Strain studies in LPCVD polysilicon for surface micromachined devices

Janak Singh, Sudhir Chandra, Ami Chand

Centre for Applied Research in Electronics, Indian Institute of Technology, Hauz Khas, New Delhi 110016, India

Received 18 August 1997; accepted 14 April 1998

Abstract

Polycrystalline silicon (polysilicon) has emerged as a preferred material for surface micromachined MEMS applications because of its compatibility with standard CMOS process. The important parameters of polysilicon films for sensor–actuator devices are the residual stress and stress gradient. For free standing microstructures, it is important to reduce the stress in the film. In order to exploit the advantage of polysilicon for MEMS applications, it is essential to develop a process to obtain low-stress polysilicon films. In the present work, we have investigated the effect of deposition parameters on 2–4 μm thick LPCVD polysilicon films using a specially designed spiral structure for strain measurements. The films were deposited in the temperature range of 580–630°C at pressures 180 to 320 mTorr. The role of post-deposition annealing at 1000°C in N2 ambient on strain reduction has been investigated using conventional furnace annealing and rapid thermal annealing (RTA). The as-deposited films show significant strain under all the deposition conditions investigated. The strain is reduced to insignificant values after 100 min of furnace annealing. In case of RTA, similar strain values are achieved in only 30 s of annealing. The overwhelming superiority of RTA over furnace annealing in terms of the thermal budget of the process has been clearly demonstrated. The effect of polysilicon doping with boron or phosphorus has also been studied for applications in electrically conducting microstructures. The final strain values after annealing are about 1 × 10^-4, which is the limit of resolution of the strain measurement scheme used in the present investigations.

Keywords: Polysilicon; Residual strain; Surface micromachining; Furnace annealing; RTA; Spiral structure

1. Introduction

Polycrystalline silicon is being extensively used as a structural material in surface micromachining technology for a variety of applications such as pressure transducers [1,2], micro-switches [3], etc. The mechanical microstructures such as cantilevers [4], bridges [4], suspended structures [5], rotors [6], etc. are the basic sensing/actuating elements for MEMS. These elements can easily be fabricated using polysilicon as a structural material and silicon dioxide as the sacrificial/spacer layer. The performance and control of the dimensions of these elements are critically dependent on the residual stress, and stress gradient in the structural layer. Low pressure chemical vapour deposition (LPCVD) of polysilicon is a standard technique for microelectronics processes. It has found wide acceptability and is being extensively used for surface micromachining applications also. Residual stress and stress gradient are inherent in as-deposited polysilicon films. The deposition and subsequent annealing parameters need to be tailored to achieve films with minimum residual stress and stress gradient, keeping in mind the compatibility of the process with standard CMOS technology.

The application of polysilicon as an active material in surface micromachining technology has intensified efforts for developing a suitable process for depositing stress-free films [7–11]. LPCVD polysilicon is obtained by pyrolytic decomposition of silane (SiH4) at low pressure in the temperature range of 570–650°C [10–13]. It is well known that the deposition parameters such as temperature, pressure, and flow rate have a profound effect on the structure and properties of the polysilicon film [10,11,14–16]. In particular, films deposited below 580°C are amorphous whereas those deposited above 600°C are crystalline in nature [14,15]. The films deposited at 600°C are reported to be of pseudomorphic (mixed amorphous-polycrystalline) structure [10,11]. Kamins [14] has also observed a similar transition at 600°C and has suggested that the deposition at this temperature should be avoided in order to obtain reproducible structure. On the other hand, it has been reported that films grown at 695°C are nearly stress-free, and a window of 600–610°C is suggested for deposit-
ting polysilicon for MEMS applications [17]. The low stress is attributed to recrystallization from an amorphous phase in a reproducible manner during annealing. The effect of post-deposition annealing on the stress and stress gradient has also been investigated by several other workers [18, 19].

This paper presents a comprehensive study for obtaining stress-free polysilicon films. The effect of deposition parameters such as pressure and temperature on the mechanical properties of the films is investigated. LPCVD polysilicon films were deposited at 580, 605, and 630°C to distinctly obtain amorphous, mixed, and polycrystalline structures, respectively. The influence of annealing on the average residual strain and strain gradient has been extensively examined with the view to develop an optimized polysilicon deposition process for MEMS applications.

