Investigation into the standardization of micromechanical components and their simulation and computation using FEM
– case study of diaphragms –

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ABSTRACT

Although certain components (such as diaphragms or beams) are used recurrently in micromechanics, the degree of standardization of components that is familiar in classic mechanical engineering is still to a great extent unknown in this field. This is due in part to the scope of MEMS for integrating the mechanics and the (evaluation) electronics together on a single chip (monolithic integration).

This paper presents a form of standardization of micromechanical components, using micromechanical diaphragms as an illustration. This involves defining various diaphragm sizes and shapes as standard, and adapting them to individual tasks by modifying them with specific additional elements. This modular principle permits standardization despite monolithic integration.

Keywords: micromechanics, diaphragm, standardization, finite element method, FEM computation membrane

1 INTRODUCTION

The development of new micromechanical systems (such as sensors) follows a fundamentally different pattern to the development of components and machines in classic mechanical engineering or precision mechanics. Besides the oft-presented "new" manufacturing technologies for Micro-Electro-Mechanical Systems (MEMS) [1, 2, 3, 4], many of which are based on the microelectronics manufacturing process, the approach taken to actual development and design work is fundamentally different.

In classic mechanical engineering, design work is outlined precisely in VDI Directives 2221 and 2222 [5, 6] and subdivided into four main phases: planning / clarification, conception, design and development. A key component of the latter two phases is the need to check components with respect to their standardization and, wherever possible, to utilize standardized components (conforming to DIN/ISO) [7]. Advantages of standardized components include: ease of replacement, low inventory holding costs, lower unit prices due to high volumes etc.

However, standardization is still to a great extent unknown in the field of micromechanics, even though certain components are used recurrently (e. g. diaphragms, beams etc.). Because of this, designers of new components are unable to draw on past experience and, for instance, obtain direct access to micromechanical components with known data and known characteristics via a suitable CAD system during the design process. The component dimensions and the associated durability calculations therefore have to be redefined for each component, whether by computation (e. g. using the Finite Element Method / FEM) or by performing complex experiments.

On the other hand, MEMS in particular do not, at first glance, appear to be easy to standardize because of the desire for monolithic integration of the mechanics and the (evaluation) electronics on a chip.

Scope for introducing standards for micromechanical components was investigated during the course of a research project conducted in GRK 384. The results will be presented here in a case study of the diaphragm component.

2 SENSOR CONCEPT

Common areas of application for micromechanical diaphragms include pressure measurements. However, as the desired pressure ranges vary considerably depending on the application and the pressure sensors consequently need to be redesigned for each new application, this component is a suitable research subject. The objective is to develop a pressure sensor consisting of standardized micromechanical components and with an overall modular design.

Such a sensor ideally consists of a basic element which contains a pressure diaphragm and the evaluation electronics. The schematic structure is shown in Figure 1. The technical production of a basic element of this type is well known and is practised in the case of the pressure sensors that are now being manufactured on an industrial scale. On the other hand, it is a new feature to concentrate on a limited number of basic elements with various diameters of diaphragm. This permits large batches of the basic module, and in turn has a beneficial effect on the item prices of the modules and therefore on the overall cost of the sensor.

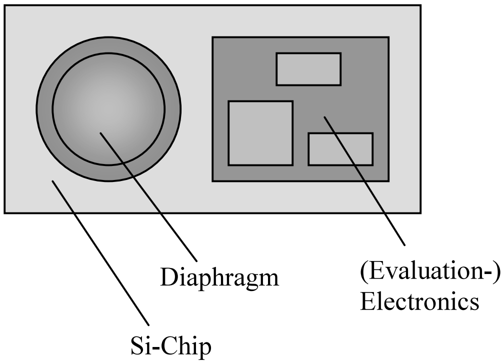


Figure 1: basic element of a pressure sensor

If a sensor is required with characteristics that cannot immediately be satisfied by the limited number of basic elements, the basic element is supplemented with parts from a "toolkit" until the desired properties are achieved with sufficient accuracy. The way these modular additional elements interact with the basic element is known.

In the case of the pressure sensor, modification can be performed straightforwardly by incorporating spacers which partly or fully support the diaphragm and thus increase the resistance of the diaphragm e.g. to higher pressures. This type of modification is shown in Figure 2.

