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POLYCRYSTALLINE AND AMORPHOUS SILICON MICROMECHANICAL BEAMS· ANNEALING AND MECHANICAL PROPERTIES*

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Abstract

The effects of a specific annealing procedure on the maximum free-standing lengths of cantilever and doubly supported micromechanical beams fabricated from polycrystalline and amorphous silicon are investigated In addition, its effect on the built-in deflection of cantilevers is observed By annealing wafers at 1100 °C for 20 minutes in nitrogen prior to beam formation, the maximum free-standing length increases from 50 to 150% for cantilever beams and from 50 to 170% for doubly supported beams, compared with unannealed wafers The built-in deflection of cantilever beams found on unannealed wafers is eliminated by this annealing procedure, except for the thinnest polycrystalline-silicon cantilevers (230 nm thick) In order to investigate how annealing affects these static mechanical properties, two different oxide supporting-layer compositions are used in beam fabrication Also, grain structures in the polycrystalline- and amorphous-silicon films are observed with a scanning electron microscope It appears that the annealing procedure induces recrystallization which allows intrinsic stress in the silicon films to relax

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Introduction

A novel process for making miniature cantilevers and doubly supported micromechanical beams from polycrystalline silicon (poly-Si) has been described recently [1, 2] The fabrication process requires only two masking steps and uses conventional MOS planar technology Figure 1 illustrates the fabrication sequence First, as shown in Fig 1(a), windows are opened in an oxide layer on the silicon wafer [2] Next, poly-Si is deposited by chemical vapor deposition (CVD) and plasma-etched in a second masking step, producing the cross section of Fig 1(b) An unmasked buffered HF etch then removes all oxide, undercutting the poly-Si film and forming the

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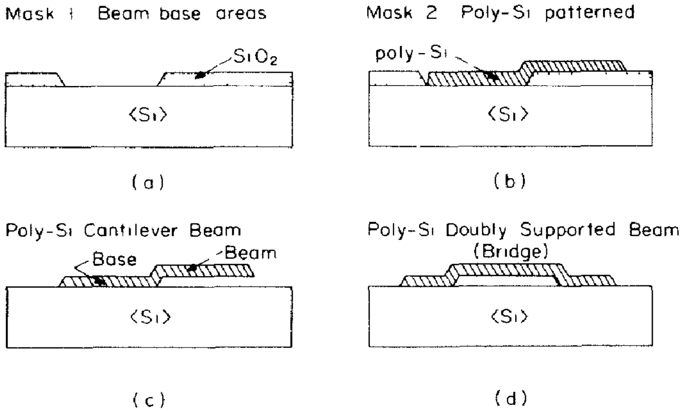


Fig 1 Poly-Si (or a-Si) microbeam fabrication

cantilever beam, as shown in Fig 1(c) Amorphous silicon beams are made by the same technique as poly-Si beams, except that the temperature of the CVD reactor is lowered to suppress grain formation Finally, Fig 1(d) illustrates that a doubly supported beam, or bridge, is made by including a second oxide window in the first mask

The maximum free-standing lengths of poly-Si cantilevers and bridges and the built-in deflection of poly-Si cantilevers have been investigated as functions of beam thickness [2] Both of these static mechanical properties restrict the dimensions of useable poly-Si micromechanical beams In the previous study, it was found that annealing the wafer prior to beam formation improved these properties, for the specific case of a wafer with a 2 0 μm-thick poly-Si layer and a 3 5 μm-thick oxide layer The annealing procedure consisted of heating the wafers to 1100 °C for 20 minutes in a nitrogen atmosphere after patterning the poly-Si in the second masking step [2] The present investigation evaluates the general utility of this annealing procedure by determining its effect on the maximum free-standing lengths of micromechanical cantilevers and bridges made from poly-Si and amorphous silicon (a-Si) In addition, the effect of this annealing step on the built-in deflection of poly-Si and a-Si cantilevers is examined Finally, the means by which annealing affects these static mechanical properties is investigated This paper does not consider the optimization of annealing procedures for improving mechanical properties, but rather focuses on the effectiveness of the above furnace annealing step

Experimental

In order to evaluate the effect of annealing on maximum free-standing length and cantilever deflection, wafers were processed both with and without an annealing step, using masks having cantilevers and bridges with a wide range of lengths The masks included 15 μm-wide cantilevers 25 to

