Influence of RTA Parameters
on Residual Stress and Stress Gradient
of Multilayered LPCVD Polysilicon Film

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This paper reports the experimental results of examining the residual stress and stress gradient of low-pressure chemical vapor deposition (LPCVD) multilayered polysilicon film according under various rapid thermal annealing (RTA) conditions in a nitrogen atmosphere. In particular, the stress gradient of multilayered polysilicon film, which ranges from –17.1 to +1.5 MPa/μm as the RTA processing time increases, could be reduced to nearly zero by selecting the appropriate RTA time. The mechanism responsible for this dependence was examined using both experimental data and material analysis using secondary ion mass spectroscopy (SIMS) and transmission electron microscopy (TEM). It is concluded that the shift of the stress gradient is mainly caused by thin nitrided layers at the surface and interface of multilayered polysilicon film.

1. Introduction

The reduction and control of residual stress and the stress gradient in polysilicon film are quite important in fabricating flat and reliable surface-micromachined structures. The main source of stress is the intrinsic stress originating from grain growth, nucleation and the incorporation of impurities during film deposition.

Choi *et al.* reported that polysilicon film with a higher phosphorous concentration has a higher stress.[1] They suggested that it is important to fabricate a symmetrical structure in terms of the layer thickness to obtain a low stress gradient. They fabricated a 6.5-μm-thick polysilicon structure using symmetrical stacking of 0.8-μm-thick layers. The film had a low stress of –7.6 MPa and a low stress gradient of –0.15 MPa/μm.

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It is widely known that oxidation of polysilicon film induces a compressive stress. Lee *et al.* found that the thin oxidized layer formed at the interface of multistacked polysilicon films plays an important role in governing the stress gradient.[2] This interface effect could be minimized by the symmetrical stacking of polysilicon films, which resulted in a low stress gradient of -0.15 MPa/μm for a 5.3-μm-thick polysilicon layer.

Fürtsch *et al.* confirmed that the diffusion of oxygen atoms causes stress changes.[3] The stress and stress gradient can be changed by subsequent annealing in an oxygen and nitrogen ambient.

All the above researchers used a conventional annealing furnace to reduce the stress and the stress gradient. We used RTA for this purpose and succeeded in reducing the stress and the stress gradient. To study the mechanism for reducing the stress gradient, we carried out several analyses.

2.   Materials and Methods

In this work, we used a standard surface micromachining process to fabricate the test structures for the observation of the stress and stress gradient of multilayered polysilicon films. A schematic cross section of the test structure is shown in Fig. 1. A 2.0-μm-thick sacrificial oxide film was deposited on 5-inch p-doped (100) Si wafers. To fabricate a polysilicon film up to 4.0 μm thickness as the structural layer, the *in situ* p-doped polysilicon film was deposited 1 to 4 times at 580°C. The thickness of each layer was typically chosen to be 1.0, 1.0, 1.0 and 0.5 μm from the bottom to the top, making the film structure asymmetrical. After patterning the polysilicon film, RTA was carried out in a nitrogen ambient at 1100°C for less than 5 min. The polysilicon test structures were finally released. We used a rotating beam pair structure and a cantilever beam array shown in Fig. 2 to measure the film stress and the stress gradient, respectively.[4]
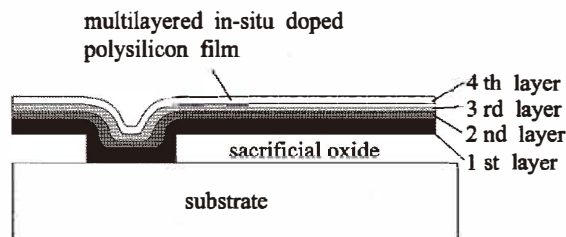

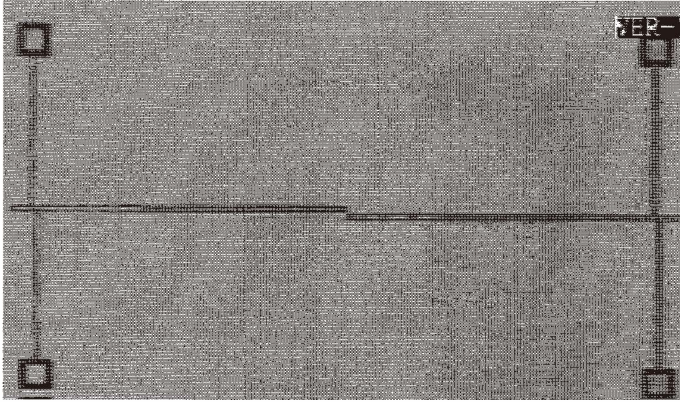Fig. 1.   Schematic view of a cross section of the test structure.

