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Abstract. The impact of singularity points on stress distribution in piezoresistive module is investigated by means of FEM simulation. The strong influence of singularities on stress distribution in silicon-glass interface is presented in this paper.

Keywords: FEM simulation, pressure sensor, singular points

КІНЦЕВО-ЕЛЕМЕНТНЕ МОДЕЛЮВАННЯ ТЕНЗОРЕЗИСТИВНОГО МОДУЛЯ ТИСКУ

Віктор А. Грідчін, Михайло А. Чебанов

Анотація. Використовуючи техніку кінцево-елементного моделювання, досліджено вплив сингулярних точок на розподіл напруг у п'єзорезистивному модулі. Показано сильний вплив сінгулярностей на розподіл напруг на інтерфейсі кремній-скло.

Ключові слова: кінцево-елементне моделювання, сенсор тиску, сингулярна точка

КОНЕЧНО-ЭЛЕМЕНТНОЕ МОДЕЛИРОВАНИЕ ТЕНЗОРЕЗИСТИВНОГО МОДУЛЯ ДАВЛЕНИЯ

Виктор А. Гридчин, Михаил А. Чебанов

Аннотация. Используя технику конечно-элементного моделирования, исследовано влияние сингулярных точек на распределение напряжений в пьезорезистивном модуле. Показано сильное влияние сингулярностей на распределение напряжений на интерфейсе кремний-стекло.

Ключевые слова: конечно-элементное моделирование, сенсор давления, сингулярная точка

I. Introduction

Silicon piezoresistive pressure sensors fabricated in compliance with microsystem technology are widely applied. Design and technology of such sensors are constantly improved. It is associated with new fields of their application, as well as with increasing metrological requirements. This results in constant complication of their mathematical models ranging from simple analytical models to complicated FEM models. Meanwhile piezoresistive modules used in real sensors consist of piezoresistive chip and temperature-compensating back-up plate (Fig.1) [1], [2]. The back-up plate stabilizes operation of piezoresistors and diminishes the impact of mechanical stresses occurred when sensor is assembled to a measuring point.

II. Problem definition

The model of piezoresistive module should output data on strains in dangerous regions. A failure of both membrane and silicon — glass interface can occur when pressure is applied. The last—mentioned fact is especially important when silicon-glass interface works in tension and if strength properties of the back-up plate are worse that of silicon (e. g. if back-up plate is made of glass).

In this paper FEM model of strained piezoresistive module is proposed. The model enables to determine features of strain distribution in piezoresistive module taken in connection with its design. The model also makes it possible to choose optimal geometric parameters of elastic element and to provide necessary factor of safety while preserving high sensitivity of sensor. However, the difference in dimensions of elastic element (units of millimeters) and piezoresistors (units or tenth of micrometers) is significant. That is why the model is separated into two parts: simulation of stresses and strains in piezoresistive module and simulation of electrophysical processes in piezoresistor. The present article is devoted to the discussion of the first part of this model.

III. Model description

Simulation object is a piezoresistive module. Its silicon elastic element has a square shape that corresponds to the technology of anisotropic etching for (100) plane. Elastic element is attached to Pyrex-7740 glass by means of anodic bonding. Temperature coefficient of linear expansion of glass is matched with that of silicon. Due to this fact it is possible to ignore thermomechanical stresses at silicon-glass interface. All dimensions of piezoresistive module are presented in Fig. 1.

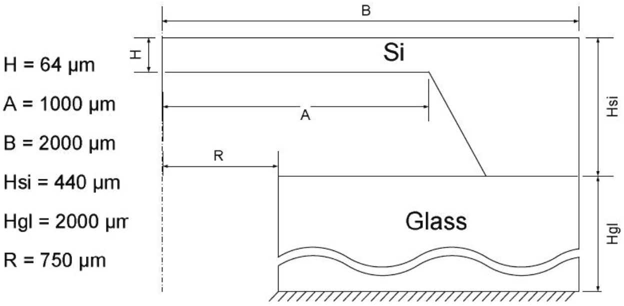

Fig. 1. Geometric dimensions of pressure sensor structure.

The simulation of stresses and strains was carried out by means of FEM in ANSYS software (version 11). Computational complexity is caused by the presence of singularity points at vertices of angles subtended at the intersection of (111) plane with (100) plane and the glass surface. Stress distribution has a divergent character near these points according to [3]:

$$T_{ij} = Kx^{-w}, \tag{1}$$

where K and w are constants, x is the distance to singularity point.

Standard software package does not enable to obtain defined values of stress components in such points. Meanwhile singularity points greatly affect the value of allowable pressure for piezoresistive module. Therefore, the submodel allowing for the stress distribution near singularities was singled out in the model.

Ordered mesh of SOLID186 3D elements was applied to compute stresses occurred far from singularity points. Clamped edge of lower surface of bottom was used as a boundary condition. Symmetric form enables to consider only j part of piezoresistive module.

