A technique for quantitative determination of the profile of the residual stress along the depth of p^+ silicon films

E. H. Yang and S. S. Yang
Microsystems Laboratory, Department of Control and Instrumentation Engineering, AJOU University, 5 Wonchun-Dong, Paldal-Gu, 442-749 Suwon, Korea

S. H. Yoo
Department of Mechanical Engineering, AJOU University, 5 Wonchun-Dong, Paldal-Gu, 442-749 Suwon, Korea

(Received 1 March 1995; accepted for publication 31 May 1995)

A quantitative method to determine the profile of the residual stress along the depth of a highly boron doped silicon film is reported. First, the stress profile relative to the stress at the neutral surface of the film is obtained by measuring deflection of p^+ silicon cantilevers with different etch depths. Second, the average of the residual stress is obtained by using a rotating beam structure. The stress profile is determined completely from these two calculations. One example of application by this method illustrates that most of the p^+ region is subjected to the tensile stress except for the region near the front surface. © *1995 American Institute of Physics.*

Most p^+ silicon cantilevers are curled up or down due to the residual stress gradient along the depth. During the boron doping, tensile stress is created since the atomic radius of boron is smaller than that of silicon.[1] Some literature[2,3] reports that the average of the stress in p^+ silicon films is tensile, and others[4–6] report only qualitative analyses of the stress gradient in films based on the buckling behavior of diaphragms or the bending of cantilevers. Because the experimental conditions are not the same, the results of the above experiments on the residual stress in p^+ films are not comparable with each other and those determinations are incomplete. This letter presents a quantitative method to determine the stress profile.

For the quantitative analysis, the residual stress σ_x is assumed to be a polynomial function of Y which is the coordinate perpendicular to the neutral surface (xz plane in Fig. 1) of the cantilever,

$$\sigma_x=\sum_{k=0}^{n} a_k Y^k, \tag{1}$$

where a_k's are coefficients to be determined. In this study, the residual stress represents the stress in the p^+ film before the cantilever is fabricated. The determination procedure consists of two calculations. One is to determine the stress profile relative to the stress at the neutral surface of the film, that is, to calculate the coefficients a_k's for $k=1,2,...,n$, where n is an integer to be determined in curve fitting. The other is to determine a_0, the stress at the neutral surface, which can be obtained from the average of the stress and the relative profile of the stress.

Figure 1(a) shows that the amount of vertical deflection of the cantilever varies with the removal of the surface layer of the cantilever, which can be explained by the residual stress profile in Fig. 1(b). If the surface layer is removed by 2δ, the neutral axis of the cantilever shifts down by δ as shown in Fig. 1. Representing Eq. (1) with the shifted coordinate y equal to $(Y+\delta)$,

$$\sigma_x=\sum_{k=0}^{n} a_k (y-\delta)^k. \tag{2}$$

If boron is diffused uniformly throughout the wafer surface, the stress σ_x is uniform along the x axis as in Eq. (1). The bending moment M_b to restore the deflected cantilever flat is obtained by integrating $-b\sigma_x y$ with respect to y, where b is the width of the cantilever. Thus, M_b is also uniform along the x axis. Neglecting the gravity effect, we obtain the deflection of the end of the cantilever v_L from the relationship between the bending moment and the deflection[7] as

$$\begin{aligned} v_L=\frac{6L^2}{Ebh^3}M_b=-\frac{6L^2}{Eh^3}\int_{-h/2}^{h/2}\sigma_x y\,dy \\ =-\frac{L^2}{E}\Bigg[\frac{1}{2}a_1-h^2\delta a_2+\left(\frac{3}{2}\delta^2+\frac{3}{40}h^2\right)a_3 \\ -\left(2\delta^3+\frac{3}{10}h^2\delta\right)a_4 \\ +\left(\frac{5}{2}\delta^4+\frac{3}{4}h^2\delta^2+\frac{3}{224}h^4\right)a_5+\cdots\Bigg], \end{aligned} \tag{3}$$

where E is Young's modulus, and L and h are the length and the thickness of the cantilever, respectively. Note that the constant term a_0 disappears in Eq. (3). Since $h=H-2\delta$, where H is the original beam thickness, v_L is a function of δ only. If the deflections of the ends and the thicknesses of the cantilevers are measured for various cantilevers with different frontside etch depths, the unknown coefficients, a_k's of Eq. (3) except a_0 are calculated by curve fitting.

