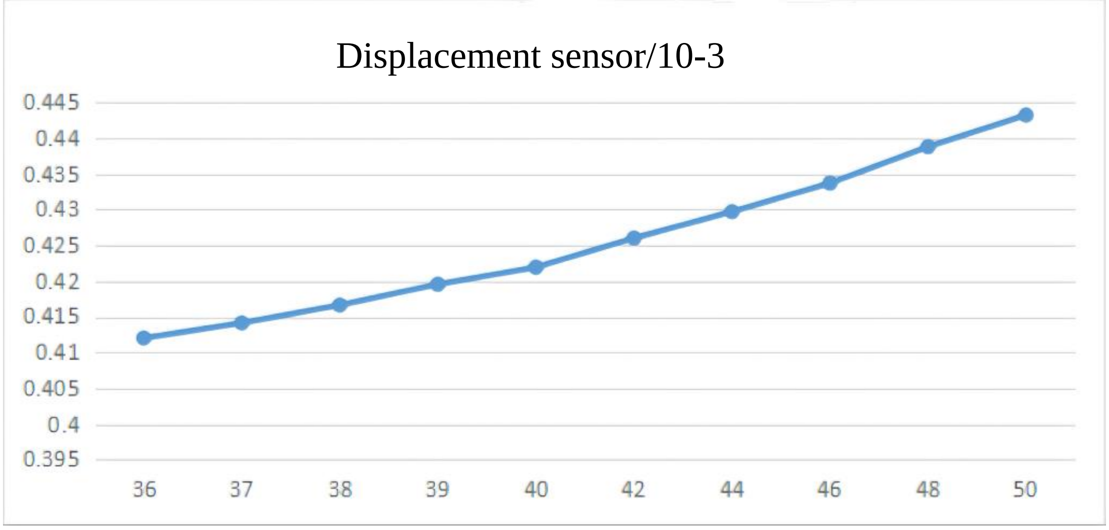

Figure 10: Effect of length of the peninsula on non-linearity

3.2.2. Peninsula-island Structure Optimization

The process of optimization is divided into two steps, the first step is to optimize the length of peninsula, and the second step is to optimize the length of island. In the first step, the proper length of the peninsula not only lightens the restraint of the silicon base, but also causes the stiffness mutation. However, as the length of the peninsula increases, the effective load of the diaphragm is reduced because more diaphragm areas will be limited by deformation. The peninsula length is optimized about 160μm based on the relationship between the maximum stress difference and peninsula length, as shown in Figure11. The length of the island also needs to be limited, as excessive length of the island structure will limit the generation of concentrated stress. In Figure12, the island length is decided about 750 μm based on the FEM results[3-6].

