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Vacuum in microsystems – generation and measurement

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This paper reviews the current state of art of vacuum encapsulation of microsystems. Different types of bonding techniques and "integrated sealing process" are described. It is concluded that the step forward in vacuum sealing of MEMS structures should be elaboration of MEMS-type micropump, which would be integrated with microsystem structure. A novel concept of a miniature orbitron pump is presented. It is also reported how vacuum inside the micropump can be measured. It is proposed that for measurement of a low vacuum level, a membrane sensor can be used, and for a high or ultra-high vacuum level - an ionization sensor. Both sensors should be integrated with a micropump structure. The results of membrane sensor study are presented.

Keywords: vacuum MEMS, micropump, vacuum sensor, interference method.

1. Introduction

Vacuum sealing is a required process for vacuum nanoelectronics and resonance--based MEMS devices [1]. For vacuum encapsulated microdevices, the water and gases penetration through the seal or outgas from substrates, films, cap and sealing materials during operation, can degrade a vacuum level and a device performance, and shorten their lifetime.

It is difficult to generate and maintain vacuum in a very small volume (less than 1 cm^3). One possible approach to improve vacuum is using a getter material [2]. This is generally a transition metal-based material which properly activated, becomes highly reactive with nitrogen, oxygen and carbon oxides. Thus, over time, a getter material acts as a small vacuum pump. As an example, SAES's St122 material absorbs about 0.7 $ccmbar/cm^2$ for a 100 μm thick film [1].

The main wafer-level vacuum packaging technologies used for MEMS devices are: "integrated sealing process" using thin film sacrificial layers, and wafer bonding processes with or without intermediate layers (Fig. 1) [1]. The integrated sealing process has the advantage of sealing micromechanical components *in-situ* prior to the chip dicing and handling steps to avoid contamination [3].

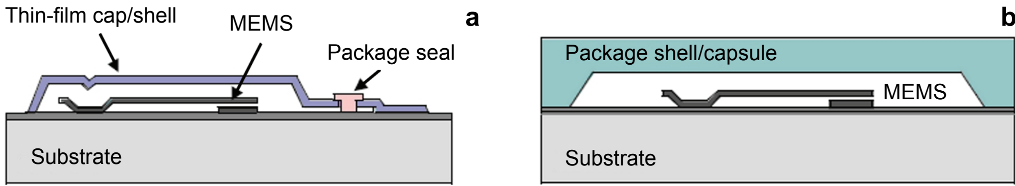

Fig. 1. Diagram of MEMS vacuum package formed by use of: integrated sealing process (**a**), wafer bonding process (**b**) [3].

There are many materials which are used as a sacrificial layer, for example: LPCVD PSG (low pressure chemical vapor deposition phosphorus silicate glass) [4], and PECVD (plasma enhanced chemical vapor deposition) oxide layer [5].

Generally, the microcavity final pressure is higher than the encapsulation layer deposition pressure. TSUCHIYA *et al.* [5] presented that a microchamber of MEMS gyroscope was encapsulated at a deposition pressure of 53 Pa. It was estimated that the resulting pressure in the microchamber was below 400 Pa. BARTEK *et al.* [6] described encapsulation process elaborated for field-emission micro vacuum tubes. The microcavity with sharp silicon tips was sealed at pressure of 2.6×10^{-4} Pa. The resulting pressure was estimated to be about 10^{-3} Pa.

Two types of wafer-level bonding processes are commonly used in MEMS fabrication [7]: direct wafer bonding (silicon-to-silicon fusion bonding and silicon-to--glass anodic bonding) and wafer bonding with intermediate layers. The two bonding surfaces must be very flat and clean, and sufficient bonding energy must be supplied in the form of heat. The anodic bonding technique was applied to fabricate absolute capacitive pressure sensors with the use of getter layer [8]. At the elevated bonding temperature, Ti getter layer effectively absorbed O_2 out-diffusing from the metal covered part of the glass cavity. The resulting pressure in the microcavity reached 30 Pa.

Glass frit sealing has been used for many years in flat display devices, automotive and medical MEMS applications. SPARKS *et al.* [9] presented chip-scale package which was obtained using glass frit bonding between the Pyrex plate and silicon wafer. They determined that without the getter a cavity pressure was about 200 Pa (vacuum chamber pressure 0.1 Pa). After using NanoGetter^{TM} the microcavity pressure has been reduced by more than 3 orders of magnitude.

