

Studies on the Sealing of Surface Micromachined Cavities Using Chemical Vapor Deposition Materials

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I. INTRODUCTION

Sealing of micromachined cavities [1-12] is an important technique that has been used by many researchers to reduce air damping for electromechanical resonators [1], to establish pressure measurement references [2,3], and to make vacuum electronics [8, 11]. As a whole, many different techniques have been applied in order to seal the cavity with a predetermined pressure, including Chemical Vapor Deposition (CVD) [1-6], thermal oxidation[4], E-beam evaporation[7,8], sputtering[9], wafer anodic bonding [10,11,12], and solder glass fritting [13]. Although these many sealing procedures have been demonstrated, there is little systematic study just on the sealing methods. Here, we report our study on sealing of surface-micromachined cavities. In this work, the main focus is to find out the required thickness to seal cavities with various geometries using different CVD materials, including LPCVD silicon nitride, LPCVD polysilicon, LPCVD Phosphosilicate Glass (PSG), and PECVD silicon nitride.

II. DESIGN AND FABRICATION

Shown in Fig. 1 are four types of test structures which are designed around a square diaphragm with different features added to it. The diaphragms are square in shape with 200 μm by the side. Type-1 structures have different numbers (4-6) of etching channels with varying channel widths (2 to 16 μm) and lengths (8 to 38 μm). The feature of type-1 structures is that these channels may have little effect on the mechanical integrity of the diaphragms. Type 2 and 3 structures have center [6] and corner etching holes on the diaphragm, respectively. Such etching hole structures do not occupy extra space in addition to the diaphragm. A range of hole sizes (2-16 μm) and numbers (1,2,6) have been included in our design. Type-4 structures have one to four side openings, 120 or 180 μm long; they are studied here because the side opening can facilitate chemicals (or gas products) to go in and come out of the cavity during sacrificial layer or silicon etching. Since our current study is based on statistical data, a large number of samples is desirable. In our design, each die ($1 \times 1 \text{ cm}^2$) has 126 different cavities (72, 36, 3, 15 for type 1, 2, 3, 4 respectively). A 4" wafer has 48 dies and therefore each individual cavity has a sample space of 48.

All the test structures are fabricated in one process which is shown in Fig. 2. Starting with 4" wafers, we deposit 600 nm low-stress LPCVD silicon nitride as the insulation layer. This nitride is patterned and plasma-etched (600 nm into the silicon for the subsequent fully-recessed LOCOS process) to define the cavity wells ($200 \times 200 \mu\text{m}^2$). Thermal oxide of 1.3 μm then is grown in the wells up to silicon nitride level to maintain wafer surface flatness. PSG is deposited and patterned as the sacrificial layer; most of the wafers have a PSG of 220 nm thick but we have included other thicknesses of 280, 480, and 720 nm for studies of gap-height effects on sealing. The wafers are then deposited with 800 nm low-stress silicon nitride as the diaphragm material, which is then patterned to have etching holes ($10 \times 10 \mu\text{m}^2$) for PSG etch. Using concentrated HF (49 %), we etch away the PSG and thermal oxide (located only underneath the diaphragm, not the channels) in 20 minutes. Since HF etches silicon nitride inside the etching channel, the gap height is the PSG thickness plus 200

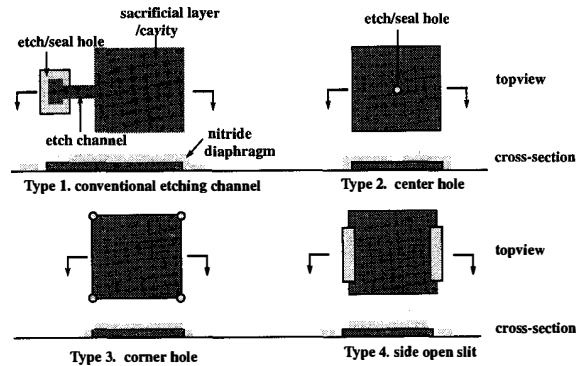


Fig.1 Schematic configurations for four different types of test structures.