Fig. 2.   A rotating beam pair structure.

3.   Results

The results of the stress and stress gradient measurements are shown in Figs. 3 and 4, respectively. As shown in Table 1, the processing conditions for the polysilicon samples regarding the data shown in Figs. 3 and 4 varied in the number of layers and the stacking structure.

While all the samples as deposited had large tensile stress, 170–230 MPa (described as a positive value), their stress became compressive after RTA. The stress value varied slightly with samples but showed no dependence on the RTA time. These results mean that just 10 s of RTA is effective in reducing the residual stress.

On the other hand, as shown in Fig. 4, the stress gradient shifts from –17.1 to +1.5 MPa/ μm with increasing RTA time, and this shift is remarkably independent of the number of layers and even the film stacking structure.

Our interest is in fabricating a polysilicon structure that is reliable throughout a device's entire life. The stress and stress gradient shown in Figs. 3 and 4 are sufficiently low for this purpose. We confirmed this by finite element analysis. Figure 5 shows the stress distribution and deformation of a simplified accelerometer model with an acceleration of 5000 G. In this case, the stress and stress gradient of polysilicon film are –40 MPa and –2.0 MPa/μm, respectively. The difference in the spring constant between this result and the case where the polysilicon film had no stress and stress gradient was less than 0.05%.

4.   Discussions

Reducing the stress gradient, however, is still important in making a large, flat polysilicon structure. Therefore, we focused on examining the cause of the stress gradient. First, we investigated the grain profile by cross-sectional TEM. Figure 6 shows the cross-sectional TEM images of sample A listed in Table 1 for (a) 10 s of RTA and (b) 4 min of
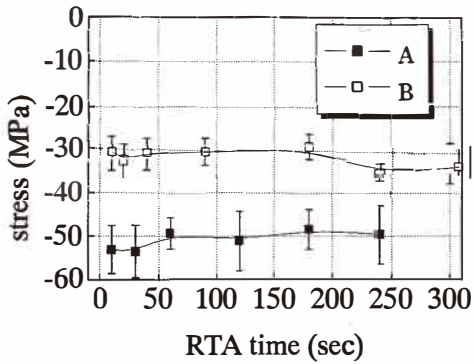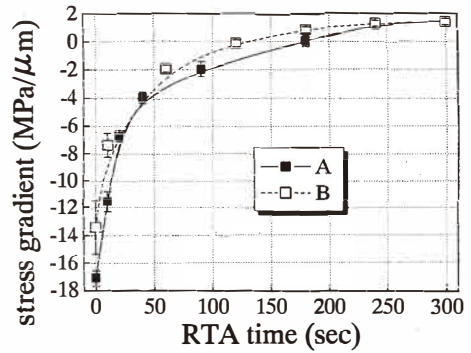
Fig. 3.   Influence of RTA time on stress.

Fig. 4.   Influence of RTA time on stress gradient.

Table 1
Fabrication conditions of polysilicon samples.

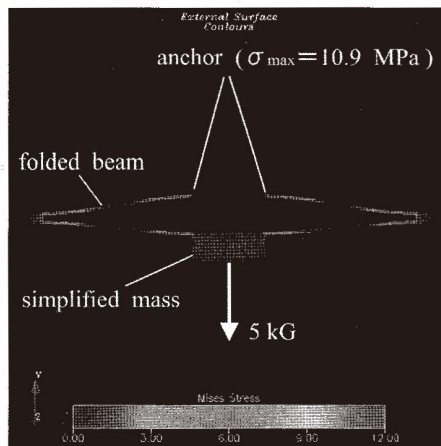| Sample	Number of poly-Si layers	Thickness of each stacked poly-Si layer
A	1 layer	3.5 μm
B	4 layers	1.0 μm, 1.0 μm, 1.0 μm, 0.5 μm

Fig. 5.   Stress distribution and deformation of test structure of a film with a -40 MPa stress and a −2 MPa/μm stress gradient.