CHIAO and LIN, the authors of Chapter 3 in [1] refer the study of HARA *et al.* on gyroscopes based on resonant MEMS structures. Free standing structures were encapsulated by vacuum anodic bonding and reflow of a solder ball (SnPb) at 200 °C. The pressure level inside the cavity was 10 Pa. The most useful bonding process with intermediate layer is the eutectic bonding technique [10]. This method use PSG, aluminum or indium as intermediate layer, and localized resistive heating structure for Si/Au eutectic bonding [1]. A vacuum sealing process using RTP (rapid thermal processing) aluminum-to-nitride bonding has been described by CHIAO and LIN [11].

Both wafers were pre-baked at pressure of 4 Pa and sealing process was done by RTP heating for 10 s at 750 °C. They obtained pressure of about 30 Pa inside the micro-cavity. All of those methods base on external pumping systems. The best solution, which would allow continuous improvement of vacuum inside the microsystems, is integrating them with MEMS-type micropump.

It is supposed that the best results could give an ion-sorption micropump, which uses gas ionization with an electron beam and getters. Till this moment there has not been reported in the literature any realization of this kind of a micropump. General purpose has been presented first time by Koops in 2005 [12] who has chosen an orbitron pump as the best candidate for miniaturization.

2. Miniature vacuum pump

In this paper a novel concept of a miniature vacuum MEMS-type pump with a microcavity of about 3 cm^3 is presented. An electron beam emitted from a central cold cathode (Fig. 2) will be used for gas ionization. Electrons will be attracted towards an anode placed on the perimeter of a microcavity, and a perpendicular magnetic field will cause their orbital movement. It will lead to increasing the probability of gas particles ionization. Generated ions will be absorbed by a collector (getter film).

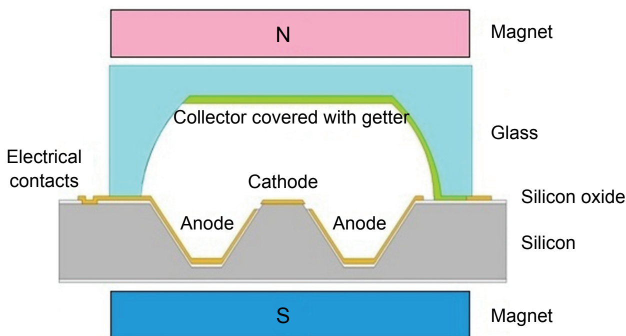

Fig. 2. Construction scheme of a miniature vacuum pump.

The most important element of the proposed construction is electron source. Previous research on lateral field-emission source gave promising results: low threshold voltages (about 15 V) and high emission current (microamperes per cathode) [13].

To control if the micropump is working correctly, it should be integrated with MEMS-type vacuum sensors. Many different examples of such devices are presented in the literature: membrane, thermal conductivity, and friction or ionization sensors [14]. Most of those sensors require fabricating many additional microelements and preparing special cavities to place them. In designed micropump, to estimate low vacuum (in which an orbitron pump starts to work), an interference method based on measuring

deflection of a thin silicon membrane will be applied [15]. It is planed that to monitor high vacuum generated by operating micropump, the measurement of collector ion current will be used.

3. Experiments

For measuring pressure in a microcavity, a series of test silicon-glass structures have been prepared. Thin membranes ($5\times5\times0.062$–0.1 mm^3) were fabricated in (100) silicon substrate. Next, silicon wafer was anodically bonded with a 1 mm thick glass substrate (Borofloat 3.3, Schott). The bonding process was carried out in air or in vacuum (10^{-3} hPa), with or without getter material (2 mm^2) located inside the microcavity. Getter in the form of thin film deposited onto a metal foil has been provided by SAESGetters. Bonding parameters were following: voltage about 2000 V, temperature from 300 to 350 °C. After bonding process the activation of getter was done at $T = 450$ °C for $t = 30$ min.

To measure a deflection of the test membrane, a transparent glass plate was placed on its top, and illumination by a light bulb was used. The incident light first reflected from the deflected membrane and then also from the glass cover. Both light waves interfered with each other and colorful stripes were observed. The most intensive – red stripes – were counted. Because an exact wavelength was unknown, whole system was calibrated using Taylor Hobson mechanical profilometer. Obtained calibrating curve was linear (Fig. 3). Having the data of the number of stripes for every test structure and the deflection corresponding to it, it was possible to estimate the pressure inside the microcavities.