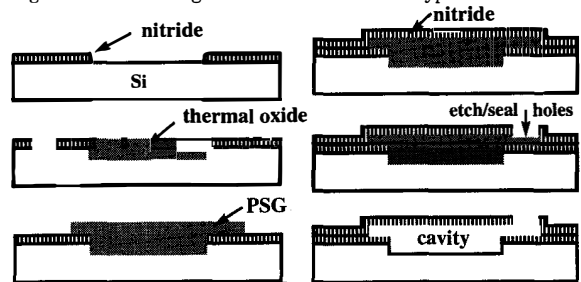


Fig.2 Major fabrication steps for micro-cavity structures.

nm (a measured value) by the end of this HF etching. Wafers are thoroughly rinsed in DI water for 20 minutes and then dried in a spin-dryer. Alley *et. al.* [14] reported a stiction problem using spin dry for their suspended polysilicon beams; however, in our case, the spin dry does not cause serious sticking problem between the diaphragm and cavity bottom (the yield is more than 95 % for all structures). Finally, wafers are baked at 400 $^{\circ}\text{C}$ in nitrogen for 10 minutes to drive out moisture in the cavities and ready for sealing experiments.

III. EXPERIMENTS AND RESULTS

Many sequential depositions with an incremental thickness (30-60 nm) of CVD materials, including LPCVD silicon nitride, LPCVD polysilicon, LPCVD PSG, and PECVD silicon nitride, are performed to seal the cavities (deposition parameters listed in Table 1). Since the diaphragm over a sealed cavity will be deformed by the differential pressure between the atmosphere and the cavity interior, interference patterns (Newton ring) can be observed on the diaphragm. The presence of Newton Ring is thus used as an indication of complete sealing. Optical microscope pictures of sealed and unsealed structures are shown in Fig. 3. After each sealing deposition, we count the quantities of successfully sealed cavities and statistically evaluate the degree

Material	flow ratio	pressure(mTorr)	temp.($^{\circ}\text{C}$)/power(W)
LPCVD nitride	$\text{NH}_3/\text{DCS}-3/1$	330	820/N.A.
LPCVD Polysilicon	Silane(SiH_4)	220	620/N.A.
LPCVD PSG	$\text{O}_2/\text{SiH}_4/\text{PH}_3-6:1:2$	150	450/N.A.
PECVD nitride	$\text{NH}_3/\text{SiH}_4-7:3$	400	300/50

Table1 CVD processing parameters for various sealing materials.

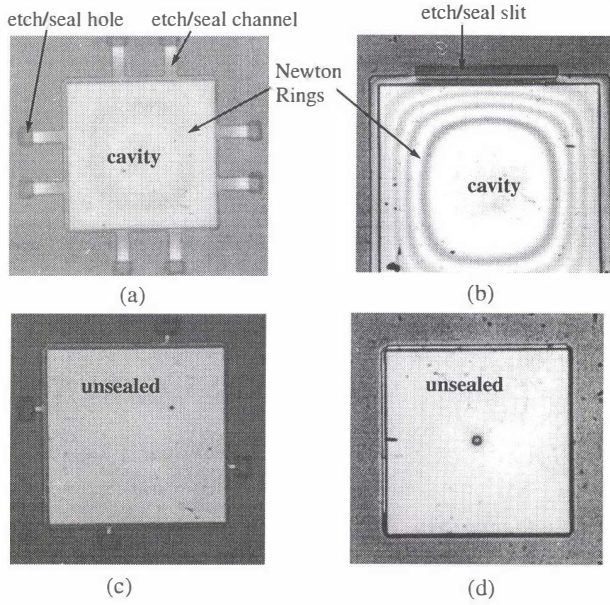


Fig. 3 Optical photographs of some test structures: (a) sealed type-1 structure, (b) sealed type-4 structure, (c) un-sealed type-1 structure, (d) un-sealed type-2 structure. Newton rings are clearly seen on sealed structures in (a) and (b), but not in (c) and (d) which not sealed.