The post-deposition annealing step has been carried out using both rapid and conventional thermal processing. It has been shown that the post-deposition rapid thermal annealing is an attractive technique for obtaining stress-free films. Doped polysilicon has a further advantage as structural material since it can be used for applying electrical fields as well in MEMS applications. With this in view, phosphorus and boron diffusion in polysilicon films have been carried out and the strain behaviour is studied. The effect of the film thickness on the strain is also analyzed. The residual strain and stress gradient have been measured using spiral and cantilever beams, respectively. The other three dimensional structures such as double supported beams and ring-beam structures have also been fabricated as these are frequently used in sensors and actuators.

2. Fabrication process

Single crystal silicon wafers of (100) orientation and 2" diameter were used as the substrates for polysilicon microstructures in surface micromachining technology. Thermally grown silicon dioxide was used as the sacrificial/spacer layer. About 5 μm thick silicon dioxide was grown at 1150°C by wet oxidation process. The thickness of the silicon dioxide was specifically kept large, keeping in mind the application of polysilicon in cantilever beam electrostatic actuators. The spacing of 5 μm between the polysilicon cantilever and the substrate would provide sufficient space for its movement. Furthermore, cantilever beams were also used for strain gradient measurements in the present investigation. A larger spacing from the substrate extends the measurement of beam bending over a wider range, if curvature is downwards. Though it takes nearly 40 h to thermally grow 5 μm oxide, the process is still cost effective as up to 60 wafers could be oxidized in one batch. The oxidation was continued uninterrupted and wafers were cooled slowly after oxidation. A two mask process sequence, schematically shown in Fig. 1, was used for fabricating the structures. Using mask #1, islands were defined in SiO₂ by etching in buffered HF (BHF). Polysilicon was then deposited by LPCVD process in a standard system (Model 4001 gas system-Omega Junior-2 furnace, Tempress, Netherlands). The ID of the process tube was 100 mm. The deposition temperature was separately calibrated by an independent thermocouple placed inside the tube under identical vacuum conditions. The thickness of the polysilicon films were chosen to be in the range of 2–4 μm. The deposition parameters for a 2 μm thick layer are summarized in Table 1. The boxes marked ‘*’ indicate that the polysilicon film was deposited with corresponding parameters whereas ‘×’ indicate that no deposition was carried out. The films of 3 μm and 4 μm thickness were deposited at 605°C and 250 mTorr. The silane flow rate was kept at 50 sccm for all the depositions. The deposition rate at 605°C and 250 mTorr was 68 Å/min. The thickness of the films were measured by Nanospec-AFT Model 210 (Nanometrics, USA) and by α-step (Tencor, USA).

The polysilicon microstructures were patterned using mask #2 as shown in Fig. 1C. Polysilicon was etched using SF₆ in reactive ion etching (RIE) system (Neubert NE-110, France). Special care was taken during photolithography to ensure good step coverage of the photore sist over the slopes in the polysilicon covered oxide islands. The thermal annealing process was carried out at this stage. Both furnace annealing and rapid thermal an-
Table 1
Polysilicon deposition parameters

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Deposition temperature (°C)</th>
<th>Deposition pressure (mTorr)</th>
<th>180</th>
<th>250</th>
<th>320</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>560</td>
<td>×</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>630</td>
<td>×</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>630</td>
<td>×</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

annealing were carried out at 1000°C in N₂ ambient. Boron or phosphorus diffusion was carried out on 2 μm thick polysilicon after patterning, though identical results are expected if doping is carried out before patterning. Boron diffusion was performed at 1000°C for 60 min using a planar Boron + source (Electro-oxide) and a sheet resistance of 14 Ω/□ was obtained. Similarly, phosphorus was diffused at 1000°C using POCl₃ and a sheet resistance of 4 Ω/□ was measured.