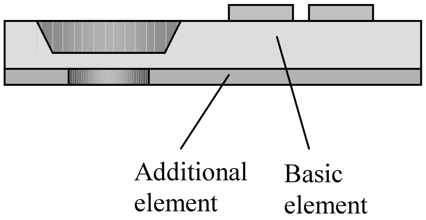


Figure 2: pressure sensor consisting of the basic element modified with an additional element

Depending on the application, various forms of spacers are conceivable. These are shown in Figure 3. Figure 3a is a plate of constant thickness, supporting the diaphragm across its full surface (the diaphragm thickness is increased), thus making the basic element also suitable for higher pressures. Figure 3b reduces the effective radius of the diaphragm and serves the same purpose as the spacer in Figure 3a. In Figures 3c and 3d, the entire diaphragm surface is available at low pressure, but at higher pressures – where the curvature of the diaphragm is correspondingly higher - the diaphragm rests against the spacer, thus reducing the effective area of the diaphragm. At low pressure, the sensor is thus able to detect even slight fluctuations in the pressure thanks to the large area of the diaphragm, but is also able to measure higher pressures (albeit with a slightly lower resolution).

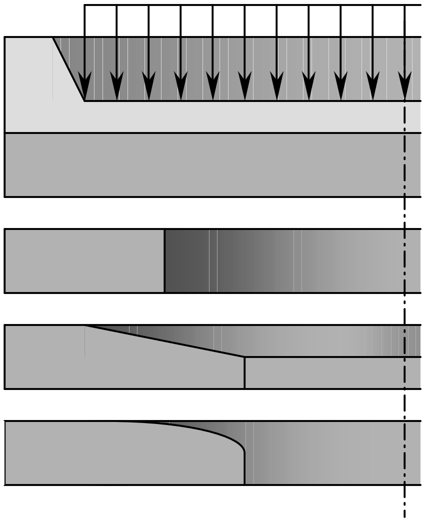


Figure 3: various forms of spacers for adapting the diaphragm to special application conditions

3 COMPUTATION UND SIMULATION

In order to adapt the basic element exactly to the desired task by means of the spacer, it is necessary to know how the individual elements interact with the basic element. As the curvature of the diaphragm depends on the pressure acting on it, the pressure can be determined by the curvature (e.g. capacitively). For this reason, only the curvatures and diaphragm tensions are considered in the following computations and simulations.

3.1 Basic element (analytical computation)

Due to the properties of the diaphragm, which is manufactured from a piece of silicon wafer e.g. by anisotropic etching, the curvature of a diaphragm can be determined analytically using Kirchhoff's equation:

$$\Delta\Delta w = \frac{p}{K} \tag{1}$$

where
Δ = Laplace operator
w = Curvature
p = Pressure
K = Flexural strength

The equation for the elastic line of a circular diaphragm is thus:

$$w(r) = \frac{p}{K}\left(\frac{1}{64}R^4 - \frac{1}{32}R^2r^2 + \frac{1}{64}r^4\right) \qquad (2)$$

where R is the radius of the diaphragm and r the radius at the point to be investigated.

The maximum curvature, which is to be found at the centre of the diaphragm (r=0), can be determined as follows from (2):

$$w_{\max} = \frac{p}{K}\frac{1}{64}R^4 \qquad (3)$$

3.2 Basic element (FEM computation)

The analytical calculation is now verified with the aid of finite-element simulation (FEM). Version 5.5 of the ANSYS program is used for this purpose.

