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Residual Stress Relaxation and Property Modifications of Polysilicon Films by Ion Implantation

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Ion implantation without any thermal treatment is applied for the residual stress relaxation of LPCVD (low-pressure chemical vapor deposition) polysilicon films in MEMS. He^+ and Ar^+ ion implantations reduce the residual stress of polysilicon films. The amount of residual stress relaxation increases as ion dose increases. TEM (transmission electron microscopy) observations show that ion implantation of polysilicon films changes the crystal state of polysilicon into an amorphous state. The residual stress relaxation of LPCVD polysilicon film in MEMS (micro-electro-mechanical systems) is attributed to the compressive stress created by the cubical expansion of polysilicon because amorphous silicon has a lower density than crystal silicon. This compressive stress counterbalances the tensile stress in the upper part of films with a positive stress gradient. The property modifications of polysilicon films by ion implantation are also investigated. The elastic modulus and hardness of polysilicon films with ion implantation is evaluated by the nanoindentation method. Ion implantation at an ion dose of 10^{16} ions/cm^2 decreases the elastic modulus and hardness of polysilicon films. However, as ion dose increases, the elastic modulus and the hardness of polysilicon films increase.

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1. Introduction

MEMS is a promising field of research which is expected not only to introduce new applications but also to lead to the development of devices with better performance than existing macrodevices. However, there are several difficulties that limit the development of MEMS applications, and one of them is the control of residual stresses in the thin-film structure.

Most thin films have residual stresses due to the mismatch of thermal expansion coefficients, nonuniform plastic deformation, lattice mismatch, substitutional or interstitial impurities, and growth processes.(1) It is well known that the mechanical response of microstructures changes markedly due to residual stresses. The presence of the residual stresses changes the elastic stiffness of the microstructure and thus the resonant frequency. A film with a positive stress gradient, that is, a film with a tensile residual stress near the free surface and a compressive residual stress near the interface, tends to bend away from the substrate when it is released. Moreover, an excessive tensile stress may cause a film to crack or delaminate, and a compressive stress may result in film buckling.

The conventional approach to solving such a problem is to relax the residual stresses in thin films by furnace annealing.(2–4) Annealing at a temperature higher than that for deposition may decrease the compressive residual stress in polysilicon thin films deposited by LPCVD.(3) However, conventional furnace annealing, that is, annealing for a long time at a high temperature, is detrimental to the ICs (integrated circuits) fabricated on the micrometer scale.

Rapid thermal annealing (RTA) can reduce thermal damage and reduce or eliminate residual stress in thin films in a few seconds.(5–7) The residual stress of LPCVD polysilicon thin films is quickly reduced after a few cycles of RTA at a high temperature.(6) However, since RTA is also conducted at a high temperature, it cannot be applied to microsystems with ICs.

Some researchers have investigated the use of the ion implantation method for reducing the residual stress in thin films. Boron implantation on polysilicon films followed by thermal annealing changes the residual stress.(8) The stress gradient of polycrystalline SiC structures was reduced by four-step multiple C^+ ion implantations.(9) Polysilicon microstructures could be reformed by ion implantation with appropriate dose, acceleration voltage and ion mass.(10) However, the previous works applied thermal treatment after the ion implantation to activate implanted ions or to recover the damage caused by ion implantation.

In this paper, we present the results of ion implantation without any thermal treatment to relax the stress gradient in polysilicon films deposited by LPCVD. The effect of ion implantation on the stress gradient in polysilicon films is investigated with respect to various ions, ion doses, and implantation energies. The microstructure of polysilicon films is also analyzed by TEM. Moreover, the elastic modulus and hardness of polysilicon films are studied after ion implantation, by the nanoindentation method using a nanoindenter.

2. Experimental Details

2.1 *Experimental procedure*

Figure 1 shows the experimental procedure of the present study. Polysilicon cantilever beams are fabricated by the conventional surface micromachining technology of MEMS. He^+, Ar^+, and N_2^+ ions are implanted onto the polysilicon cantilever beams before the beams are released.

