Production technology of micromechanical vacuum gauge

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Abstract. The article describes technological issues of micromechanical vacuum gauge manufacturing, designed for pressure measurements in the range from 10 to 10000 Pa

1. Introduction

One of the important problems in modern industry is development and production of devices and systems for vacuum measurement. It is important to investigate new methods and approaches for vacuum measurement. JSC GYROOPTICS and VNIIM carry out a project dedicated to development of a micromechanical vibration vacuum gauge [1]. Schema of the vacuum gauge is presented in figure 1.

![Figure 1](image-url)

Figure 1. Schema of micromechanical vibration vacuum gauge cross section. 1 is top glass, 2 is silicon plate, 3 is bottom glass, 4 are torsions, 5 is silicon frame, 6 is gap.

Micromechanical vibration vacuum gauge consists of three layers: 75 μm of silicon between 400 μm of glass. Silicon plate with dimensions of 0.9x0.9 mm fixes on torsions which provide vibration motion along oz axis. There is 3 μm gap between silicon and glass. The gap is formed by plasma etching technology. There are metal electrodes on top and bottom glasses. They provide a silicon plate vibration motion by electrostatic force. Also they allow to detect an oscillation amplitude and frequency during vacuum gauge operation.
Output signal of vacuum gauge is resonance frequency of silicon plate which depends on pressure. This phenomenon based on addition of gas springs in vibration system. Parameters of the spring are function of pressure. In this paper we describe technology issues of micromechanical vacuum gauge manufacturing.

2. Manufacturing technology of micromechanical vacuum gauge

Group technology is used for micromechanical vacuum gauge production. It means that a lot of gauges produced on one wafer at the same time. In manufacturing cycle wafers are treated by standard set of microelectronics and micromechanics processes.

Micromechanical vibration vacuum gauge process flow includes initial preparation of separated wafers: two glass wafers and one silicon wafer. Two thin layers of Al form electrodes on glass wafers by sputtering and lithography processes. 3 μm cavities in silicon wafer are formed by plasma etching process. Top glass wafer is bonded with silicon one by anodic process with alignment. Grinding and polishing processes of silicon layer down to 75 μm thickness are the next steps. Then we carry out two lithography and etching processes on silicon surface. They form the bottom 3 μm cavity and free micromechanical structure of vibration vacuum gauge. Then we carry out the second anodic bonding and form outside metallization and contact pads.

Most of described operations are standard for MEMS production. But vacuum gauge design creates several technological issues, which must be careful development. Also we need investigate a technology tolerance for described process flow.

3. Analyses of technology tolerance

Uniform and flatness of gap between silicon plate and electrode on glass is one of the most important parameter in vacuum gauge design. This 3 μm cavity is formed by plasma etching in silicon. The process has own uniformity of etching rate along wafer. It can lead to parameter distribution for batch of micromechanical vacuum gauges. To evaluate this uniformity we carried out series of tests. 5 wafers with 21 structures on each (total 105 pcs.) have been etched and cavity depth was measured. Obtained data after statistical treatment present in figure 2.

![Figure 2](image2.jpg)

**Figure 2.** Cavity depth distribution in test structure set.

![Figure 3](image3.jpg)

**Figure 3.** SEM image of cavity bottom after plasma etching.

It is possible to note that presented distribution has maximum at 3.65 μm. Maximal deviation from this value is plus 0.25 μm and minus 0.55 μm that corresponds 7 and 15 %.

Flatness of cavity bottom was checked on test structures. Etching depth was increased from 3 μm to 15 μm for accuracy investigation. Etched structures were prepared for cross section investigation by SEM. Example of test structure SEM image is presented in figure 3. We can note that cavity bottom
has high uniformity and flatness if etching process is tuned accurately. It is possible to conclude that plasma etching process of cavity in silicon plate allow to form a gap between plate and electrodes.