(a)   (b)
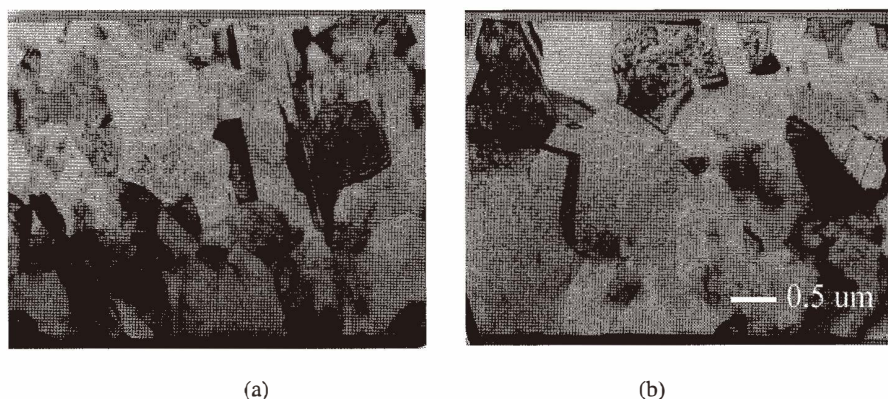
Fig. 6.   Cross-sectional TEM images of poly-Si sample A listed in Table 1: (a) 10 s RTA and (b) 4 min RTA.

RTA. From these TEM images, we obtained the grain size distributions. Although grain growth is observed as RTA time increases, a distribution in the thickness direction correlating to the stress gradient is not observed. From the results in Figs. 3, 4 and 6, it is concluded that grain growth due to the increasing RTA time up to 5 min has no correlation with the stress gradient.

Therefore, we assumed that the stress gradient is correlated in some way with the profile of the impurities contained in the polysilicon film. To explain the stress gradient behavior, we developed a model consistent with the results in which the stress gradient shifts from negative to positive with increasing RTA time. We focused on the well-known phenomena that oxidized silicon film induces a compressive stress and that nitrided silicon film has a tensile stress. The model shown in Fig. 7 illustrates the schematic stress distribution in the thickness direction of a multilayered polysilicon film. We assumed that the total stress gradient of the multilayered polysilicon film is governed mainly by the stress of the polysilicon layer, the oxidized layer and the nitrided layer. The total bending moment is equal to the residual stress multiplied by the distance between that layer and the midpoint of the film thickness. If this assumption is correct, the total stress gradient shows a correlation with the concentration of oxygen and nitrogen atoms in a polysilicon film and the location of these atoms.