of sealing completeness. These data points are then compared between sealing materials, deposition thickness, cavity geometry and channel heights. To quantify the sealing results of a specific structure at a cumulative deposition thickness, we define the sealing factor, SF, as the ratio between the number of sealed cavities and the total number of the cavities of its kind (48, in our case); an SF of 1 means that all 48 cavities are sealed. We also define an unitless thickness t_n as the cumulative deposition thickness normalized by the gap height. The $t_{n,min}$ then is the minimum t_n that is required to seal a cavity with SF larger than 0.95. Because we can only deposit sealing materials with a finite thickness increment (30–60 nm), there is an inherent error associated with $t_{n,min}$.

Our experiment results show that type 1 structures have been successfully sealed by all the deposition materials at certain t_n 's, whereas some structures of types 2, 3 and 4 can not be sealed by certain materials within reasonable deposition thickness range. As type-1 structures provide a larger and more complete data base compared with other types they are thus the emphasis of our sealing data analysis.

Material Effects — Deposited materials greatly influence the sealing results. The material effects are studied by concentrating on data analysis of type-1 structures. For example, Fig. 4abc show the SF vs. deposition thickness for three different LPCVD materials. Each figure provides information for 12 type-1 cavities, all having 8 channels with the same 420 nm gap height but different lengths and widths. One can clearly see that for each LPCVD material, there is a t_n value (0.338 for nitride, 0.173 for polysilicon, and 1.86 for PSG) that any smaller t_n will not seal the structures at all. On the other hand, there is another value (0.67 for nitride, 0.62 for polysilicon, and 4.52 for PSG) that any larger t_n will seal the structures completely. Any t_n between these two values will have partial seal of the structures.

Due to size variations, SF data points scatter; therefore we compare sealing data obtained from a fixed structure to study material effects. In our case, all data points are obtained for a

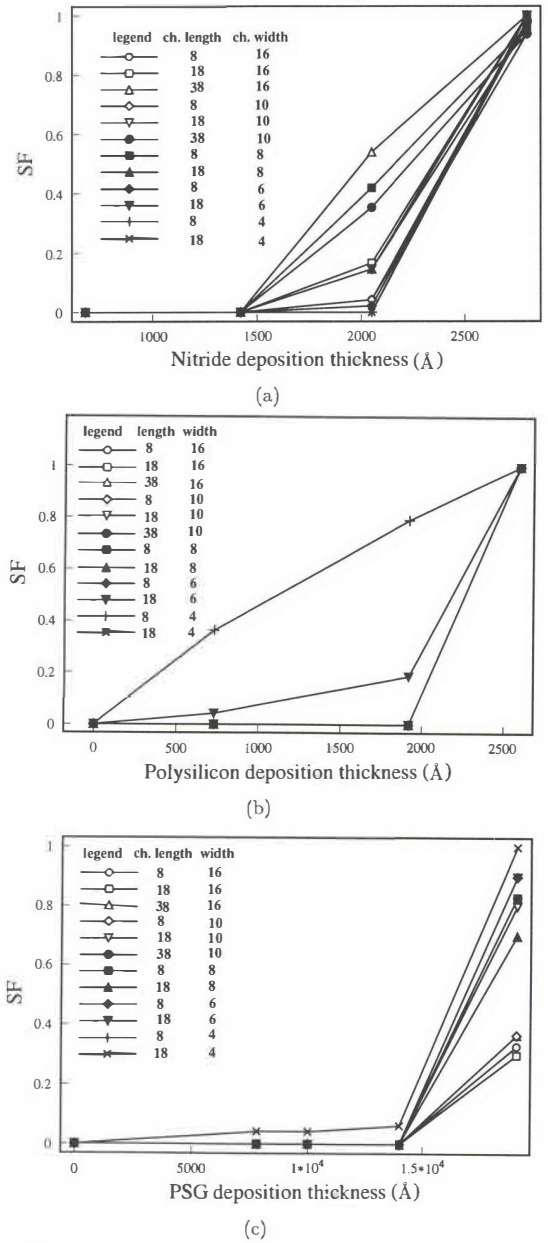


Fig. 4 SF as a function of deposition thickness of three LPCVD materials for twelve type-1 structures. The channel height for the samples are all 420 nm. The lengths are 8, 18 and 38 μm and the widths are 16, 10, 8, 6 and 4 μm .