The polysilicon cantilever beams without any treatment have a positive stress gradient, thus they bend away from substrate when it is released. The magnitude of the stress gradient can be evaluated by measuring the tip deflection of the released cantilever beam with a laser profiler. By comparing the tip deflections of an ion implanted cantilever beam with that of an as-deposited cantilever beam, it can be determined whether the stress gradient is relaxed or not. The microstructures of the polysilicon films are observed by TEM, and it is found that the microstructures are changed by ion implantation. Samples for

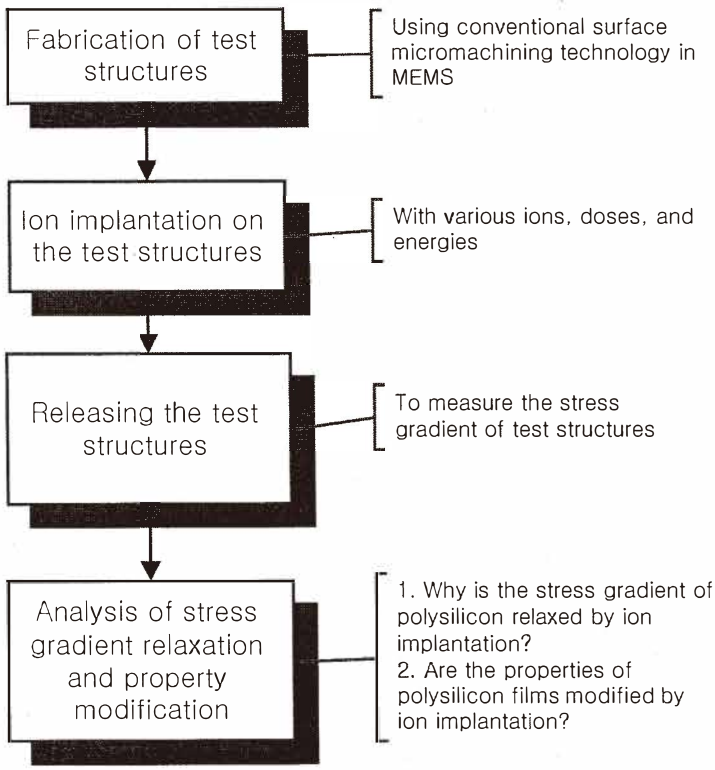


Fig. 1. Experimental procedure.

TEM observation are prepared by mechanical polishing followed by ion milling. Cross-sectional TEM images give an indication of the cause of the stress gradient relaxation in polysilicon films upon ion implantation.

Moreover, in order to measure the hardness and elastic modulus of films before and after ion implantation, indentations were made using a Nano-indenter II (MTS) system with a Berkovich diamond indenter with a tip radius of approximately 120 nm. The Nano-indenter II system has a force resolution below the sub-micronewton level and a displacement accuracy below 0.1 nanometers. The Nano-indenter II system gives the depth profile of a elastic modulus and hardness from the surface to the maximum indentation depth[11,12] while the conventional nanoindentation method only gives a elastic modulus and hardness at the maximum indentation depth.[13] Indentation experiments were carried out by loading (indentation depth control, 2 nm/s) to a maximum depth of 300 nm; then unloading (indentation depth control, 2 nm/s) to 5% of the maximum load and holding for 20 s to correct for thermal drift; and then completing the unloading. To obtain reliable data, a minimum of nine indents were made on each sample. The elastic modulus and hardness of each sample were averaged with respect to indentation depth.

2.2 *Fabrication process of test structures*

The polysilicon cantilever beams are fabricated following the procedures shown in Fig. 2. Only two masks are required for the whole fabrication process. A 4-inch *n*-type silicon wafer with a thickness of 525 μm is used as the substrate. After the silicon wafer has been cleaned, a 2-μm-thick TEOS (tetraethylorthosilane) film is deposited on the silicon wafer as a sacrificial layer using PECVD (plasma enhanced chemical vapor deposition) with an O_2 flow rate of 220 sccm, a TEOS flow rate of 220 sccm, an RF power of 350 W, and a pressure of 9 Torr at 390°C. To make anchors, the TEOS film is patterned using MERIE (magnetically enhanced reactive ion etching) with a CHF_3 flow rate of 25 sccm, a CHF_4 flow rate of 5 sccm, an Ar flow rate of 70 sccm, an RF power of 600 W, a magnetic field of 60 Gauss, and a pressure of 130 mTorr. Then, a 2.1-μm-thick polysilicon film is deposited as the structure layer by LPCVD with a SiH_4 flow rate of 60 sccm and a pressure of 300 mTorr at 625°C. To make the cantilever beams, the polysilicon film is patterned using DRIE (deep reactive ion etching). Ion implantation is performed on the polysilicon film with various ions, doses and energies before the structures are released. The TEOS film of a sacrificial layer is removed using 49 wt% HF solution to release the polysilicon cantilever beams.