Oxide supporting-layer thickness

Silicon layer thickness	1 1μm	1 7μm	3 5μm
230nm			o
300nm	□		
800nm		o	
1 45μm	△		
1 65μm	□		
2 0μm			o

o poly-Si/PSG
△ poly-Si/thermal SiO_2
□ a-Si/thermal SiO_2

Fig 2 Silicon and oxide thicknesses used to fabricate beams

400 μm in length, and 15 μm-wide bridges which were 100 to 500 μm long Wafers with several combinations of silicon film and oxide supporting-layer thicknesses were processed using these masks Figure 2 lists the silicon and oxide layer thicknesses that were employed in micromechanical beam fabrication The utility of the annealing procedure is assessed by the improvements in static mechanical properties of beams on annealed wafers in comparison to unannealed wafers

Two different oxide compositions were used to fabricate micromechanical beams The first oxide layer consisted of a sandwich of 10% thermal oxide covered with 90% phosphosilicate glass (PSG) (about 8 75% phosphorous content) The PSG was densified at 1100 °C for 20 minutes in a nitrogen atmosphere prior to silicon film deposition This oxide composition etches rapidly in buffered HF, which allows the beams to be quickly undercut The second oxide layer was entirely thermal oxide, grown at 1100 °C in atmospheric steam A tapered oxide window-edge, as illustrated in Fig 1(a), is desirable to avoid an abrupt step in the silicon layer [2] For both oxide compositions, a tapered edge was produced by creating a thin, rapidly etching damaged layer on the oxide surface via a low energy argon implant [3]

These oxide compositions were chosen to determine whether the underlying oxide layer has an influence on the improvement in mechanical properties brought about by annealing the silicon films The annealing step was performed after the poly-Si or a-Si film had been patterned in the second masking step, but before the final unmasked oxide etch The wafers were heated to 1100 °C for 20 minutes in nitrogen This annealing procedure is adequate to reflow the PSG in the first oxide layer [3], as well as to induce recrystallization in the silicon film Since wafers with thermal oxide supporting layers do not experience oxide reflow during annealing, the significance of reflow of the oxide layer to annealing-induced changes in the mechanical properties of silicon films could be ascertained

Poly-Si films were deposited by low pressure CVD at 640 °C Amorphous silicon was deposited in the same reactor at a lower temperature, 570 °C Grain-structure observations on the silicon film were made by viewing the film in cross section in an SEM The wafer was first cleaved and then etched in 5 1, H_2O Wright etch [4] for 40 seconds in order to delineate the grain boundaries This dilution and etch were found to reveal satisfactorily the grain structure of the film Three samples were observed in cross section, including two poly-Si films (800 nm and 1 45 μm in thickness) and the 1 65 μm-thick a-Si film These samples were sufficiently thick to yield clear pictures of the grain structure of the films No grains were resolved in the unannealed a-Si films at 45,000X magnification Grain sizes of the unannealed poly-Si films were found to be 30 to 50 nm

Results

All but one of the combinations of silicon film and oxide-layer thicknesses tabulated in Fig 2 yield some free-standing micromechanical beams, both with and without annealing The exception is the unannealed 300 nm-thick, a-Si sample

As observed previously, both cantilevers and bridges beyond a certain critical length are found either to deflect downward, ultimately contacting the substrate, or to deflect upward severely [2] This critical length is called the maximum free-standing length L_m The dependence of L_m on thickness is determined by observing a series of 15 μm-wide cantilevers and bridges with increasing lengths When one length is consistently free standing and the next longer beam consistently contacts the substrate, L_m is estimated as the average of the two lengths In the case where a particular length is only sometimes free standing and all shorter lengths are reliably free standing, L_m is estimated as that length

Maximum free-standing length L_m for cantilever beams is plotted against beam thickness in Fig 3 Data points for cantilevers fabricated with an annealing step are represented by filled symbols In every case, L_m is greater for annealed cantilevers than it is for unannealed cantilevers Without annealing, even the shortest cantilevers (25 μm long) are not free standing for the 300 nm-thick a-Si sample Since L_m cannot be measured for this sample, its data point is missing in Fig 3