Another property of described production flow of micromechanical vacuum gauge is etching of top gap by plasma etching process in silicon-on-glass wafer. This wafer (after the first anodic bonding process) has different electrical and heat transfer properties then silicon one. It means plasma etching process carry out in different way with increased distribution of etch rate. It is a reason of technological problem of top and bottom equivalent gap production. So we should investigate influence of gap difference on micromechanical vacuum gauge parameters.

To solve this problem we made analytical mathematical model which describe pressure changes in gap during silicon plate oscillation as function of cavity depth. We considered cases with equivalent top and bottom gaps (3 and 4 μm) and case when top gap is 3 μm and bottom one is 4 μm and vise versa. Plots of pressure changes depend on plate displacement for this cases are presented in figure 4.

We can note that gap increasing from 3 μm to 4 μm leads to reducing of pressure difference at set value of silicon plate displacement. The same behavior we obtain when increase only one gap, top or bottom separately.

The first derivative of pressure difference describes sensitivity. This parameter has weak nonlinearity as it presented in figure 5. Ideal vacuum gauge should have high sensitivity independent of oscillation amplitude. Physical principle of vacuum gauge operation could not provide linear characteristic. For low amplitude (0.03) calculated nonlinearity has value around 0.3%. For high amplitude (0.1) nonlinearity increase up to 3 %. This is a reason to restrict maximum displacement of silicon plate. We find interesting effect when top and bottom gap are not equivalent. For separated cases nonlinearity increases to 1.2%. But when we unit this cases, because plate has oscillation motion, nonlinearity are summarized and total value is only 0.5 % (for low amplitude).

4. Computer simulation

Computer model of micromechanical vacuum gauge was developed for investigation of technological inaccuracy. Influence of natural gravity acceleration (1 g) on silicon plate was investigated. Computer simulation results show that maximum displacement of silicon plate in the case is 0.0684 μm. The value is lower than technology tolerance of gap and lower than plate oscillation amplitude. By the reason we can do not take in account plate displacement under standard gravity acceleration.

In addition we carried out simulation of vacuum gauge operation at absolute vacuum and at pressure in range from 10 to 2000 Pa. In case when pressure does not zero we should include gas springs in vibration system which changes a resonance frequency. These gas springs have different influence on different vibration modes. We can simulate this effect changing one gas spring on many springs, distributed along silicon plate. In figure 1 simulation results of resonance frequency at different pressure are presented.
Table 1. Calculated values of the resonant frequency as a function of pressure.

| Pressure, Pa | Stiffness of gas spring, N/m | Frequency, Hz (Simulation) | Frequency, Hz (Analytical model) |
|--------------|------------------------------|-----------------------------|----------------------------------|
|              |                              | 1 gas spring                | 5 gas springs                   |
| 10           | 5,649                        | 1294,04 (1 mod)             | 1293,97 (1 mod)                 |
| 492,127      | 278                          | 6741,04 (3 mod)             | 6739,75 (3 mod)                 |
| 994,876      | 562                          | 9542,43 (6 mod)             | 9538,78 (4 mod)                 |
| 1498         | 846                          | 11689,8 (6 mod)             | 11683,1 (4 mod)                 |
| 2000         | 1130                         | 13498,9 (6 mod)             | 13488,6 (4 mod)                 |

These results show that pressure increasing leads to changing of vibration mode of parallel plate motion along oz axis. At zero pressure this motion is the first vibration mode but at 2000 Pa it is the fourth mode. It means that there is some pressure when frequencies of different modes are equivalent. It may lead to problem during vacuum gauge operation and we need take in account this effect.

5. Conclusions
In this work we present results of modeling, simulation and technological tests which dedicate to technological issues of vibration micromechanical vacuum gauge production. Results describe formation problem of equivalent top and bottom gap. Analytical calculations show that technological inaccuracy of cavity depth does not influence on vacuum gauge parameter significantly. Obtained results allow begin a manufacturing process of micromechanical vacuum gauge.

References
[1] Gorobey V N, Garshin A Ya and Kuvandykov R E 2017 Vacuum Technology and Technologies - 2017. Proceedings of the 24th All-Russian Scientific and Technical Conference with International Participation)