Figure 3 shows SEM (scanning electron microscopy) images of the fabricated test structures. Cantilever beams and bridges of 50 μm–500 μm in length are fabricated. As shown in Fig. 3(a), the compressive residual stress of polysilicon films triggers a buckling motion of microbridges. Figure 3(b) shows the cantilever beams bent upward by a positive stress gradient. The deflection profiles are measured with a laser profiler to confirm the stress gradient relaxation of polysilicon films by ion implantation.

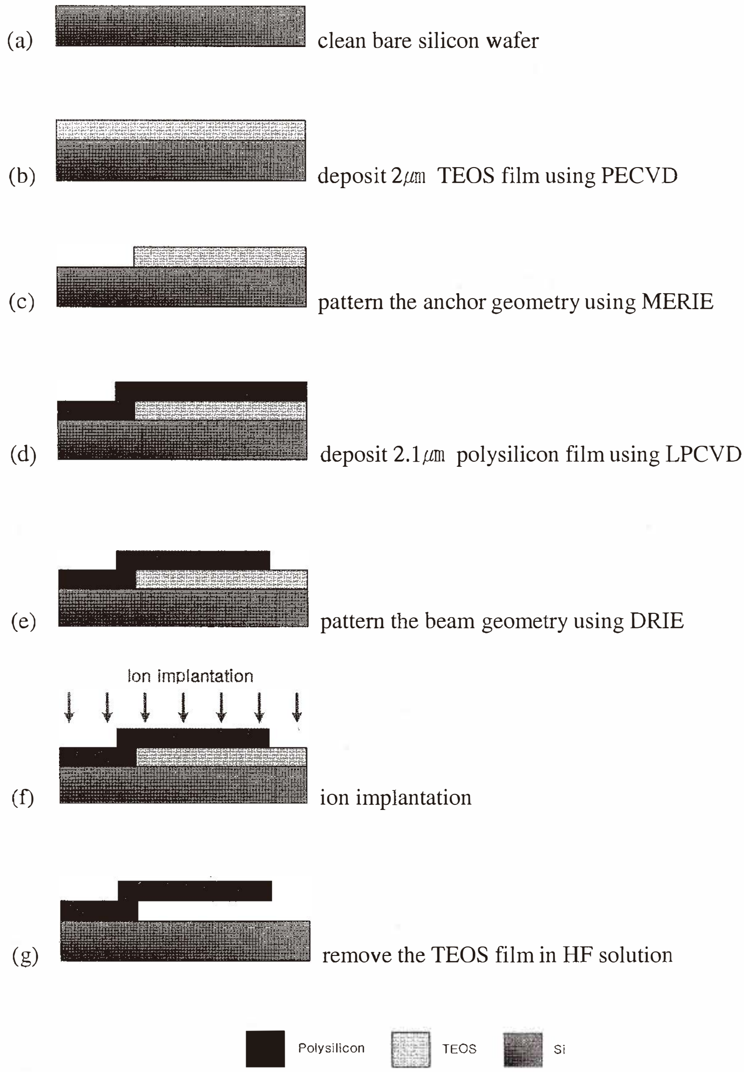


Fig. 2. Fabrication process of polysilicon cantilever beams.

3. Experimental Results and Discussion

3.1 *Stress gradient relaxation by ion implantation*

N_2^+, He^+, and Ar^+ ions are implanted on the polysilicon cantilever beams at doses of 10^{16} ions/cm^2 and 10^{17} ions/cm^2. The experimental parameters of the ion implantation are listed in Table 1. The penetration depth of each ion is calculated by performing the Monte Carlo

(a)

(b)