To confirm the appropriateness of this model, we carried out an SIMS on sample B listed in Table 1. The concentration profiles in the thickness direction are shown in Fig. 8, for (a) as-deposited and (b) annealed in the RTA furnace for 4 min. A large amount of oxygen accumulated at each interface of the film. Although other atoms also seem to have peaks at the same interfaces, these are mainly caused by a peculiarity of the analyzer in that the sensitivity is increased in the oxygen-rich region. Phosphorous is uniformly distributed throughout the film in both cases. Therefore, the difference between these results is just the nitrogen concentration at the interface. The nitrogen atoms pile up at the interface due to
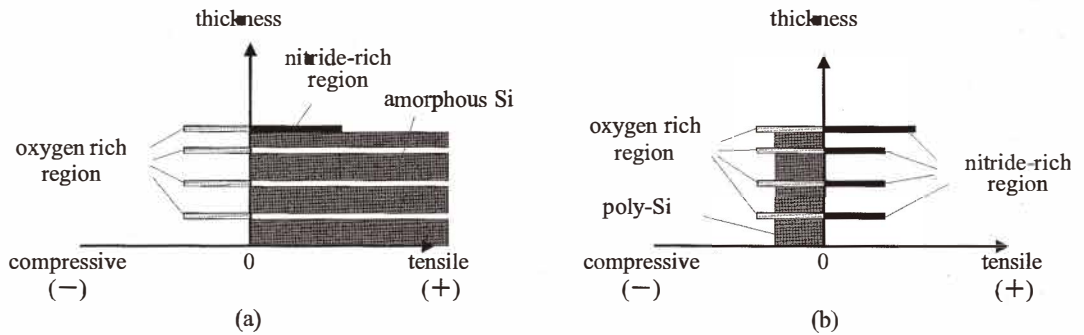
Fig. 7.   Schematic stress distribution of test structure: (a) sample B (4 layers, as deposited); (b) sample B (4 layers, 4 min RTA).
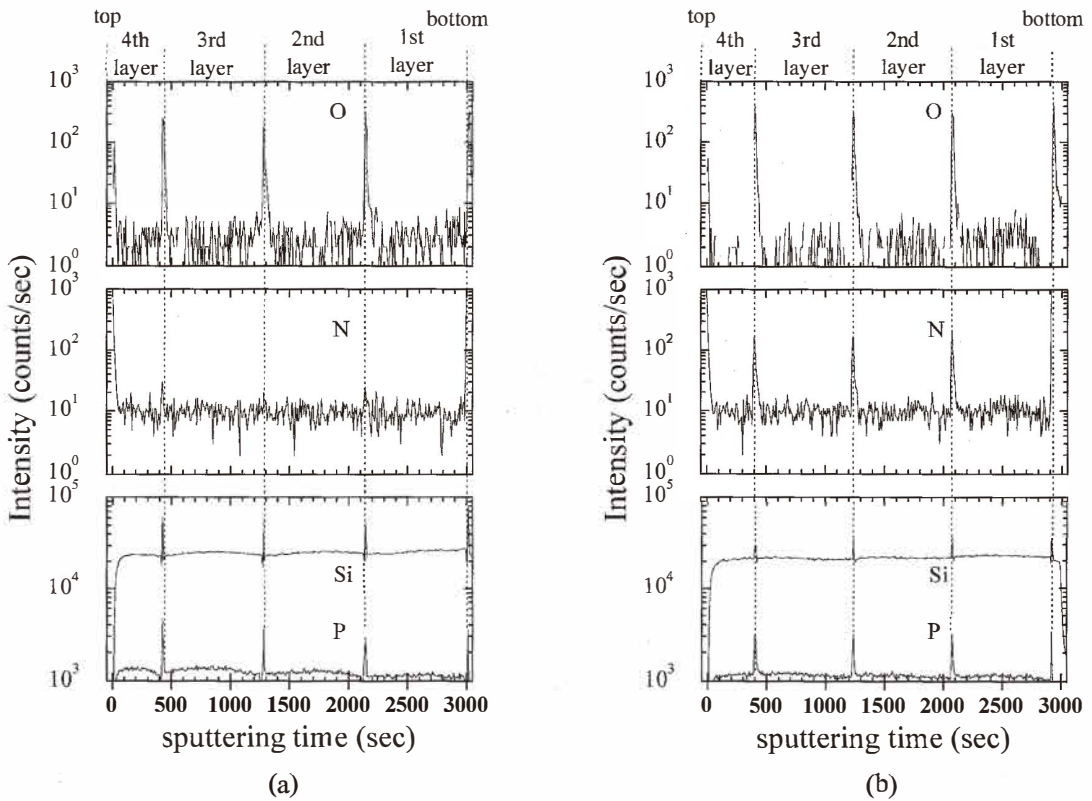

Fig. 8.   SIMS concentration profiles of sample B listed in Table 1: (a) as deposited and (b) annealed at 1100°C by RTA for 4 min.

RTA. Considering the results shown in Figs. 3 and 5 in which no meaningful correlation between stress gradient and grain structure was observed, it is concluded that the shift of the stress gradient from negative to positive is mainly caused by the thin nitride-rich region at the surface and the interface of the multilayered polysilicon film. As is the case of multilayered film, single-layered film has a nitride-rich region at the surface.

5. Conclusions

We have presented a study of the influence of RTA on the residual stress and stress gradient of multilayered LPCVD polysilicon film. In contrast to the fact that grain growth by extending the RTA time has no significant influence on stress, the decisive factor for the shift of the stress gradient is the duration of the RTA. The stress gradient of multilayered polysilicon film, which ranges from -17.1 to $+1.5$ MPa/μm as the RTA time increases, can be reduced to nearly zero by setting the RTA time to approximately 150 s. Our method which uses less than 3 min of RTA to fabricate large polysilicon structures can lower the thermal budget much more than other methods which require annealing in a conventional furnace for several hours. We confirmed that the shift of the stress gradient is mainly caused by the thin nitride-rich region at the surface and the interface of multilayered polysilicon film.

Acknowledgement

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