OTIMIZAÇÃO DO TRANSDUTOR DE PRESSÃO DE SEMICONdutoRES COM ELEMENTO SENSÍVEL BASEADO NA ESTRUTURA DE “SILÍCIO SOBRE SAFIRA”

OPTIMIZATION OF SEMICONDUCTOR PRESSURE TRANSDUCER WITH SENSITIVE ELEMENT BASED ON “SILICON ON SAPPHIRE” STRUCTURE

ОПТИМИЗАЦИЯ ПОЛУПРОВОДНИКОВОГО ТЕНЗОПРЕОБРАЗОВАТЕЛЯ ДАВЛЕНИЯ С ЧУВСТВИТЕЛЬНЫМ ЭЛЕМЕНТОМ НА ОСНОВЕ СТРУКТУРЫ «КРЕМНИЙ НА САПФИРЕ»

GAVRYUSHIN, Sergey S.¹; SKVORTSOV, Pavel A.^{2*}; SKVORTSOV, Arkady A.³

¹ Bauman Moscow State Technical University, Department of Computer System for Production Automation
5/1 2-ya Baumanskaya Str., ZIP code 105005, Moscow – Russian Federation
(phone: + 499 263-6391)

^{2,3} Department of Dynamics, Durability of Machines and Resistance of Materials, Moscow Polytechnic University
38 Bolshaya Semenovskaya Str., ZIP code 107023, Moscow – Russian Federation
(phone: +79851763034)

* Corresponding author
e-mail: SkvortsovPA@ya.ru

Received 20 December 2017; received in revised form 15 May 2018; accepted 03 August 2018

RESUMO

O artigo é dedicado ao estudo do processo de otimização do transdutor semicondutor de strain gauge na estrutura de silício sobre safira (SOS). Como objeto do estudo, foi utilizado um elemento do tipo membrana elástica com um extensômetro semicondutor na forma de uma estrutura de silício sobre safira. Para estudar a superfície da safira, utilizou-se o método de fotolitografia óptica. No contexto desta tarefa, os parâmetros de controle e os parâmetros de qualidade do extensômetro fabricado em série foram determinados. O artigo descreve a metodologia para otimização multicritério e também um cálculo de otimização para o extensômetro no silício sobre safira. O principal resultado foi a obtenção de variantes de projeto ótimas de Pareto que excedem a variante básica por todos os critérios de qualidade.

Palavras-chave: *Otimização multicritério, não-linearidade, tensão equivalente, deformação, coeficiente de transmissão.*

ABSTRACT

The paper is devoted to the study of the process of optimizing the semiconductor strain-gauge transducer on the structure of the SOS. As an object of the study, an elastic membrane-type element with a semiconductor strain-gauge in the form of a silicon-on-sapphire structure was used. To study the surface of sapphire, the optical photolithography method was used. In the framework of this task, the control parameters and the quality parameters of the serially-manufactured strain gauge were determined. The paper describes the methodology for multicriteria optimization, and also an optimization calculation for the strain-gauge on the SOS. The main result is the obtaining of Pareto-optimal design variants that exceed the basic variant by all quality criteria.

Keywords: *multicriteria optimization, nonlinearity, equivalent stress, deformation, transmission coefficient.*

АННОТАЦИЯ

Работа посвящена исследованию процесса оптимизации полупроводникового тензопреобразователя давления на структуре КНС. В качестве объекта исследования авторами использовался упругий элемент мембранного типа с полупроводниковым тензопреобразователем в виде структуры кремний-на сапфире. Для изучения поверхности сапфира применялся метод оптической фотолитографии. В рамках этой задачи были определены параметры управления и параметры качества серийно-выпускаемого тензопреобразователя. В работе приведено описание методики многокритериальной оптимизации, а также произведен оптимизационный расчет для тензопреобразователя на КНС. Основным результатом является получение Парето-оптимальных вариантов конструкции, которые превосходят базовый вариант по всем критериям качества.

Keywords: многокритериальная оптимизация, нелинейность, эквивалентное напряжение, деформация, коэффициент передачи.