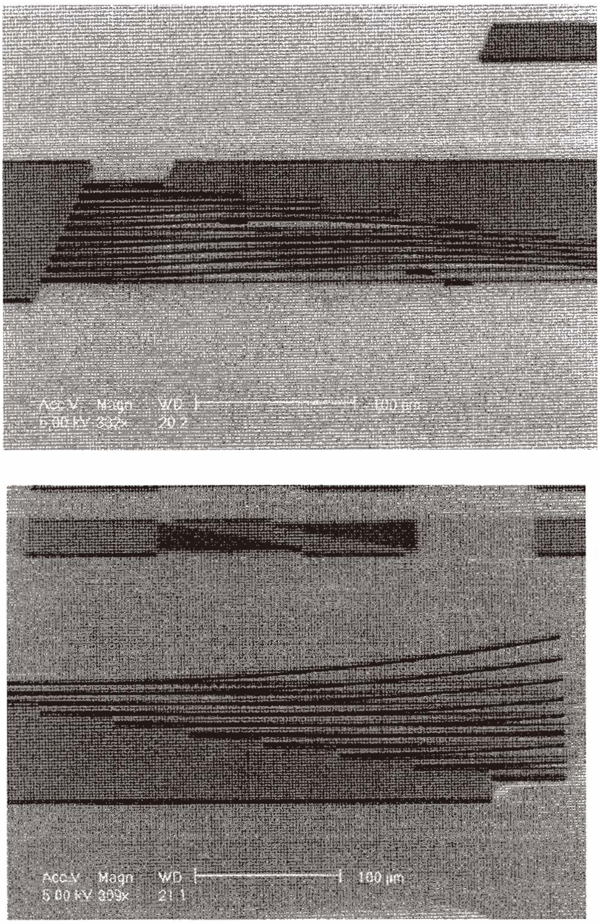


Fig. 3. SEM images of released test structures: (a) microbridges buckled by compressive stress, (b) microcantilever beams bent upward by positive stress gradient.

Table 1
Ion implantation conditions.

Ion	He^+	Ar^+	N_2^+
Ion dose (ions/cm^2)	10^{16}, 10^{17}	10^{16}, 10^{17}	10^{16}, 10^{17}
Implantation energy (KeV)	40	100	50
Penetration depth (nm)	480	110	140

simulation with TRIM'98 code as shown in Fig. 4. The depth profile is similar to a Gaussian distribution. The maximum point of an atom/ion indicates the location in the thickness direction where the maximum quantity of implanted ions exists. As the ion energy (acceleration voltage) is increased or the ion mass is decreased, the maximum point of the atom/ion is shifted deeper into the film.

The tip deflection of the polysilicon cantilever beam is plotted for various ions and ion doses as shown in Fig. 5. The dimensions of the beam are 2.1 μm in thickness, 100 μm in length, and 20 μm in width. As shown in Fig. 5, the tip deflection of the cantilever beam with He^+ and Ar^+ ion implantation decreases with increasing ion dose. This indicates that the tensile residual stress in the upper part of polysilicon cantilever beams with a positive stress gradient is reduced by ion implantation, and thus the stress gradient of the polysilicon film is relaxed by He^+ and Ar^+ ion implantation. However, the N_2^+ ion implantation does not show a clear decrease in the tip deflection of the cantilever beam as ion dose increases. It is presumed that N_2^+ ion implantation changes polysilicon into a layer which has similar characteristics as silicon nitride. The silicon nitride is well known to have tensile residual stress in general.

The microstructure of the polysilicon film with ion implantation is examined by TEM. Figure 6(a) shows a cross-sectional TEM image of a polysilicon film without ion implantation. It clearly shows the polycrystalline structure of the film. Figures 6(b)~6(g) show cross-sectional TEM images of the ion implanted areas in polysilicon films with various

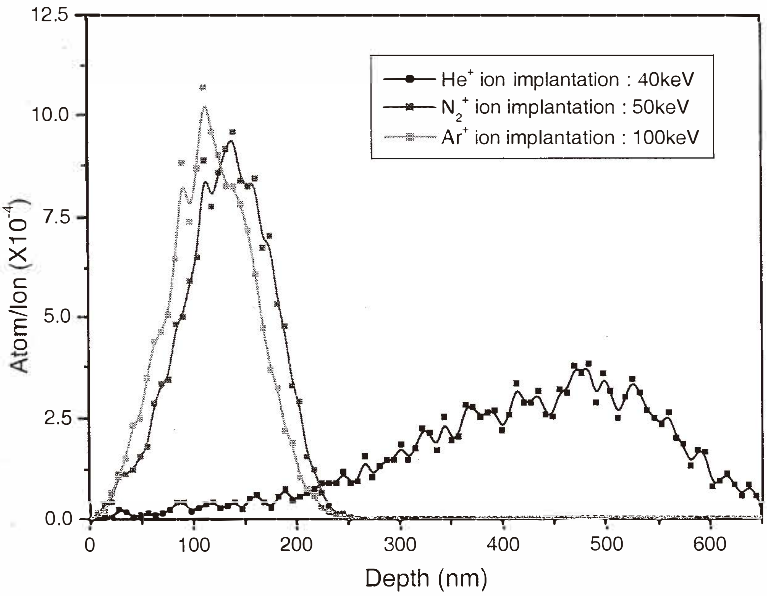


Fig. 4. Implanted ion depth profiles simulated by TRIM'98.