To determine the constant a_0, the average stress of the p^+ silicon film must be measured. In this letter a rotating beam structure[8] to obtain the average stress is fabricated. The numerical analysis on the displacement of the tip under residual stress is performed by using a general purpose FEM package, ABAQUS. By measuring the tip displacement, the

 0003-6951/95/67(7)/912/3/$6.00

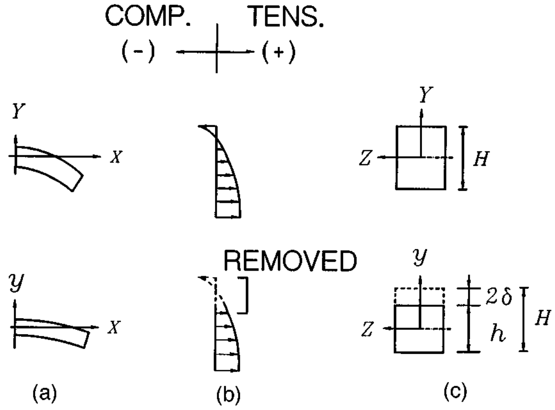

FIG. 1. The beam deflection before (upper) and after (lower) the removal of the front surface: (a) the deflection after beam fabrication; (b) the residual stress in the films; (c) the cross section of the beam.

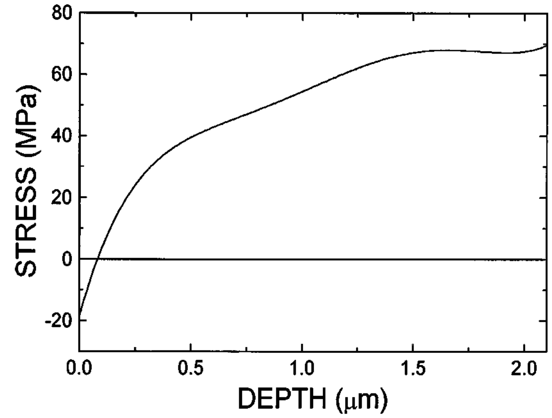

FIG. 3. The profile of the residual stress along the depth of the p^+ silicon film.

average stress is determined from the result of the numerical calculation. Finally, it is straightforward to determine a_0 with the average stress and the relative profile of the stress.

For the fabrication of the structures, *n*-type, 10–20 Ω cm, (100), double side polished silicon wafers are used. First, thermal oxide is grown for the patterning of the windows for boron diffusion. The boron predeposition with a solid source at 1100 °C for 9 h in N_2 ambient gas is performed. After removal of BSG, the wafer are oxidized in wet O_2 ambient gas in 1100 °C for 40 min. The backside of the wafers are etched for $(t_w - t_{2\delta})$ min, where $t_{2\delta}$ is the time to etch the front surface of the p^+ cantilever by 2δ μm and t_w is the time to etch the whole thickness of the wafer at low doping concentration. Finally, both sides of the wafer are etched simultaneously by using EPW for $t_{2\delta}$ min so that the frontside of the cantilever is etched by 2δ μm. By means of the sequential etch processes, the backsides of cantilevers are exposed to etchant for the same time, t_w. In the case of the rotating beam structure, the frontside is protected from the etch with SiO_2. Figure 2(a) is the SEM photograph of the rotating beam structure and Fig. 2(b) shows a group of the cantilevers of which the frontsides are etched by 0.4 μm.