Stress analysis near singularity points was thoroughly examined in [4]. Its authors suggested to simplify 3D model and to use 2D model instead of it. The same method was used in this study, but it was complemented with the subtraction of circular region near the singularity point with further decrease of its radius (Fig. 2). Thus, it is possible to obtain a set of stable values for stress component under study. Maximum radius of circular region should be chosen so as not to distort the stress state of the structure as a whole. Stress component of interest was determined along the region perimeter with the help of data processing means of ANSYS.

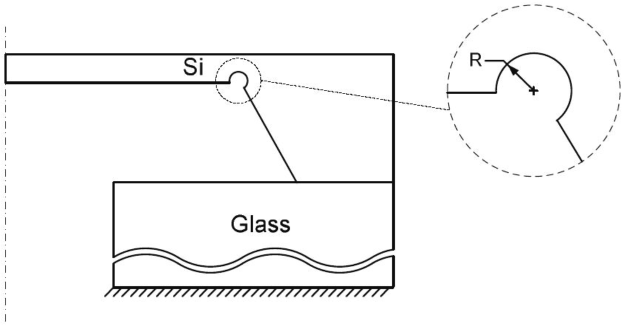

Fig. 2. Operating principle of the method: subtraction of circular sector in the singularity region.

Boundary conditions in the above-mentioned submodel were specified in the form of a restraint of displacement for the bottom along all degrees of freedom. Nodes located along the Y axis were fixed with respect to X coordinate. Simulation was carried out by means of finite element PLANE183 that is intended for application in two-dimensional solid-state structures. Fig. 3 shows the example of finite-element model used for studying singularity in the region of silicon-glass interface.

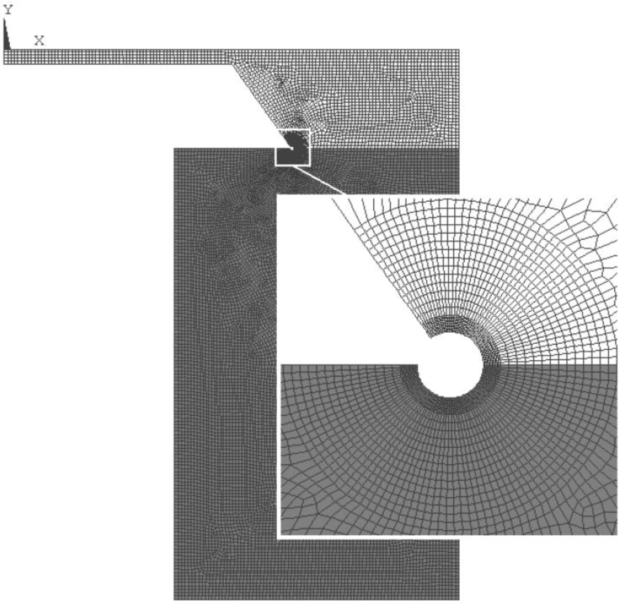

Fig. 3. Example of finite-element model.

IV. Results and discussions

Stress distribution in the planar surface containing piezoresistors is the most important factor when designing pressure sensor. Fig. 4 shows the distribution of Tx stress component in the range from the edge (x = 0 mm) to the center (x = 2 mm) of the elastic element. This distribution was determined by means of 3D simulation. Pressure was applied from the inside. As seen in Fig. 4, the maximum is shifted to the center of elastic element by the value of about 20 μm. Such behavior coincides with the data obtained in other papers [4], [5].

It is caused by non-compliance of clamped-edge condition in the singularity region. This results in stresses occurring outside the membrane edge (x < 1 mm). At the initial segment their distribution can be approximated by a linear dependence having coefficients given in Fig. 4

Fig. 4 also depicts stress distribution obtained by variation method in analytic form [6] (dotted line) in the case of clamped edge at point x = 1 mm. As one can see, analytic description presents overstated values in the singularity region, and it agrees well with the results of numerical model in the center of elastic element.

Stress dependence on the radius R of circular region near the interplanar angle between (100) and (111) is approximated by power function having the coefficient b = 0.3464 (Fig. 5). This result agrees well with simulation results of [4] (b = 0.365 was obtained in the mentioned paper). Fig. 5 shows that stress at singularity point is the determining factor for failure of elastic element. Stress at this point exceeds maximum stress in the planar surface even at R = 10 μm.

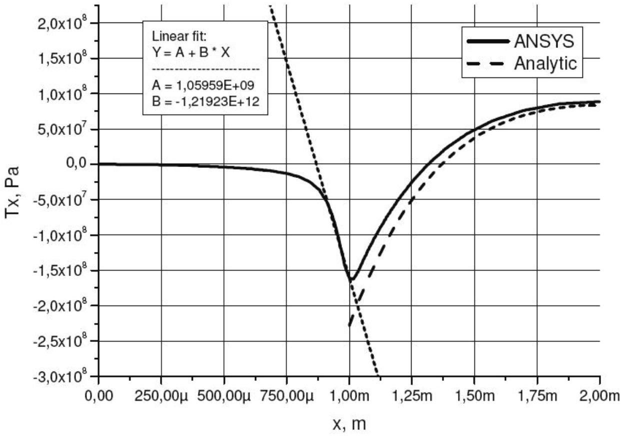

Fig. 4. Stress distribution in the planar surface (along z = 0). Solid line — 3D simulation, dotted line — analytic calculation. Linear approximation coefficients are presented in the picture.