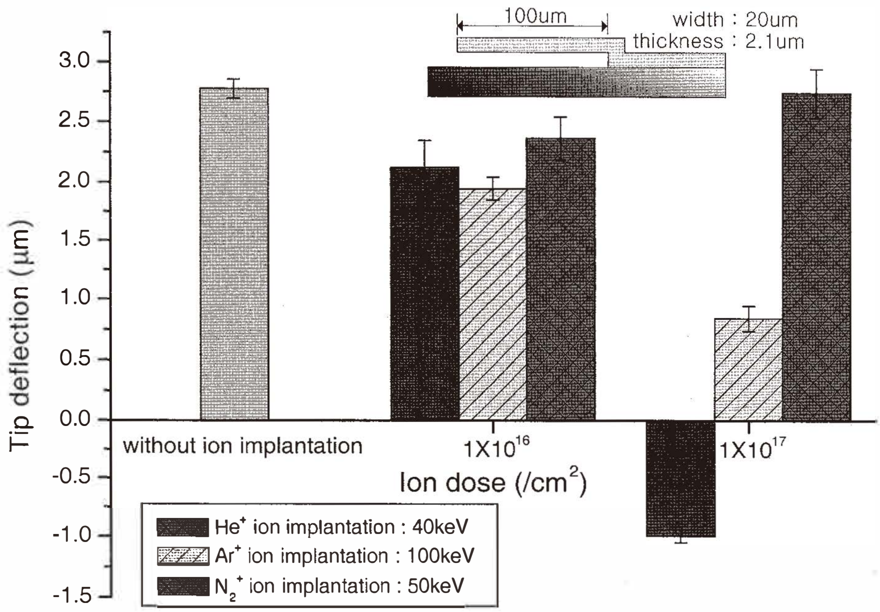


Fig. 5. Tip deflection of a cantilever with respect to ion and ion dose.

ions of He^+, Ar^+, N_2^+ and ion doses of 10^{16} ions/cm^2 and 10^{17} ions/cm^2. As evident in the images, the polycrystalline structure of the film changes into the amorphous region after ion implantation regardless of the type of ion, and the amorphous region increases with ion dose. It is presumed that the amorphous region has a close relationship with the stress gradient relaxation of polysilicon films by ion implantation. Note that the polysilicon film has more relaxation of the stress gradient as ion dose increases as shown in Fig. 5.

The density of amorphous silicon is lower than that of crystal silicon; it is known to be 73–99% of that of crystal silicon, depending on the formation conditions.(14) Therefore, the structure change of the polysilicon films from the crystal state to the amorphous state results in the cubical expansion of the ion-implanted area. The cubical expansion creates a compressive residual stress in that area. The upper part of a cantilever beam with a positive stress gradient has a relatively high tensile residual stress. Therefore, the compressive residual stress due to the cubical expansion reduces the tensile residual stress of the upper part of the beam with a positive stress gradient. Consequently, the tip deflection of the cantilever beam decreases with ion implantation due to the state change of polysilicon film from polycrystalline to amorphous.

