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Estimation of boron diffusion induced residual stress in silicon by wafer curvature technique

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ABSTRACT

Heavily boron doped silicon layer is being used to control the thickness of the bulk micro-machined micro-electro-mechanical system (MEMS) based structures. Residual stress generated due to the doping may affect the functioning and reliability of the MEMS devices. This paper presents a model for estimation of the diffusion induced residual stress by wafer curvature technique. Boron diffusion induced residual stresses in the silicon (100), (110) and (111) wafers are found to be 475 MPa, 963 MPa and 957 MPa respectively.

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1. Introduction

Doping of impurities in semiconductors is one of the most fundamental processes used in making semiconductor devices [1,2]. Boron doping (concentration: $>5\times10^{19}$ atoms/cm^3) in silicon is being used to control/ alter the etch rate of silicon in specific etchants [3–8]. This phenomenon of change in etch rate is being utilized to control of the thickness of micromechanical structures during bulk-micromachining or dissolved wafer processes (DWP) [7–14]. It offers high reproducibility, excellent uniformity, high yield, and ease of processing during fabrication of micro-mechanical structures [4,7–14].

However, incorporation of such high levels of boron atoms induces large stresses in the fabricated MEMS structures based on these p^{++} layers [12,14–17]. The residual stresses may influence the behavior of the final MEMS device as well as their reliability. Thus, estimation of the residual stress is one of the key issues for fabricating reliable and reproducible devices.

Majority of the previously published literature discusses about the boron concentrations and its' etch stop properties in aqueous alkaline solutions [3–12]. Few papers have reported on generation of residual stress due to the diffusion process [14–18]. In those papers, the residual stress is measured either by Raman spectroscopy [14,18] or by bending of p^{++} Si cantilever structures [8,14–17].

Residual stresses can also be measured by wafer curvature technique. However, this technique is valid only for the thin films deposited on (or removed from) the substrate [19–22]. In this technique, wafer curvature is measured before the thin film deposition (or removal) and after the thin film deposition (or removal) and then by employing the Stoney's equation [19] the residual stress in the film is calculated. During the estimation of residual stress due to the removal of thin film, thickness thin film is denoted with a negative sign. Advantage of this technique is that average macroscopic residual stress of the thin film can be estimated without knowing the nature/ state of the material (amorphous or polycrystalline or multiphase) of the film and its mechanical properties [19–22]. Till now the wafer curvature technique is not being used to estimate the diffusion/implantation induced residual stress in substrates. In this paper, we are reporting the estimation of diffusion induced residual stress using the wafer curvature technique.

It is well known that during the deep boron diffusion in silicon wafers oxygen gas is introduced in the diffusion furnace along with the nitrogen gas [1–2,14,18]. This enhances the diffusivity of boron in silicon such that the diffusion depth into the silicon crystal increases [1,14,18]. However, presence of oxygen along with a post-diffusion low temperature oxidation process (to dilute the hard doped-oxide generated during such a prolonged diffusion process) creates a SiO_2 layer (typically <0.5 μm thick) on top of the doped silicon wafers. Residual stress due to the diffusion process can be estimated by using this oxide layer in the following way:

Initially, radius of curvature (R_0) of the silicon substrates is measured before the boron doping as the reference point. The changes in radius of curvatures after deep boron diffusion (with oxide layer) (R_1) and after the removal of doped oxide layer (R_2) are recorded. The residual stress due to the combined effects of the boron diffusion and the oxide layer formation is denoted by σ_1 as written in Eq. (1). Eq. (2) corresponds to the residual stress (σ_2)

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due to the oxide layer (removal) only.

$$\sigma_1 = \left(\frac{E_s}{1-\nu_s}\right)\frac{t_s^2}{6t_{\text{oxide}}}\left[\frac{1}{R_1}-\frac{1}{R_0}\right] \tag{1}$$

$$\sigma_2 = \left(\frac{E_s}{1-\nu_s}\right)\frac{t_s^2}{6(-t_{\text{oxide}})}\left[\frac{1}{R_2}-\frac{1}{R_1}\right] \tag{2}$$

Thus, the difference between σ_1 and σ_2 determines the residual stress (σ_{diff}) due the boron diffusion as presented in Eq. (3).

$$\sigma_{diff} = \sigma_1 - \sigma_2 \tag{3}$$

This well-known equation is valid only in the thin-film regime ($t_s \gg t_{\text{oxide}}$). Hence, the calculation of residual stress in the film only requires knowledge of substrate Young's modulus (E_s) and Poisson's ratio (ν_s) and does not rely on the material properties of the film.

In this paper, deep boron diffused p^{++} silicon layers (>10 μm thick) of boron concentration above 5×10^{19} atoms/cm^3 are fabricated in Si (100), (110) and (111) wafers. The residual stress due to the boron diffusion in the silicon wafers is estimated using wafer curvature technique.