Figure 4**a** presents the deflections of the different membranes (62, 70, 85 and 100 μm thick) bonded in different conditions (BA – bonding in air, BAG – bonding in air with getter, BV – bonding in vacuum and BVG – bonding in vacuum with getter). It is evident that for thinner membranes the deflection was bigger than 30% of their

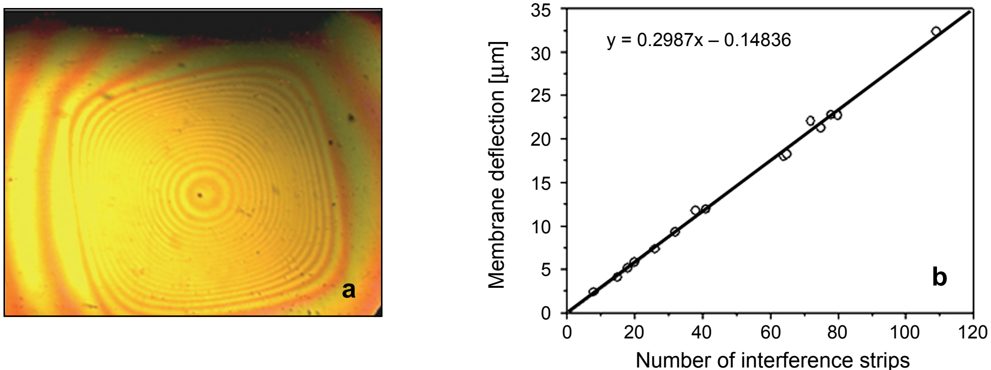

Fig. 3. Example of interference image (**a**) and calibration curve (**b**).

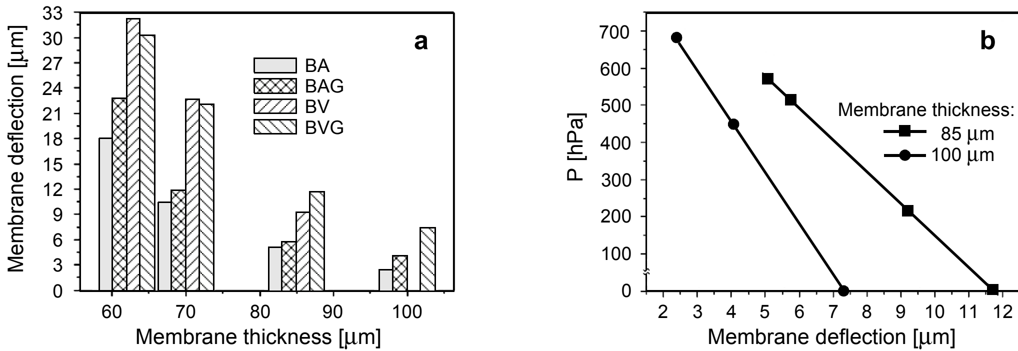

Fig. 4. Experimental results: membrane deflection *vs*. thickness of membrane (**a**), pressure inside test structures *vs*. membrane deflection (**b**).

thickness. Because their nonlinearity can be high, pressure was estimated only for thicker membranes: 85 and 100 µm. In calculations it was assumed that the microcavity pressure in bonding conditions (BVG) was on a level of 10^{-1} Pa (tested by SAESGetters), and that the deflection is proportional to the differential pressure (between atmosphere and pressure inside a microcavity).

The range of membrane deflection varied from few to over 30 µm, which corresponds from several to over hundred interference stripes. The space between two stripes corresponded to the deflection of about 0.3 µm.

The applied method makes it possible also to recognize structures bonded in different conditions. Bonding in air (BA), because of the elevated temperature of the process, caused the decrease in pressure from 3×10^4 to 4×10^4 Pa. Moreover, for every type of structures with getter inside (BAG), a significant improvement of vacuum level (10–20%) was observed. Encapsulation in vacuum conditions (BV) caused the deflection about twice bigger than bonding in air (BA). According to SAES measurements it should correspond to a pressure of about 100 Pa. Bonding in vacuum with the use of the getter material (BVG) gave pressure of about 10^{-1} Pa. The interference method should not be applied for pressure lower than 100 Pa.

4. Conclusions

Obtained data allow confirming the usefulness of the presented interference method for low vacuum (pressure higher than 1000 Pa) estimation. It could be used in presented construction of the orbitron micropump, especially when it starts to operate. In a range of ultra high vacuum (it is a level that should be achieved with this micropump) a method of measuring ion current was proposed.

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