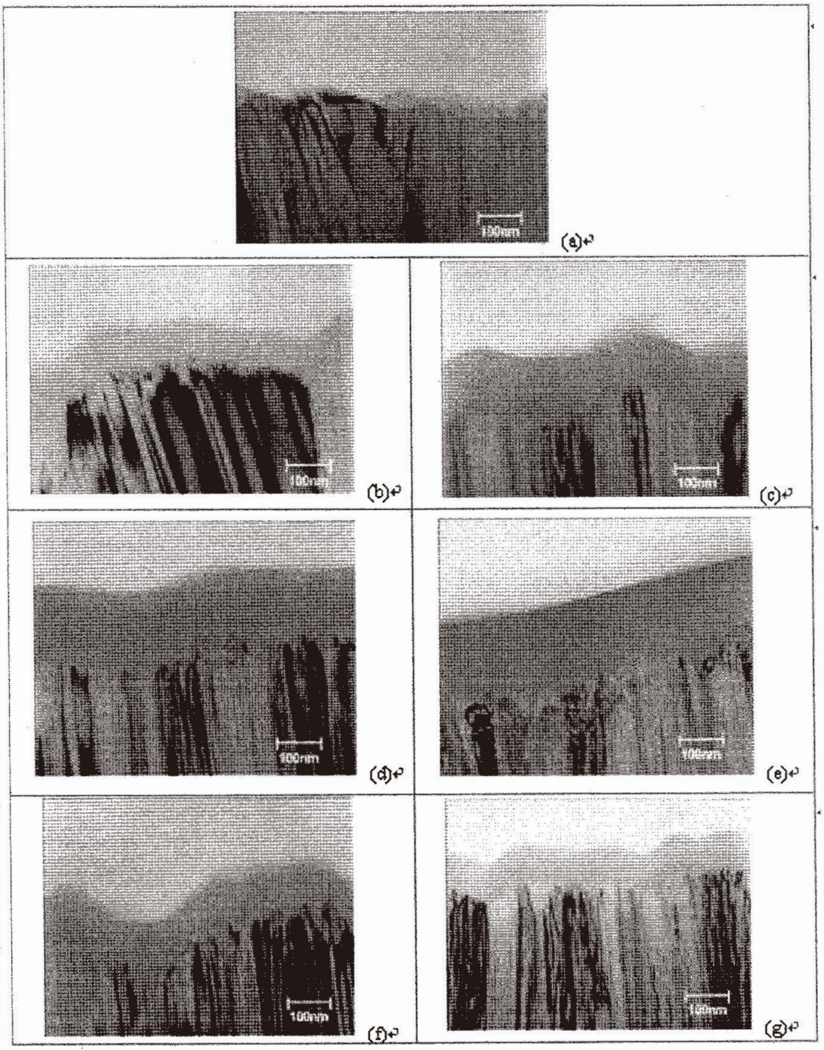


Fig. 6. Cross-sectional TEM images of polysilicon films with various ions and ion doses : (a) without ion implantation, (b) He^+ with 10^{16} ions/cm^2, (c) He^+ with 10^{17} ions/cm^2, (d) Ar^+ with 10^{16} ions/cm^2, (e) Ar^+ with 10^{17} ions/cm^2, (f) N_2^+ with 10^{16} ions/cm^2, and (g) N_2^+ with 10^{17} ions/cm^2.

If the dose of ion implantation increases, the amorphous region also increases and thus the compressive residual stress due to cubical expansion also increases. Therefore, more stress gradient relaxation in the polysilicon films is achieved by ion implantation. The mechanism of the stress gradient relaxation of polysilicon films by ion implantation is illustrated in Fig. 7.

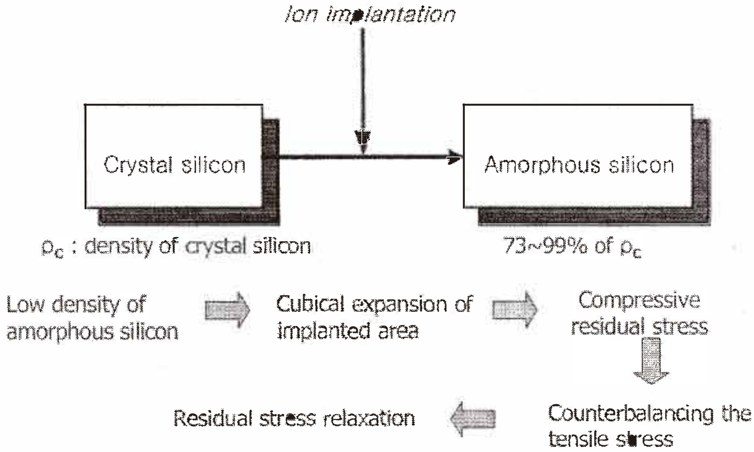


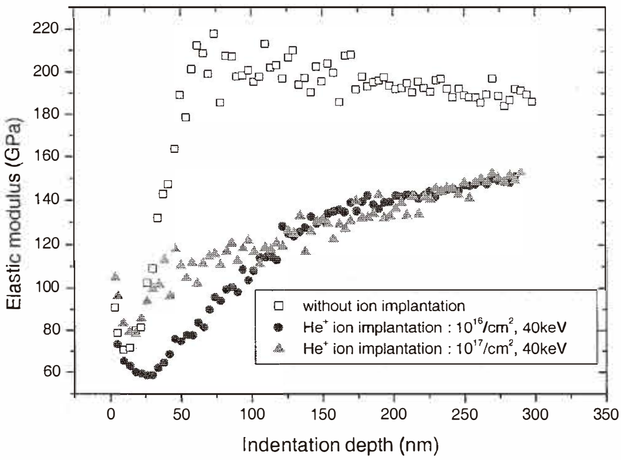
Fig. 7. Mechanism of the residual stress relaxation of polysilicon films by ion implantation.