The structures were then released by etching the sacrificial silicon dioxide layer in buffered HF (Fig. 1D). It was observed that annealing performed after releasing the structures leads to deformation of their shape which could not be recovered subsequently. In all the studies reported in the present work, the polysilicon was patterned and annealing or diffusion was performed before releasing the structures. This also implies that a fresh sample was taken for every data point. The final rinsing of the wafer was carried out in surface tension weakening solution, still it was observed that large sized structures tend to stick on the wafer. The etch however has no adverse effect on the accuracy of the strain measurements [16]. The SEM micrograph of the completely released cantilever and centrally anchored spiral structures are shown in Fig. 2a and b, respectively.

3. Strain measurement

It is well known that stress and strain are related by elastic constants of the material. The measurement of strain (∆L/L₀, where L₀ is the length of the structure) can thus be used to estimate the stress in the material. Residual strain in the films can be measured by (i) observing buckling of double supported structures of varying lengths, (ii) rotation technique, and (iii) by measuring change in length of large sized structures [20–22]. In the first method, arrays of double supported beams and ring-beam structures of a range of lengths are required for measuring compressive and tensile strain, respectively. The accuracy of the measurements depends on the step size between successive structures. Thus a large number of structures are required to be fabricated for fairly accurate measurements. Furthermore, it is difficult to identify the first buckled structure using SEM and optical microscopes because of very small deflection. The measurement of tensile strain using ring-beam structure is further difficult because of uncertain boundary conditions [22]. In the rotation technique, only a single hinge type structure having two support arms and a rotating arm is required for the measurement of both compressive and tensile strain [22]. This structure converts displacement (due to change in length of the support arms) into rotation and is used to calculate the strain in the film. However, the shape and the width of the turning point are very critical for obtaining appreciable deflection at the tip of the rotating arm. Further, the boundary conditions at the turning points are very complicated. For obtaining accurate strain values, a simulated correction factor is needed to account for the finite width of the turning points [22]. These limitations may be overcome using spiral structures of large lengths. An appreciable change in length is obtained even for a small stress level due to larger length of the spiral. The added advantage is that both compressive as well as tensile strain can be measured with the same accuracy and a few structures are required. The design scheme of a spiral is shown in Fig. 3. The semicircles of increasing diameters have been joined end to end to complete the structure. The total length of the spiral can be calculated as described below.

Fig. 2. (a) SEM micrograph of completely released cantilevers. (b) SEM micrograph of a completely released spiral microstructure.
Cantilever beam is a very useful structure to measure strain gradient in the thin films. Bending of the free end takes place due to stress gradient in the beam. If $\delta t$ is the deflection of the beam tip then strain gradient ($\delta \varepsilon / \delta y$) in the film is given by:

$$\frac{\delta \varepsilon}{\delta y} = \frac{\delta t}{L^2}$$

where $L$ is the length of the cantilever beam and $y$ is the direction along the beam thickness.

4. Results and discussions

The measured strain values as a function of annealing time at 1000°C in N$_2$ ambient for films prepared under different deposition parameters are shown in Figs. 4–7. It is clear from these curves that all the as-deposited films have a large compressive strain as indicated by negative values of strain ($\Delta L_s/L_s$). The effect of deposition pressure (180 mTorr and 250 mTorr) at 605°C deposition temperature for 2 µm thick film is depicted in Fig. 4. Significant reduction in strain is observed in the first 10 min of annealing. The strain is also seen to change from compressive to tensile and again to compressive as annealing progresses. However, the values of the strain changes only gradually after the first 10 min of annealing. After about 80 min of annealing, the strain reduces to negligible values. The behaviour is similar for films deposited at 180 mTorr and 250 mTorr pressures. Earlier Guckel et al. [18] have also reported the transition of strain from compressive to tensile and back to minimum value after annealing. The overall stress in the film, deposited in mixed amorphous-polycrystalline phase, depends on the ratio of the amorphous and polycrystalline layers [16]. The tensile strain in the film is probably associated with the volume contraction on transition from amorphous phase to poly-

![Fig. 3. The design scheme of spiral microstructures.](image)

![Fig. 4. Residual strain as a function of furnace annealing time for 2 µm thick poly-silicon films deposited at 605°C temperature; pressures: ● 250 mTorr, □ 180 mTorr.](image)
crystalline phase [16]. The film deposited at 320 mTorr were fragile in nature as only broken spirals could be obtained. The effect of deposition temperature (605 and 580°C) at 250 mTorr pressure is shown in Fig. 5. Here also the strain undergoes changes from compressive to tensile before stabilizing to negligible values after about 80 min of annealing. Poor quality polysilicon films were obtained at 630°C. This can be attributed to the higher deposition rate of the polysilicon film in <220> preferred texture [8,11].