structure with 8 channels, each 18 μm long and 4 μm wide. Fig. 5 is partly extracted from Fig. 4 and, with the addition of PECVD sealing data points, shows comparison of sealing results using four different CVD materials. It is found that $t_{n,min}$ is about 5.2 for PECVD nitride, 4.5 for LPCVD PSG, 0.67 for LPCVD nitride and 0.62 for LPCVD polysilicon. Clearly, LPCVD polysilicon and nitride require the thinnest deposition to seal the structure, thus are the most effective materials. On the other hand, although thicker deposition is required, PECVD methods have the advantage of sealing at a much lower temperature about 300 $^{\circ}\text{C}$.

Gap Height Effects — For each sealing material, it is important to find out whether $t_{n,min}$ obtained at one gap height can be applied to various other heights. Extra wafers with different gap heights (520 nm, 743 nm, and 1.01 μm) are prepared, and sealing tests are performed on those wafers by incremental LPCVD

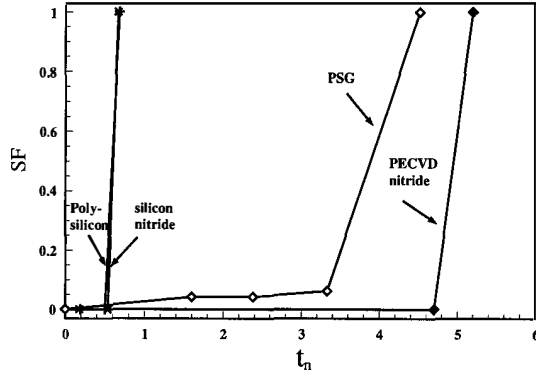


Fig. 5 SF vs. t_n plots for different materials, including LPCVD nitride, LPCVD polysilicon, LPCVD PSG, and PECVD nitride. Structures under study are type-1 with eight etching channels, each $18 \mu\text{m}$ long and $4 \mu\text{m}$ wide. Etching channel height is 420 nm . Clearly, $t_{n,min}$ required for successful sealing depends on the sealing materials, 0.67 for LPCVD nitride, 0.62 for LPCVD polysilicon, 4.5 for LPCVD PSG and 5.2 for PECVD nitride.

silicon-nitride deposition. Fig. 6 shows the results of $t_{n,min}$ vs. gap heights; $t_{n,min}$'s are 0.57 ± 0.08 , 0.347 ± 0.03 , 0.449 ± 0.04 and 0.44 ± 0.03 for the four gap heights studied. Taken into account of experimental errors, the trend shows that $t_{n,min}$ converges to a constant value of approximately 0.44 for larger gap. Since the incremental deposition thickness is finite, the error in $t_{n,min}$ is thus large for small gap height and small for large gap heights.

Currently, gap height effects for other materials are not available for various reasons. For example, in the case of LPCVD PSG, thick PSG tends to fracture when the film is over $4 \mu\text{m}$

In another case, LPCVD polysilicon becomes opaque when its thickness exceeds 300 nm and making identification of sealed structures by Newton rings impossible.

Geometric Effects — For type-1 structures, it is also found through our experiments that geometry could affect the sealing significantly. In fact, different materials have totally different effects. To study geometric effects, we compared sealing data of various sized type-1 structures at a fixed material deposition thickness. Fig. 7abc plots SF vs. channel length with widths ranging from 4 – $16 \mu\text{m}$ using three LPCVD material thicknesses. For LPCVD silicon nitride ($t_n = 0.49$), Fig. 7a shows the trend that longer and wider channels can be sealed with higher seal-