3.2 *Property modification of polysilicon films by ion implantation*

Figures 8–10 show the elastic modulus and hardness of polysilicon films deposited on silicon wafer by the LPCVD method with respect to indentation depth. As shown in the figures, the elastic modulus and the hardness of polysilicon film decrease with ion implantation at a light dose. It is known that the elastic modulus and the hardness of amorphous silicon are lower than those of crystalline silicon.(14) Considering the results of TEM observation, it is presumed that this decrease in elastic modulus and hardness is related to the microstructure change of polysilicon films from the crystalline phase to the amorphous phase by ion implantation. However, elastic modulus and hardness tend to increase as the weight and dose of the implantation ion increase. As shown in Fig. 10, the hardness of polysilicon films with Ar^+ ion implantation at a dose of 10^{17} ions/cm^2 is higher than that without ion implantation. Therefore, it is thought to be possible to improve the elastic modulus and the hardness of polysilicon films by optimizing ion implantation. The increases in elastic modulus and hardness can be useful in terms of the wear resistance, but they may exert a negative influence on the relaxation of residual stresses. Further study on the effect of ion implantation on elastic modulus and hardness will be conducted in the near future.

4. Concluding Remarks

The stress gradient of polysilicon films fabricated by LPCVD is relaxed by ion implantation. He^+ and Ar^+ ion implantations effectively release the stress gradient of polysilicon films. The stress gradient relaxation is presumed to be primarily due to the state change of polysilicon film from polycrystalline to amorphous. The amorphous region of polysilicon films relaxed by ion implantation has a lower density than that of crystal silicon films. The microstructural change of polysilicon film results in cubical expansion in the



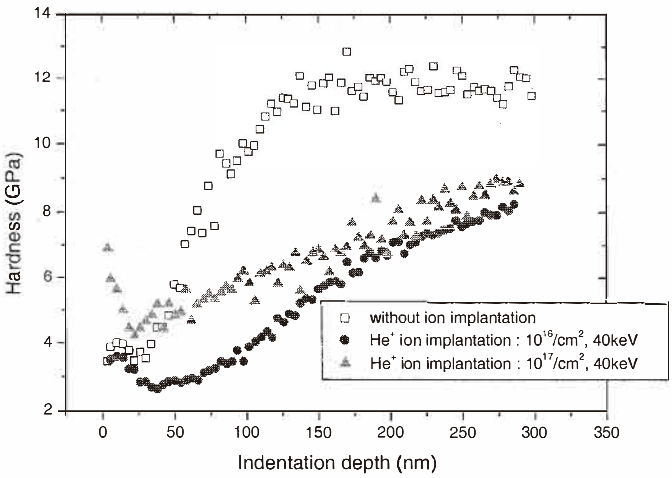


Fig. 8. Elastic modulus and hardness of polysilicon film with respect to indentation depth showing the effect of He^+ ion implantation.

implanted region, and then creates a compressive residual stress in the region. The compressive residual stress induced by cubical expansion counterbalances the tensile residual stress of the upper part of polysilicon films with a positive stress gradient. However, N_2^+ ion implantation does not clearly lead to stress gradient relaxation. It is presumed that N_2^+ ion implantation changes the upper part of polysilicon into silicon nitride, which usually produces the tensile residual stress.