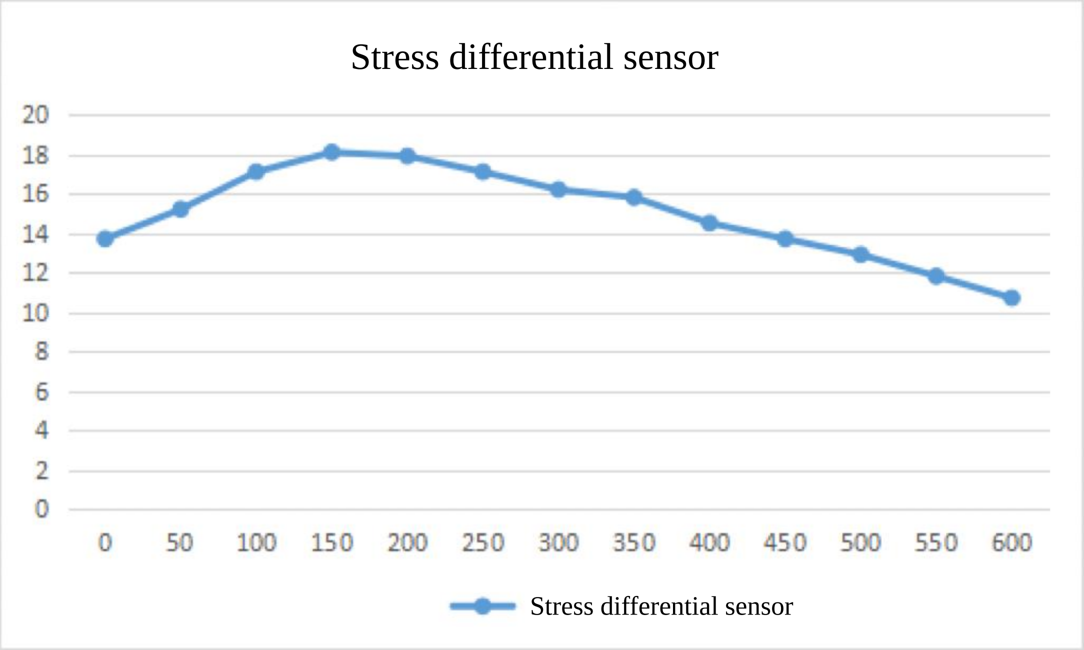

Figure 11: The relationship between the stress difference and the length of the peninsula

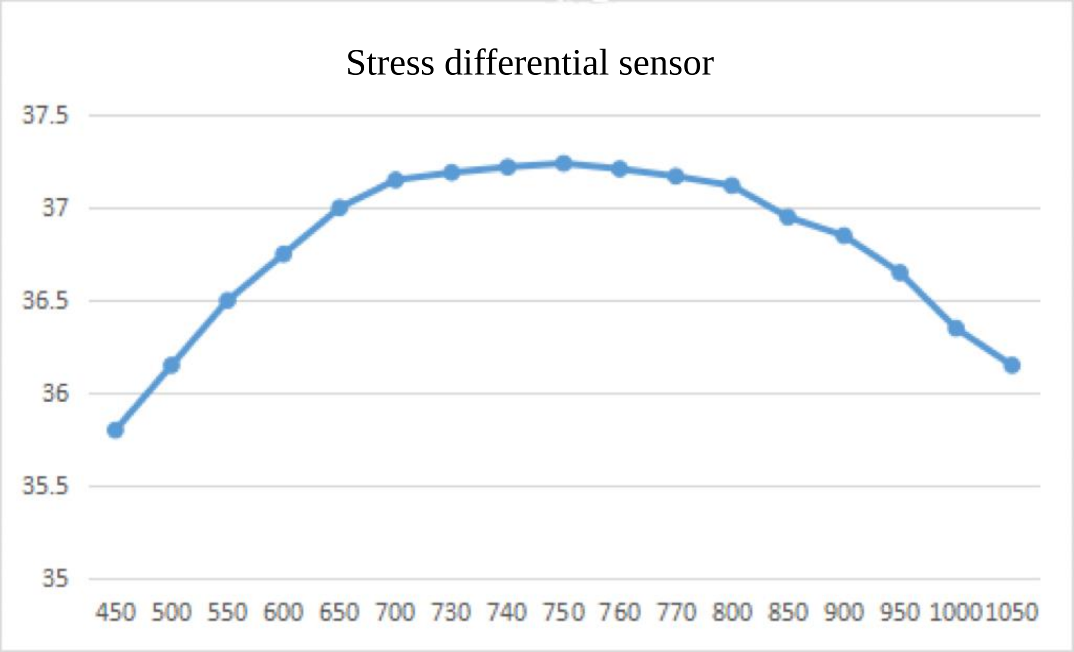

Figure 12: The relationship between the stress difference and the length of the island

4. Conclusions

In this work, a novel structure of a piezoresistive pressure sensor is developed by introducing grooves into the traditional peninsula-island-based diaphragm. The scheme provides a solution for enhancing the sensitivity and linearity simultaneously. To verify the feasibility of the scheme, the model has been simulated and optimized. The simulation results show that incorporating grooves can improve sensitivity and the linearity. The future work will be to produce the sensor and conduct corresponding experiments to verify our simulation results.

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