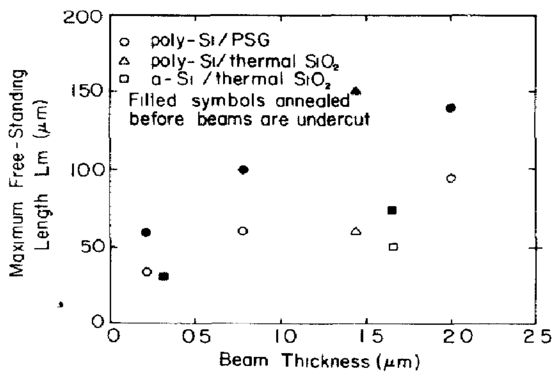
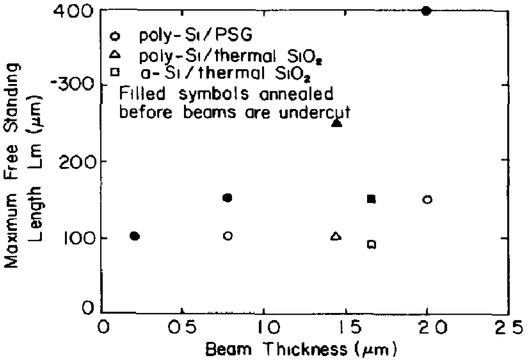


Fig 3 Dependence of maximum free-standing length on beam thickness for cantilevers

Figure 4 presents the dependence of L_m on beam thickness for doubly supported beams (bridges) Data points for 230 nm-thick unannealed poly-Si bridges and 300 nm-thick a-Si bridges (both annealed and unannealed) are missing since even the shortest (100 μm long) bridges contact the substrate As was the case with cantilevers, all of the annealed bridges in Fig 4 had a larger L_m than the unannealed bridges

A second mechanical property of silicon cantilevers is their deflection along their length The deflection of the tip of the cantilever y is found to be proportional to the square of the beam length L Hence, deflection for a given sample can be characterized by the quantity (y/L^2), as in an earlier study [2] Figure 5 shows the dependence of (y/L^2) on beam thickness for annealed and unannealed poly-Si and a-Si cantilevers Positive values of y correspond by convention to deflection away from the substrate As in Fig 3, the 300 nm-thick unannealed a-Si sample is not plotted, since none of the cantilevers were free standing Several points about Fig 5 are worth noting The trend is towards smaller deflection with increasing beam thickness All of the unannealed poly-Si samples show an upward deflection, whereas the unannealed a-Si sample has a downward deflection Annealing prior to cantilever beam formation eliminates the deflection, confirming the single observation made earlier [2] The only exception is the annealed 230 nm-thick poly-Si sample, which has a small residual downward deflection

In view of the results presented in Figs 3 - 5, we conclude that annealing significantly improves the static mechanical characteristics of poly-Si and a-Si beams Both the maximum free-standing length and cantilever deflection are dependent on the internal stress in the silicon film One contribution to the internal stress is due to grain nucleation and growth phenomena, so we expect that grain structure will be related to mechanical properties



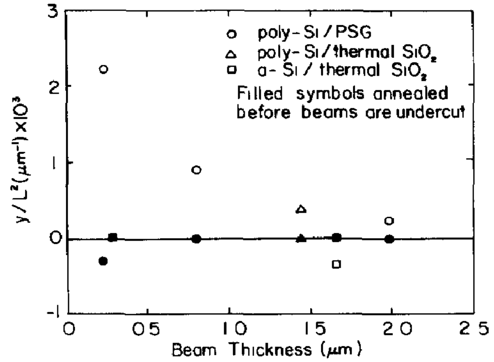
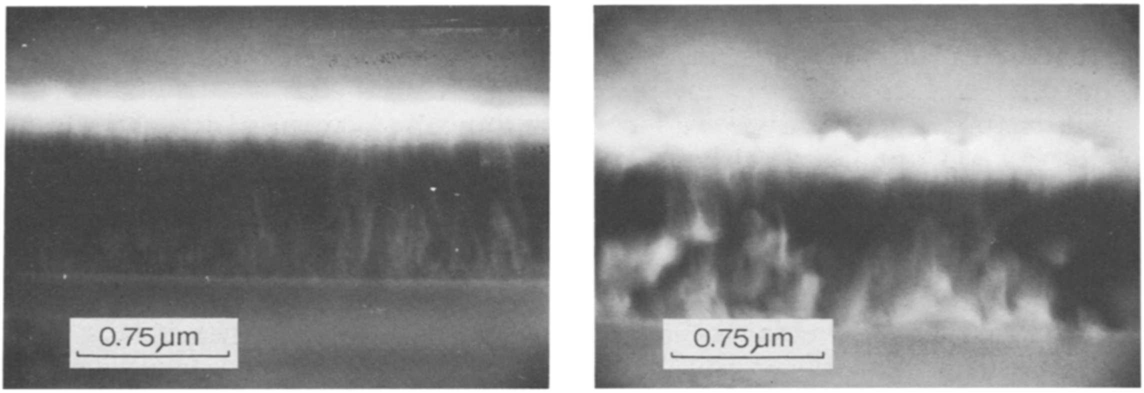