INTRODUCTION

Pressure sensors on the structure "silicon on sapphire" (CNS) in Figure 1 are used in a wide variety of fields: aerospace, oil and gas production, military equipment, nuclear energy. This class of sensors is designed to measure the pressure of oils and their vapors, fuel, air, neutral and corrosive liquids and gases. Advantages of using semiconductor sensors on CNS are obvious: high sensitivity, speed, no leakage currents, operability over a wide range of temperatures, high accuracy, stability, chemical and radiation resistance (Ganghoffer and Goda, 2018; Nelson *et al.*, 2017; Wang *et al.*, 2018; Jiang *et al.*, 2017). However, despite the fact that strain gauges (TP) pressure on the CNS are actively produced, and the structure of the CNS itself has been the object of research for more than 30 years, at present there is no single methodology for calculating and designing such devices (Enayati *et al.*, 2018; Wang *et al.*, 2017). In practice, classical bending theories of thin plates, which do not properly describe the process of deformation of the elastic element of the calculated strain gage, are used for calculation, and often developers act intuitively, based on their own experience. All this leads to a decrease in the accuracy and reliability of the devices (Yang and Zhao, 2016; Chen, 2018). The existing CAE-systems allow analyzing a device, but they are not aimed at solving problems of designing semiconductor strain gauges.

The purpose of this work is to create a system that allows using the capabilities of the ANSYS software package to provide the process of designing semiconductor TP on the SPS with an elastic element of the membrane type (Kim *et al.*, 2016). At the same time, the program should

not only analyze individual TPs, but also solve the problem of multi-criteria design.

MATERIALS AND METHODS

The elastic element of the membrane type (Figure 2) with a semiconductor strain-gauge in the form of a silicon-on-sapphire crystal (Figure 3) acted as a research object. The latter is an epitaxial layer of silicon 10 μm thick grown on the surface of a monocrystalline sapphire. By methods of optical photolithography on the sapphire surface, the structure shown in Figure 3 is formed.

The principle of operation of the TP on the structure of the CNS is that the measured pressure is transformed into a deformation of the elastic membrane of Figure 2, on the surface of which there is a semiconductor sensitive element in Figure 3, which is a sapphire (Al_2O_3) substrate on which silicon strain gauges connected to the bridge scheme. A change in the electrical resistance of the strain gauges leads to unbalance of the bridge, which in turn changes the electrical output signal in proportion to the pressure. In this paper we consider the process of optimization of the elastic element, shown in Figure 2.

RESULTS AND DISCUSSION:

3.1. The device and principle of operation of the strain gauges under consideration

In the TP under consideration, the mid-bases of strain gages are at a distance of 3.7 mm from the center of the membrane. For such a

strain diagram with the same initial values of the resistances of the radial R_r and tangential R_t strain gauges ($R_r = R_t = R$), the change in the output signal U_{out} under the action of pressure when the bridge is powered by a constant voltage U_{pt} is (Equation 1) (Kozlov and Stechebnikov, 2014):

$$\Delta U_{out} = U_{pt} \frac{(\Delta R_t - \Delta R_r)}{(2R + \Delta R_t + \Delta R_r)} \approx U_{out} \frac{(\Delta R_t - \Delta R_r)}{2R} \quad (1)$$

where ΔR_t - the change in the resistance of tangential strain gauges, ΔR_r - the resistance of radial strain gauges under pressure.

From the relation (Equation 1) it follows that at a fixed supply voltage, in order to obtain the maximum change in the output signal of the strain gage, it is necessary that the difference in the relative changes in the resistances of the strain gauges located in the adjacent arms of the bridge circuit be maximal (Equation 2):

$$\frac{\Delta R_t}{R} - \frac{\Delta R_r}{R} \rightarrow \max \quad (2)$$

It was shown in (Krivulin *et al.*, 2012) that the relative changes in resistances $\frac{\Delta R_r}{R}$ and $\frac{\Delta R_t}{R}$ for semiconductor silicon strain gauges depend on the basic coefficient of elastoresistance m_{44} and are described by the expression (Equation 3):

$$\left| \frac{\Delta R_t}{R} - \frac{\Delta R_r}{R} \right| \approx m_{44} |\varepsilon_t - \varepsilon_r| = m_{44} |\Delta \varepsilon|. \quad (3)$$

Using the data of (Stechebnikov, 2005), we take the value of the coefficient $m_{44} = 62$. Substituting expression (3) in (1), we obtain the relationship between the output signal and the deformation of the elastic element (Equation 4):

$$\frac{\Delta U_{out}}{U_{pt}} = \frac{1}{2} m_{44} |\Delta \varepsilon|. \quad (4)$$

Manufacturers of measuring equipment, as a rule, tend to ensure that the dependence of the output signal on the actual load is linear. However, in practice, due to many reasons (imperfection of the elastic properties of the material, hysteresis, the influence of temperature and imperfection of the technological process) (Andreeva, 1981), the real characteristic is

different from linear.