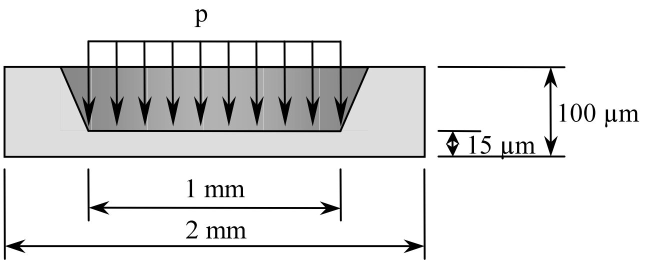


Figure 4: Dimension of the diaphragm used for FEM simulation

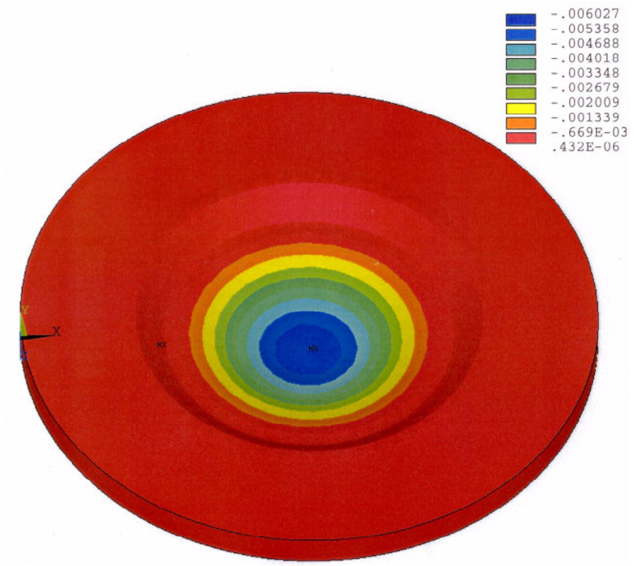


Figure 5: FEM computation of a basic element (displacement / mm)

An average modulus of elasticity of $1.6 \cdot 10^{11}$ N/m^2 is assumed for polysilicon; the directionally dependent moduli of elasticity for monocrystalline silicon can be determined from the matrix of coefficients of elasticity [4]. The values for the moduli of elasticity then fluctuate from $1.30 \cdot 10^{11}$ N/m^2 in the (001) plane, through $1.69 \cdot 10^{11}$ N/m^2 in the (011) plane, to $1.88 \cdot 10^{11}$ N/m^2 in the (111) plane.

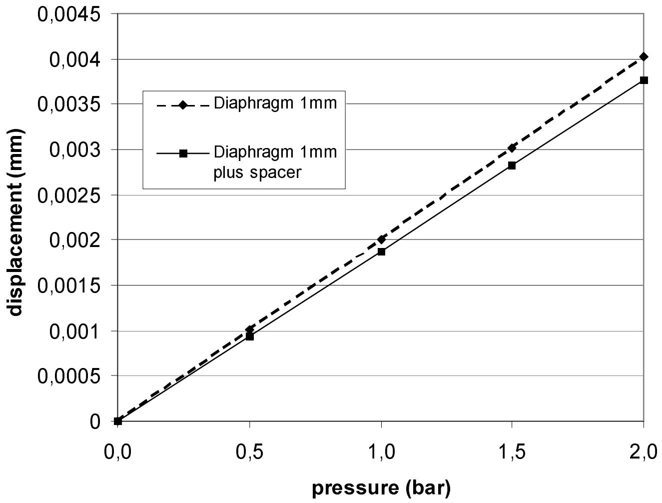
The computation results of the analytical computations performed to verify the FEM model agree with the results of the FEM computations in every case considered. One example of an FEM computation of a basic element is shown in Figures 4 and 5.

3.3 Complete element (FEM computation)

FEM computation of the complete element (i.e. basic element plus spacer) is barely possible by analytical means in view of the geometrical complexity. These computations are therefore conducted exclusively by means of the FE method. In the case of the combinations in Figure 3a and 3b, the computation is relatively simple to handle, as the model from chapter 3.2 is used and elaborated on. The combinations 3c and 3d, on the other hand, represent a contact problem, as the diaphragm initially makes no contact with the spacer, but then moves up against it under the influence of pressure.

These contact problems necessitate on the one hand greater attention during creation of the geometry, and on the other hand significantly more computing work and therefore computing time. These contact problems can, however, likewise be computed with ANSYS. Figure 6 shows an ANSYS computation for case 3c.

The following pressure-curvature diagram shows the results of the computations. This allows the results to be made available in a simple form to the sensor designer. If a curve matches the desired characteristic, the corresponding spacer is used and the sensor assembled on a modular basis.