Fig 4 Dependence of maximum free-standing length on beam thickness for bridges

Fig 5 Cantilever beam tip deflection as a function of beam thickness



(a) (b)

Fig 6 SEM cross sections (45 000× magnification) of (a) unannealed and (b) annealed, 800 nm-thick poly Si thin films on PSG

The SEM grain-structure observations indicate that for all three samples, the grain size is larger in the annealed silicon films The increase in grain size is greater near the interface with the underlying oxide layer Figures 6(a) and (b) are SEM cross sections of unannealed and annealed 800 nm-thick poly-Si films Phosophosilicate glass constitutes the layer beneath the poly-Si in this sample The increase in grain size upon annealing, especially near the interface, can be seen clearly by comparing Figs 6(a) and (b)

Discussion

Both poly-Si and a-Si are suitable for making micromechanical beams using the new technique of etching away an underlying oxide layer Annealing the wafers at 1100 °C in nitrogen for 20 minutes after patterning of the silicon film, but prior to beam formation, greatly improves two static mechanical properties of these beams The maximum free-standing length L_m increases from 50 to 150% for cantilevers and from 50 to 170% for bridges, compared with beams on unannealed wafers The built-in deflection of cantilevers is generally eliminated by the annealing procedure given above Only in the case of very thin poly-Si cantilevers does any residual deflection remain Our results show that poly-Si beams can be made longer than a-Si beams, whether or not the annealing step is included in beam fabrication

These results can be applied immediately to the fabrication of poly-Si or a-Si micromechanical beams For example, annealing enables the reliable fabrication of deflection-free, 150 µm-long cantilevers and 250 µm-long bridges from 1 45 µm-thick poly-Si, using a 1 1 µm-thick thermal oxide supporting layer Without the annealing step, the maximum free-standing lengths of cantilevers and bridges made of 1 45 μm-thick poly-Si are only 60 μm and 120 μm, respectively

A tentative explanation can be given for the way in which annealing affects the static mechanical properties of poly-Si and a-Si micromechanical beams The SEM observations indicate that recrystallization occurs in the silicon thin film even with thermal SiO_2 as the underlying oxide layer Previously, it had been thought that reflow of a PSG underlayer might contribute to altering the mechanical properties [2] However, these grain-structure observations and the evidence of Figs 3 - 5 that the changes in L_m and (y/L^2) are similar for films with thermal oxide or PSG supporting layers invalidate this suggestion As the thin film recrystallizes, the variation in internal stress through the film is relaxed and so annealed cantilevers have no internal bending moment [2] and consequently show no built-in deflection The non-uniform internal stress is most likely due to the intrinsic stress in the film, which is a result of grain nucleation and growth phenomena [5] The first 100 nm of the silicon would be the most highly stressed from these causes and so it is expected that grain restructuring and growth should be greatest in this interfacial region In fact, the cross sections in Fig 6 indicate that grain growth in the annealed films is largest at the interface with the underlying oxide For the thinnest poly-Si sample, 230 nm in thickness, the highly stressed interfacial region is a relatively large fraction of film thickness Therefore, the incomplete relaxation of the internal stress indicated by the residual cantilever beam deflection is not surprising

In addition to eliminating internal stress variation through the silicon film, the annealing procedure used in this study also largely eliminates the average compressive internal stress in the film [6] This experimental result is consistent with the observation that L_m is greater for annealed poly-Si or a-Si bridges than it is for unannealed bridges Unannealed films have a large average internal stress which is compressive An unannealed bridge consequently tends to buckle when the underlying oxide layer is etched away Since this compressive stress is greatly reduced in all but the thinnest annealed silicon films [6], bridges fabricated from annealed poly-Si or a-Si have much less tendency to buckle Therefore, they can be made longer than unannealed bridges

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