2. Experimental procedure

To study the diffusion induced residual stress, three p type silicon (resistivity: 1–10 Ω-cm) wafers of (100), (110) and (111) orientations were taken. The diffusion experiment was done in a three-zone horizontal furnace at 1175 °C in a mixture of oxygen (flow rate: 200 ml/min) and nitrogen (flow rate: 2 L/min) environment for 15 h. The Boro-Disc™ wafers are used as the source for boron dopant. Detailed optimization of deep boron diffusion to create p^{++} layer having thickness ≥ 10 μm with concentration $\geq 5\times10^{19}$ atoms/cc was reported elsewhere [18]. The diffusion profiles are studied by secondary ion mass spectrometry (SIMS) (model: CAMECA IMS 7F)

The residual stress due to the diffusion process is determined by ex-situ wafer-curvature measurements using TOHO FLX-2320S laser reflectance system. To average out the residual stress value, two curvature measurements are taken perpendicular as well as parallel to the primary flat of the silicon wafers. For the stress calculations, Young's moduli of Si (100), (110) and (111) wafers are taken to be 130 GPa, 170 GPa and 185 GPa respectively and the Poisson's ratio (ν_s) is considered to be 0.28 [4,6].

3. Results and discussions

During the diffusion process, the smaller boron atom replaces bigger silicon atom and occupies the substitutional site in the silicon lattice. Thus creates tensile stress in the silicon lattice. Fig. 1 shows the SIMS profiles of the boron atoms in silicon (100), (110) and (111) wafers. All of them had almost identical SIMS profile of heavy boron diffusion ($>5\times10^{19}$ atoms/cc) up-to 12 μm depths.

In this study, radii of curvatures of the silicon samples are estimated by measuring the bowing of the wafers. Fig. 2 shows bowing of the silicon wafers before and after the diffusion process as well as after the doped oxide removal. Thickness of the doped oxide is found to be ~0.25 μm. The radii of curvatures of the silicon wafers are tabulated in Table 1. Using Eqs. (1) and (2), the residual stresses in the silicon wafers are estimated and are also reported in the Table 1. During the diffusion, bigger silicon atoms (atomic radius: 0.111 nm) substituted by smaller boron atoms (atomic radius: 0.09 nm). Thus creates tensile stress in the silicon lattice. The doped oxide generated during the deep boron diffusion process exerts a compressive stress ~800 to 850 MPa (σ_2). The average macroscopic residual stresses due to the boron diffusion ($\sigma_{\text{diff}}=\sigma_1-\sigma_2$) are estimated to be 475 MPa, 963 MPa and 957 MPa corresponding to the Si (100), Si (110) and Si (111) samples respectively. Previously, we reported the boron diffusion induced residual stress (microscopic) in Si (100) (454 MPa), Si (110) (908 MPa) and Si (111) (908 MPa) samples by Raman spectroscopy [18]. Disparities in the measured residual stresses were also explained there [18]. Thus one can see that the macroscopic and microscopic residual stress values are matching well.

Previously, Nazafi et al. [15] (1.83×10^8 dynes/cm^2) and Ning [16] (1×10^9 dynes/cm^2) have estimated residual stress due to boron diffusion in Si (100) samples by fabricating diaphragm and cantilever structures. Our measured stress value in Si (100) sample is quite high (~475 MPa) compared to that reported by them [15,16]. This may be due to the larger diffusion depth (hence, prolonged diffusion time) compared to that reported by them.

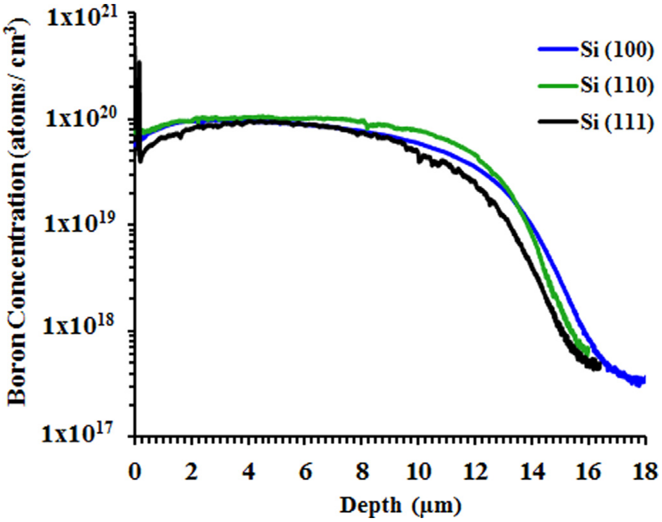

Fig. 1. SIMS profiles of boron dopant.

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