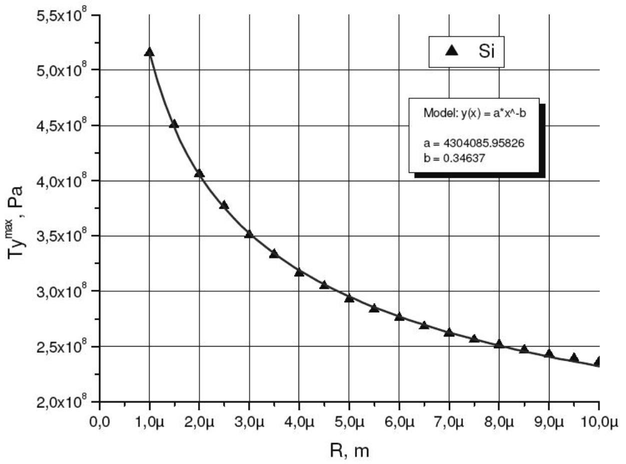

Fig. 5. Stress dependence on the radius of circular region at the singularity point.

In (1) power exponent depends on the value of angle. When α = 54°74 exponents have the following values: b = 0.3705 for silicon and b = 0.4073 for glass. This difference is concerned with the difference in elastic properties of silicon and glass.

Singularity substantially affects the stress distribution at silicon-glass interface. Fig. 6 shows this distribution at z=0 (dependence 1). Simulation data illustrates that stress zone affecting the strength of piezoresistive module occupies the narrow region 300 μm width near the singularity point. Main body of the rigid rim is stressed weakly, and the stress sign is reversed at rim edges. However, it does not mean that dimensions of rim in piezoresistive module can be diminished. The stress concentration at the angular point increases as follows from dependences 2 and 3. This promotes the failure of piezoresistive module in the region of interface.

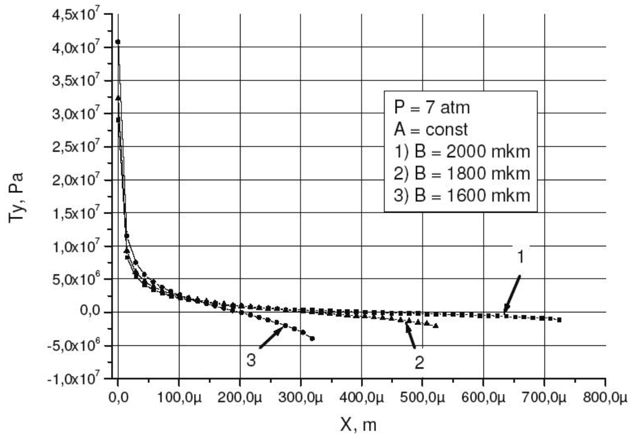

Fig. 6. The dependence of Ty normal component of stress at silicon-glass interface. Reference point corresponds to the interface edge. Simulation was carried out for a circular region having R = 10 µm.

When the pressure is applied to outer side of piezoresistive module singularity points still play role of stress concentrators, and the power law (1) remains valid. Compressive strength is higher than the tensile one therefore piezoresistive module is capable of withstanding higher pressures in comparison with the case of inside pressure application.

Stress value in singularity point depends on the interplanar angle. This value increases when decreasing the angle. Fig. 7 shows the angular dependence of Ty component in the range of $54° \le \alpha \le 125°$. This range has a practical importance in this case.

V. Conclusion

Numerical simulation shows that angles substantially affect the occurrence of regions with dangerous stresses in piezoresistive module with elastic element formed by means of anisotropic etching. The quality of silicon-glass interface in the region of about 300 µm near the angular point is important for the strength of piezoresistive module. The finite-element model implemented in this paper gives the possibility to obtain stable solutions for the region of angular singularities in elastic elements.

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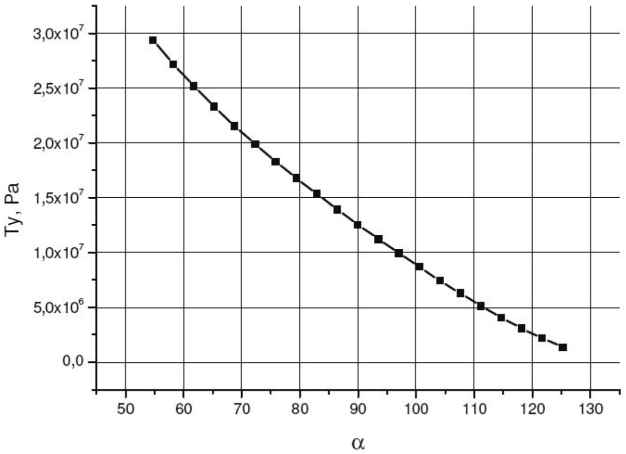

Fig. 7. The angular dependence of Ty normal component of stress. The dependence corresponds to the singularity region at silicon-glass interface; the subtracted region is 10 µm.

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