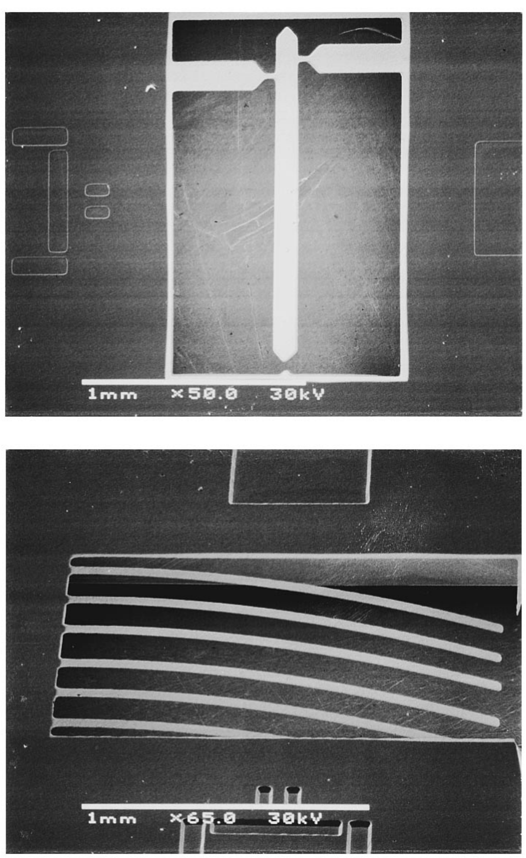

FIG. 2. The SEM photographs of the stress measurement structures: (a) the rotating beam structure; (b) a group of the cantilevers etched by 0.4 μm from the front surface.

The frontside etch depths of cantilevers after the final etch are measured with an α step. The SEM is used for the cross-sectional observation of p^+ silicon films before and after the final etch. The deflections of p^+ silicon cantilevers are measured by means of focusing a calibrated microscope. The vertical displacements of the ends of cantilevers were measured for various thicknesses. The coefficients of Eq. (3) except a_0 are determined using the measured data. By measuring the tip displacement of the rotating beam with the SEM photograph and comparing it with the simulation result, the average of the residual stress distribution is determined to be 50 MPa, and a_0 is calculated. Figure 3 illustrates the profile of the residual stress along the depth of the p^+ silicon film. The figure shows that the film is subjected to tensile residual stress except for the region near the front surface (about 0.1 μm deep), where the stress gradient is steep. The determination error in the relative profile of the residual stress is attributed to the measurement of the vertical deflection and the etch depths of the cantilevers. The deflection due to the gravity is about 1% of that due to the residual stress, which can be ignored. The total error in the determination of the residual stress is estimated to be less than 10% of the peak value.

This work was supported by Korea Science and Engineering Foundation (Grant No. 941-1000-004-1).

[1] K. E. Petersen, Proc. IEEE **70**, 420 (1982).
[2] X. Ding, W. H. Ko, and J. M. Mansour, *Proceedings of the International Conference on Solid-State Sensors and Actuators* (IEEE Electron Devices Society, Montreaux, Switzerland, June 1989), p. 866.

[3] L. B. Wilner, *Technical Digest, IEEE Solid-State Sensor and Actuator Workshop* (IEEE Electron Devices Society, Hilton Head, SC, June, 1992), p. 76.
[4] F. Maseeh and S. D. Senturia, in Ref. 2, p. 861.
[5] X. Ding and W. H. Ko, *Technical Digest, International Conference on Solid-State Sensors and Actuators* (IEEE Electron Devices Society, Montreaux, Switzerland, June 1991), p. 93.
[6] W. H. Chu and M. Mehregany, IEEE Trans. Electron Devices **ED-40**, 1245 (1993).
[7] S. H. Crandall, N. C. Dahl, and T. J. Lardner, *An Introduction to the Mechanics of Solids* (McGraw-Hill, New York, 1978), pp. 512–518.
[8] J. F. L. Goosen, B. P. Drieënhuizen, P. J. French, and R. F. Wolffenbuttel, *Technical Digest, International Conference on Solid-State Sensors and Actuators* (IEEE Electron Devices Society, Yokohama, Japan, 1993), p. 783.