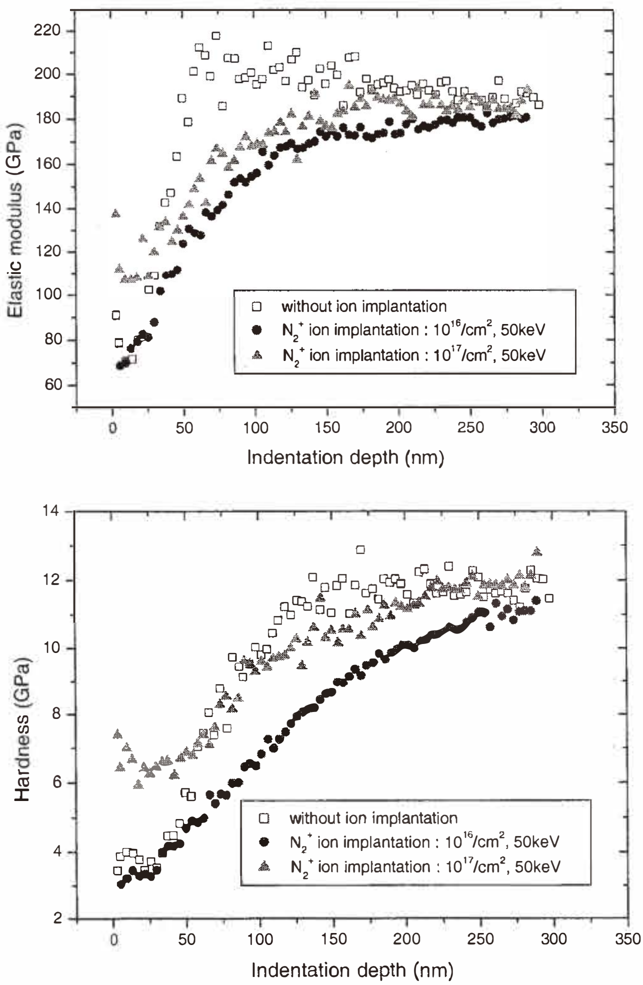


Fig. 9. Elastic modulus and hardness of polysilicon film with respect to indentation depth showing the effect of N_2^+ ion implantation.

The microstructural change of polysilicon film by ion implantation affects the elastic modulus and the hardness of the film. The amorphous state resulting from ion implantation at a light dose is presumed to reduce the elastic modulus and the hardness of the polysilicon film. However, they show an increasing trend with increasing ion dose. Therefore, it is thought to be possible to improve the elastic modulus and the hardness of polysilicon film by optimizing ion implantation.

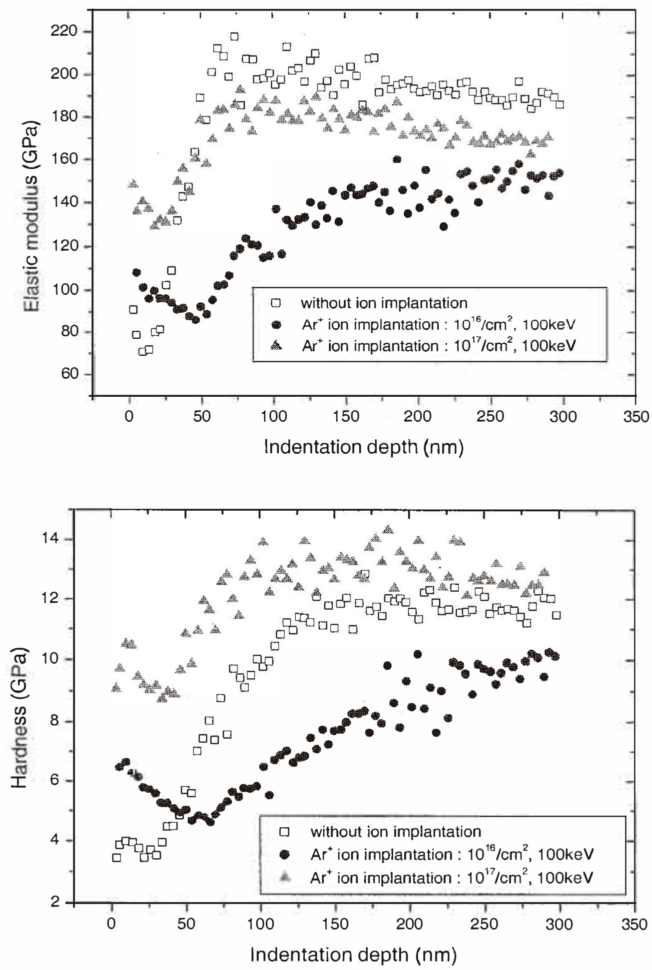


Fig. 10. Elastic modulus and hardness of polysilicon film with with respect to indentation depth showing the effect of Ar^+ ion implantation.

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