The nonlinearity η of the characteristic is the greatest deviation $\Delta_{\max}$ of the actual characteristic from the linear characteristic, referred to the largest value of the estimated quantity (in our case $\Delta U_{out \max}$). Thus, to evaluate the nonlinearity of the output signal, the following expression will serve (Equation 5) (Bairaktarova and Eodice, 2017):

$$\eta = \frac{\Delta_{\max}}{\Delta U_{out \max}} \cdot 100\% \quad (5)$$

In our case, the reason for the nonlinearity is the geometric nonlinearity, which can be interpreted as a non-fulfillment of the principle of invariance of the initial dimensions. Internal friction in the metal within the framework of this problem can be neglected. The problem of calculating the nonlinearity was considered in detail in (Gavryushin and Skvortsov, 2016; Gavryushin and Skvortsov, 2017; Gavryushin *et al.*, 2014a).

To estimate the magnitude of the output signal, we introduce the notion of the working transfer coefficient of the RSC - the maximum output signal at a supply voltage level of 1 V.

3.2. The task of designing

The main objective in the design of TP at the CNS is to ensure a high level of accuracy. However, manufacturers are also trying to minimize the overall dimensions of the sensor while maintaining the required margin of safety and increase the value of the RCP.

The work on improving the properties of the strain-gauge is carried out according to the multi-criterion (Gavryushin and Gavrilencov, 2015; Gavryushin *et al.*, 2014b; Sobol and Statnikov, 2006) optimization scheme in Figure 4. Developers define a group of variable parameters, which makes up the space of control parameters. With the help of functional restrictions on equivalent voltages and the magnitude of the output signal, deliberately inefficient solutions are eliminated. The variant of the product is evaluated according to three parameters: the magnitude of the output signal (RCP), the nonlinearity of the output characteristic, and the maximum equivalent voltages. Developers check the mathematical model, set functional limitations,

and define the space of control parameters.

3.3. Process optimization of the elastic element

In this paper, the geometric dimensions of the calculated structure of Figure 5 serve as control parameters. The material of the elastic element is a titanium alloy VT-9. Physical characteristics of the material are given in Table 1.

The functional restriction is formed from the requirement for the sensor, which consists in the fact that after the application of the load, plastic deformations should not occur in the structure of the strain gage in question. The restriction will be defined as follows (Equation 6):

$$\Sigma_{ekv} < [\sigma_t],$$

However, it should be remembered that the design of the TP based on the CNS includes a sensitive element that is soldered to the titanium membrane (Gurentsov *et al.*, 2017). In this connection, it is inadmissible that plastic deformations occur in the solder layer (PS-72). Preliminary calculation showed that the maximum equivalent voltage arising in the design of a mass-produced TP is 798 MPa. Let us take this voltage value as the maximum allowable value for our TP. The minimum RCP value will be taken as 2 to avoid the possible influence of external noise on the output signal.

For optimization, the elastic element was calculated by the finite element method in the ANSYS software package. The problem was solved in a geometrically nonlinear formulation. For the finite-element discretization of the design, an eight-node axisymmetric element Plane 183 Figure 6 was used. The design model was fully parameterized for use in the optimization process. For the automatic generation of options for calculating and evaluating the quality parameters of the elastic element, a special program was developed in C # in Figure 7. This program allows you to:

1) Define the variation of individual parameters and form a macro of this variation in the language APDL. To work the program needs a parametrized calculation model, which was done earlier.

2) Run the variation macro for calculation in ANSYS in batch mode without user

intervention. The results of the variation are picked up by the program also in automatic mode.

3) To evaluate the quality parameters: the nonlinearity of the output characteristic, the maximum equivalent voltage, the working transmission coefficient. Also, the program selects the rational position of strain gages on the surface of the elastic element.

The results are presented to the user in the form of graphs. You can also save the results for further processing. The developed program together with the calculation of the elastic element made it possible to select the rational parameters for the design of the elastic element.

In the process of optimization calculation, 100 variations were calculated, the number of allowable variations was 29, of which Pareto-optimal 7. A comparison of the quality parameters of the initial and the resulting TP design on the SPS is shown in Table 2. In the Pareto optimal variant No. 2, we obtained decrease in the working transmission coefficient, but the maximum equivalent stresses were obtained by the smallest of all the design variants obtained. In this regard, the final decision on the adoption of a particular design option remains with the Person making the Decision (LPR).

CONCLUSION

Thus, in this paper, the author's technique for calculating and designing semiconductor TP on the SPS was demonstrated. As a result of the calculation, variants of the tensor converter designs were obtained, which exceed the original version for all quality parameters. In the future, the authors also plan to evaluate the effect of hysteresis and residual thermal stresses on the output signal of the designed strain gage, and also apply the method of visual-interactive analysis to automate the process of multi-criteria design.