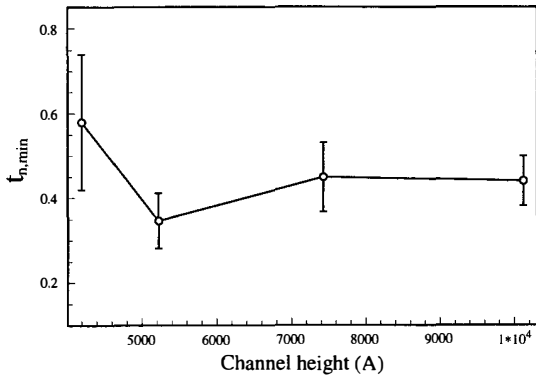
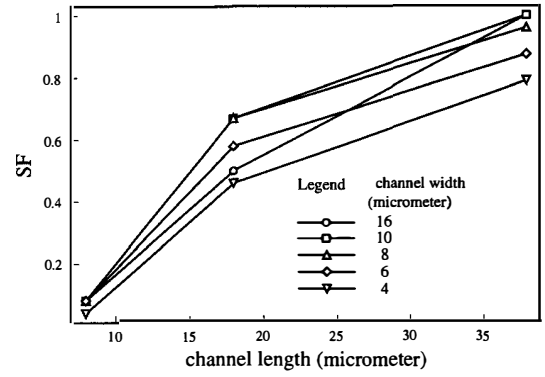
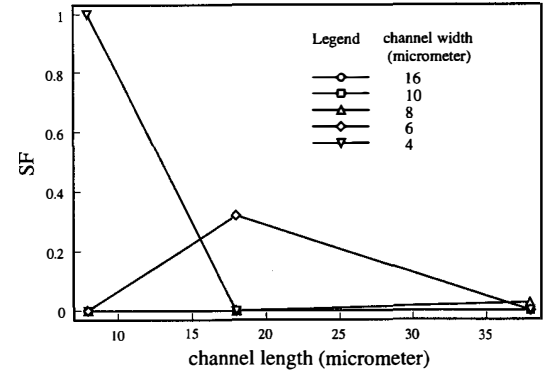


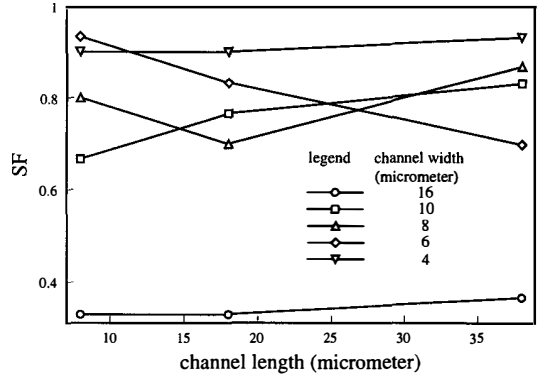
Fig. 6 Values of $t_{n,min}$ at various channel heights (420 nm , 520 nm , 743 nm , and $1.01 \mu\text{m}$) using LPCVD nitride sealing. The test structure is the same one that is used in Fig. 5: a type-1 cavity with eight channels, each $18 \mu\text{m}$ long and $4 \mu\text{m}$ wide.



(a)



(b)



(c)

Fig. 7 SF as functions of channel lengths and widths for LPCVD silicon nitride, polysilicon and PSG sealing.

material	length	width	SF
LPCVD Nitride	↑	↑	↑
LPCVD Polysilicon	↓	↓	↑
LPCVD PSG	—	↓	↑

Table 2 For type-1 structures, trends of geometric effects on SF within the range of our current design.

ing percentage. For LPCVD polysilicon ($t_n = 0.45$), however, it seems that (as shown in Fig. 7b) shorter and narrower channels have a higher SF although this trend is not as conclusive as in the silicon nitride case because of limited data points. As for LPCVD PSG ($t_n = 4.5$), the narrower the channels, the better SF. Channel length has little effect. As a whole, the trends of the geometric effects of sealing type-1 structures are summarized in Table 2.