The strain as a function of annealing time for film thicknesses of 2, 3, and 4 μm is shown in Fig. 6. The films were deposited at 605°C and 250 mTorr pressure. As expected, thicker as-deposited films show smaller strain because of higher flexural rigidity and strength. The low temperature annealing at 605°C during deposition time of thicker films may also be contributing in reducing the strain [11]. However, annealing reduces the strain to negligible values irrespective of film thickness. It can be extrapolated that as-deposited films having 5 μm or larger thickness may show negligible strain.

The effect of RTA on 2 μm thick films deposited at 580°C and 605°C (250 mTorr) is shown in Fig. 7. It is interesting to note that strain reduces to negligible values in just about 20 s of RTA. This is very important from thermal budget considerations especially if the process is to be made compatible with CMOS process. For boron or phosphorus diffused samples, the strain was found to be negligible without any additional annealing. However, it may be mentioned that diffusion process carried out at 1000°C for 60 min itself contributes to annealing and grain growth [20].

A downward bending of cantilever beams in as-deposited polysilicon samples as shown in Fig. 2a, indicates a negative strain gradient. In all the as-deposited samples, average value of strain gradient varies from 1.0 E-4 to 4.0 E-4 μm⁻¹. It reduces to negligible values in lowest time of furnace annealing and RTA i.e., 10 min, and 5 s, respectively.

The annealing is understood to cause structural changes in polysilicon. For example, the grain size, grain boundaries, and crystal structures undergo changes during annealing. The films grown at 580°C are expected to be predominantly amorphous whereas the films deposited at 605°C are of mixed (amorphous-poly-crystalline) structures [10,11,16]. However, both of these show considerable strain in as-deposited form as shown in Fig. 5. Annealing at 1000°C for 100 min in N₂ ambient reduces the strain to negligible values for the entire range of deposition parameters investigated. The fluctuations of strain between compressive and tensile during annealing process are believed to be due to structural changes occurring in films of amorphous and mixed structures [16,23]. The dominant role of the thickness is clearly evident on the strain in as-deposited films. If high temperature annealing is undesired due to some processing constraints, thicker films have a distinct advantage.

The boron or phosphorus doped films show very small residual strain. We believe that annealing occurring during diffusion cycle is responsible for this rather than incorpora-
tion of boron–phosphorus in the film. Doped polysilicon is attractive from the application point of view where electric fields may be required for microstructure actuation. The superiority of the RTA over furnace annealing has been clearly established in this investigation. RTA is particularly attractive when the micromachining process is carried out after the fabrication of electronic circuitry on the same chip for smart sensor systems because high temperature furnace annealing may change characteristics of the circuitry.

5. Conclusions

The studies reported in this paper clearly demonstrate that as-deposited polysilicon films up to 3 μm deposited in either amorphous or amorphous–polycrystalline form (deposition temperature 580, 605°C, respectively) are not suitable for MEMS applications because of inherent residual strain and strain gradient. However, strain in the films can be minimized to negligible values using high temperature furnace annealing or RTA processes. The superiority of RTA over furnace annealing has been clearly demonstrated. It is further concluded that film grown at 320 mTorr, 605°C; and also at 250 mTorr, 630°C are unsuitable for MEMS applications. As-deposited thicker films (≥ 4 μm) have been shown to be useful for micromachining processes where high temperature annealing is undesirable. Doped polysilicon films have been obtained with negligible stresses. Their application in devices requiring electrostatic actuation is of special interest. Strain gradient is observed in as-deposited films which reduces to negligible values in minimum time of annealing.

Acknowledgements

One of the authors, Janak Singh, acknowledges the financial assistance given to him by Council for Scientific and Industrial Research (CSIR) to carry out research work. The help provided by the laboratory staff and specifically by Mr. Govind Ram to carry out various processes is also acknowledged.

References