ACKNOWLEDGEMENT

This study is conducted with financial support from the Ministry of Education and Science of the Russian Federation (grant No. 8.8392.2017)

REFERENCES:

1. Andreeva, L.E. *Elastic elements of devices*, Moscow: Mashinostroenie, 1981.
2. Bairaktarova, D., Eodice, M. *Advances in Engineering Education*, **2017**, 6(2), 1-18.
3. Chen, B. *Journal of Engineering Design*, **2018**, 29(3), 87-130.
4. Enayati, H., Chandy, A.J., Brauna, M.J. *International Journal of Thermal Sciences*, **2018**, 123, 42-57.
5. Ganghoffer, J.-F., Goda, I. *International Journal of Engineering Science*, **2018**, 127, 53-79.
6. Gavryushin, S.S., Baryshnikova, O.O., Boriskin, O.F. *Numerical analysis of machine elements and devices*, Moscow: Publishing house MSTU. N.E. Bauman, 2014a.
7. Gavryushin, S.S., Gavrilencov, S.I. *Engineering Herald*, **2015**, 10, 538-547.
8. Gavryushin, S.S., Nepochatov, A.V., Godzikovsky, V.A. *Proceedings of the Moscow State Technical University MAMI*, **2014b**, 4, 88-94.
9. Gavryushin, S.S., Skvortsov, P.A. *Mechanical Engineering and Engineering Education*, **2017**, 3(52), 56-63.
10. Gavryushin, S.S., Skvortsov, P.A. *Modeling of a two-membrane pressure transducer on a "silicon on sapphire" structure*. Materials of the XXII International Symposium "Dynamic and Technological Problems of Mechanics of Constructions and Continuous Media" named after A.G. Gorshkov, Vyatichi, 2016.
11. Gurentsov, E. V., Eremin, A.V., Mikheyeva, E.Yu. *High Temperature*, **2017**, 55(5), 723-730.
12. Jiang, Y., Sun, R., Zhang, H.B., Min, P., Yang, D., Yu, Z.Z. *Composites Part A: Applied Science and Manufacturing*, **2017**, 94, 104-112.
13. Kim, K., Ju, H., Kim, J. *Polymer*, **2016**, 91, 74-80.
14. Kozlov, A.I., Stechebnikov, V.M. *Devices*, **2014**, 7, 41-44.
15. Krivulin, N.O., Pavlov, D.A., Shilyaev, P.A., Korotkov, E.V., Gladysheva, V.A., Bobrov, A.I. *Bulletin of the Nizhny Novgorod University named after N.I. Lobachevsky*, **2012**, 3(1), 30-33.
16. Nelson, K.G., McKenna, A.F. Brem, S.K., Hilpert, J., Husman, J., Pettinato, E. *Journal of Engineering Education*, **2017**, 106(2), 218-244.
17. Sobol, I.M., Statnikov, R.B. *The choice of optimal parameters in problems with many criteria*, Moscow: Izd-vo Drofa, 2006.
18. Stechebnikov, V.M. *Radio engineering and electronics*, **2005**, 50(6), 678-696.
19. Wang, Y., Li, J., Liu, H., Weng, Y. *International Journal of Thermal Sciences*, **2017**, 122, 12-25.
20. Wang, Z.-G., Gong, F., Yu, W.-C., Huang, Y.-F., Zhu, L., Lei, J., Xu, J.-Z., Li, Z.-M. *Composites Science and Technology*, **2018**, 162, 7-13.
21. Yang, G., Zhao, C.Y. *International Journal of Heat and Mass Transfer*, **2016**, 94, 199-210.

Figure 1. Semiconductor strain gage on the structure of CSN

Figure 2. Two-membrane pressure transducer

Figure 3. Semiconductor sensor of the load cell on the CNS

Figure 4. The scheme of multicriteria optimization of the design of an elastic element

Figure 5. Calculation scheme with control parameters

Figure 6. Finite element model of the design

Figure 7. User program interface for optimizing the design of a dual-membrane TP on the CNS

Table 1. *Physical characteristics of VT-9 alloy*

Young's modulus, GPa	Poisson's ratio	Yield strength, σ_t , MPa	Strength limit, σ_B , MPa
118	0,34	980	1150

Table 2. *Comparison of the parameters of the original construction and Pareto-optimal solutions*

Quality parameters	Initial design	Pareto-optimal variant No 1	Pareto-optimal variant No 2	Pareto-optimal variant No 3
$\sigma_{ekv\ max}$, MPa	798	754	480	651
Nonlinearity of the output characteristic, %	0,39	0,07	0,16	0,09
Operating transmission factor, mV/V	4,6	5,0	3,6	6,2