Sealing of Types 2, 3 and 4 Structures In our work, geometric effects on sealing types 2, 3 and 4 structures were also using

samples of a fixed height. Conceptually, type-2 cavities require much thicker deposition to seal than structures of other types because of the large gap height, which is 1.3 μm thick thermal oxide plus PSG thickness. This has been confirmed using nitride and polysilicon. Type-3 structures show excellent sealing quality using all three LPCVD sealing materials. Compared with type-1 structures, type-3 structures have identical gap heights and thus comparable sealing performance; SF's for all type-3 structures exceed 0.95 at t_n 's of 0.67 (for silicon nitride), 0.62 (for polysilicon) and 4.5 (for PSG). As for type-4 structures, only cavities with one side opened survive the fabrication process for sealing analysis; cavities with more side openings tend to stick to the bottom. For a type-4 structure with one side opening 120 μm long (60 % of the cavity side length), SF's of greater than 0.95 are achieved at a t_n of 0.67 for nitride and a t_n of 0.62 for polysilicon deposition. The general trends of sealing types 2,3 and 4 structures are summarized in Table 3.

	TYPE 2	TYPE 3	TYPE 4
LPCVD nitride	poor	good	good
LPCVD polysilicon	poor	good	good
LPCVD PSG	na	good	na

Table 3 For type 2, 3 and 4 structures, general sealing performance by the three LPCVD materials. na indicates that conclusive experimental results are not available.

Sealing Profile — Sealing qualities of cavities should be related to the step coverage of the CVD materials. Various studies on step coverage, both experimentally [16,17] and theoretically [18], have been done in the past. It has been concluded that step coverage depends on three major mechanisms: direct transport, re-emission, and surface diffusion [17].

Conceptually, knowledge on the step coverage of various materials in a etching hole or etching channel [16–18] should help to understand the material and geometric effects of sealing. In order to study the sealing mechanisms, a scanning electron microscope is used to view the cross-section at cleaved sealing holes. Initial results, for example the coverage profiles of a PSG-sealed type-1 structure at a test structure and a etching hole, is shown in Fig. 8. Cavities are sealed by PSG when the two deposition fronts meet at the entrance of the etching channel. Pictures confirm that deposition inside the cavity is very little compared with the deposition on the front of the wafer; it agrees with the conclusion of Cheng *et al.* [17] that surface diffusion is not a strong factor in LPCVD PSG step coverage. Currently, study on sealing profiles of nitride-sealed and polysilicon-sealed samples is underway.

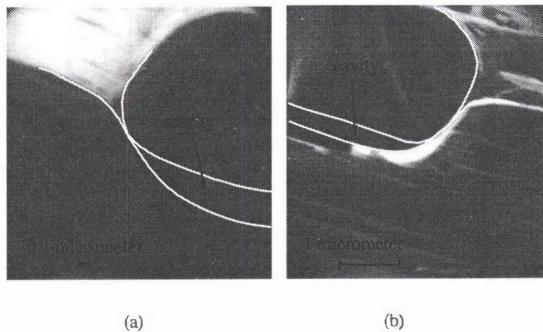


Fig. 8 SEM photographs of the sealing profile after approximately 1.9 μm of PSG deposition. (a) A specially designed overhanging test structure; (b) a etch/seal hole of a type 1 structure. The gap height is 4200 $\text{\AA}$. White lines indicate the contour of deposited PSG.

IV. CONCLUSIONS

We have fabricated test structures and studied the sealing of four types of surface-micromachined cavities using LPCVD nitride, polysilicon, PSG, and PECVD nitride. Among all tested materials, LPCVD nitride and polysilicon provide the most effective sealing. LPCVD PSG and PECVD nitride requires higher $t_{n,min}$ to seal but offers the advantage of low temperature processing. Using LPCVD nitride as the sealing material, $t_{n,min}$ almost remains constant (0.44) for different gap heights. Qualitative geometric effects have also been studied for type-1 structures; the results point out geometric trends for designing cavity structures that are easy to seal. Sealing results for types 2,3 and 4 structures are briefly discussed; cavity structures and materials that could produce good sealing results are identified.

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