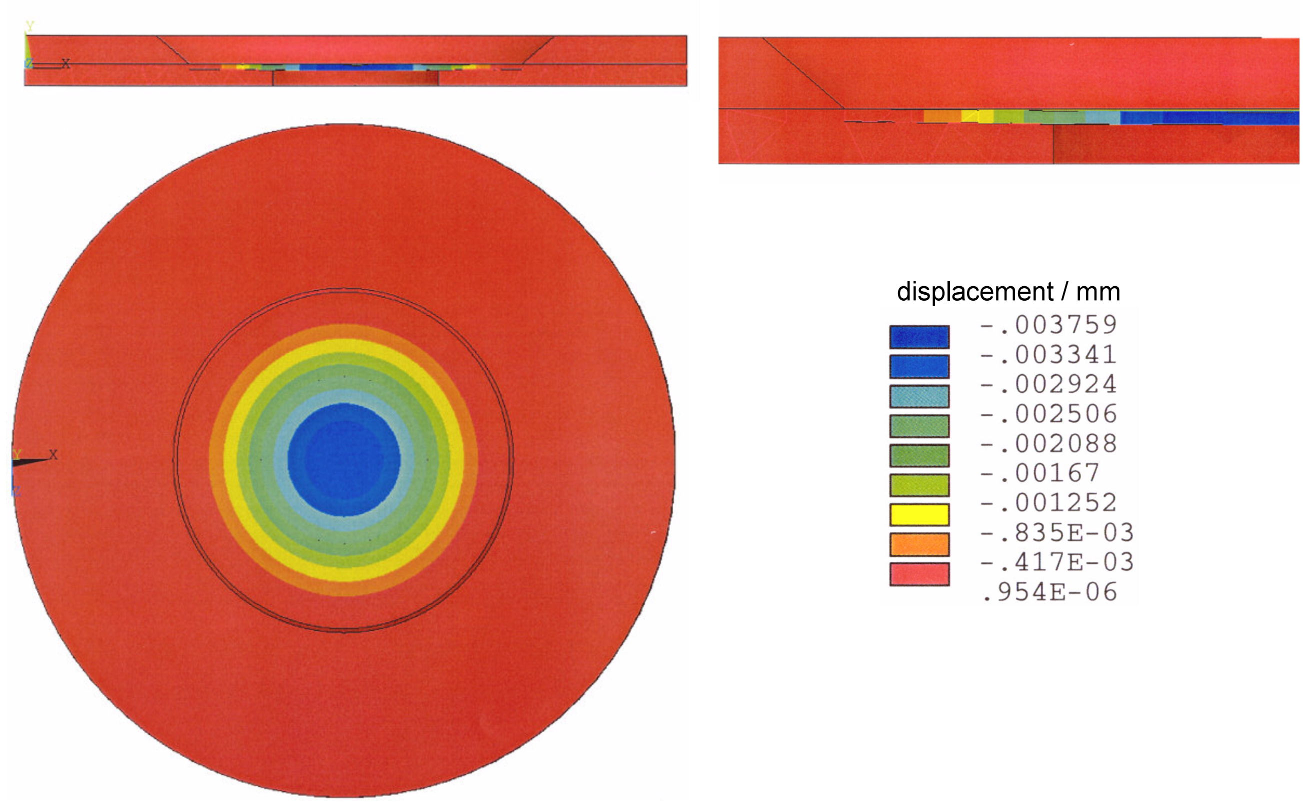


Figure 6: FEM computation of a complete element (basic element plus spacer 3c)

4 CONCLUSION AND OUTLOOK

The procedure described in this paper means that it is now possible in microsystems technology to put together components (in this case sensors) from a modular toolkit, along the lines customarily used in mechanical engineering (e.g. when selecting bearings), and to adapt them to the desired requirements. In view of the large number of common parts, low-cost production of the components is assured and the extent of computations and simulations required for the design process is minimized, as the computations do not always need to be performed afresh and existing results, tables and diagrams can be used. This form of standardization therefore facilitates working with microsystems technology components for the designer.

Future developments include considering whether the form of standardization presented can be transferred to other components in microsystems technology in a similar way. Could there for instance be other scope for standardization of other components in microsystems technology?

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