'94 대한전기학회 추계학술대회 논문집(1994. 11. 18)

응력측정 구조를 이용한 p+ 박막의 응력분포 추정

°양 의 혁, 양 상 식, *박 응 준, *유 승 현
아주대학교 제어계측공학과　　*아주대학교 기계공학과

Estimation of the Stress Profile of p+ Silicon Films Using Stress Measurement Structures

°E. H. Yang, S. S. Yang, *E. J. Park and *S. H. Yoo
Dept. of Control and Instr. Eng. AJOU University
*Dept. of Mechanical Eng. AJOU University

Abstract - In this paper, a new technique for quantitative estimation of the stress profile along the depth of p+ silicon films is presented. The p+ silicon cantilevers with various beam thickness and a rotating beam supported by two cantilevers are used for estimating the stress profile of the films. The average of the residual stress distribution is estimated to be 50 MPa. Most of p+ silicon films are subjected to the tensile stress, except the region near the frontside.

I. Introduction

Recently, the measurement of residual stress distribution of thin films has been of interest in many areas of micromachining. The p+ silicon films have been widely used as elements of microsensors and microactuators. When they are used for mechanical devices, residual stress of the films degrade the performance significantly. The analyses of the residual stress have been performed by some researchers.[1~4] However, those studies are imperfect, that is, the results provide only either the average of the stress distribution or the qualitative estimation of the relative stress profile. It is needed to develope the quantitative method to estimate the stress profile along the depth of the films.

A new method of the quantitative estimation of the relative stress profile using p+ silicon cantilevers has been suggested previously.[5] For the estimation of the absolute profile of the stress, the average of the stress distribution must be determined. This paper presents the method to quantitatively estimate the absolute stress profile along the depth of p+ silicon films and the experimental results.

II. Analysis of Stress Profile

The residual stress, σ_x is assumed to be a polynomial function of y which is the coordinate perpendicular to the neutral surface of the cantilever.

$$\sigma_x = \sum_{i=0}^{n} a_i y^i \qquad (1)$$

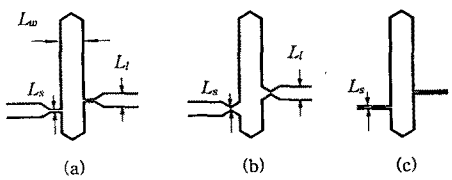
where a_i's are coefficients to be estimated.

1. Relative Stress Profile

There exists a relationship between the stress distribution and the deflection of the cantilever. So, the deflection can be expressed as a function of y, which includes a_i's except a_0. If the frontside of the p+ silicon cantilever is etched, the amount of the deflection is changed. The deflection of the end of the cantilever and its thickness are measured as the frontside of the cantilever is being etched away. Then, the coefficients of the polynomial in Eq. (1) except a_0 are calculated using the measured data.

2. Average Stress Profile

For the estimation of the coefficient of the polynomial, a_0, the average stress of the p+ silicon film is measured. Rotating beam structures which enable to determine the average of the stress of the film is designed, calculated and fabricated. The rotating beam supported by two cantilevers converts the lateral average stress to the rotating angle of the beam.[6] Fig. 1 shows three kinds of rotating beam structures. Using the rotating beam structure both the tensile stress and the compressive stress can be measured.



L_w = 500 μm, L_l = 100 μm, L_s = 20 μm

Fig. 1. The rotating beam structures.
(a) The Structure I (b) The Structure II
(c) The Structure III

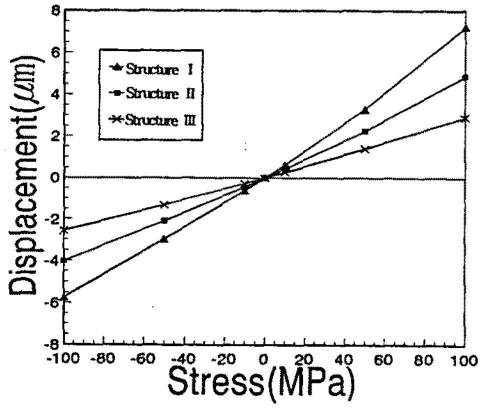


Fig. 2. The displacements of rotating beams vs. average stress.

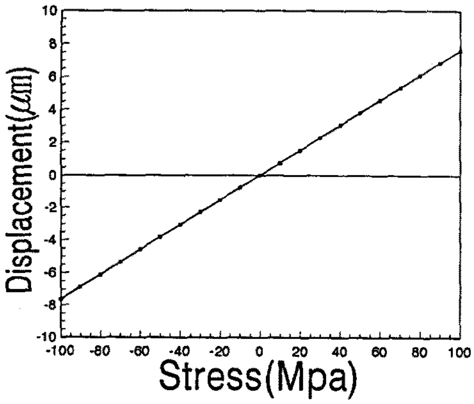


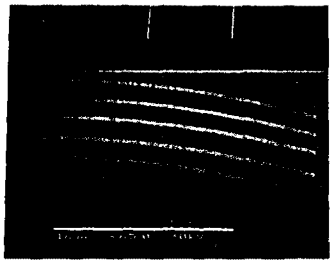
Fig. 3. The displacement of the rotating beam Structure I vs. average stress.

The numerical analysis on the displacement of the tip of the rotating beam structures is performed by using FEM package, ABAQUS. The Young's modulus E is 122 GPa[4] and Poisson's ratio is 0.25. The results of the numerical analysis for three Structures are shown in Fig. 2. It is noticed that the Structure I is adapt to the measurement structure. The result of the numerical calculation for Structure I with the structural parameters optimized as L_w = 100 ㎛, L_l = 100 ㎛, and L_s = 20 ㎛ is illustrated in Fig. 3.

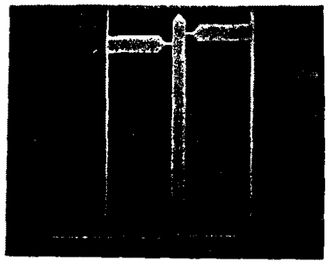
III. Fabrication of Test Structures

The etch rate of the silicon in EPW depends on the boron dopant concentration in the silicon. The time, t needed to etch the boron doped silicon of the proper depth, d is as follows.[5]

$$t=\frac{d}{R_i}[\,1 + (C_B/C_o)^a\,]^{(1/a)} \qquad (2)$$



(a)



(b)

Fig. 4. The SEM photograph of measurement structures. (a) The cantilever (b) The rotating beam

where C_o is the boron concentration when the etch rate is abruptly changed, and C_B is the boron concentration, R_i is the etch rate of pure silicon, and a is a constant determined from experiment. In this study, a is set to 1.2, and C_o, to 3×10^{19} cm^{-3}. TSUPREM Ⅳ simulation is performed to get the boron doping profile. Eq. (2) and the data obtained from the simulation are used to determine the etch time for the fabrication of $p+$ silicon cantilevers with different thickness.

For the fabrication of the stress measurement structures, n - type, 10 ~ 20 Ωcm, (100), 330 ± 10 ㎛ in thickness, double side polished silicon wafers are used. The boron predeposition from a solid source at 1100 ℃ for 9 hr in a gas of N_2 is performed. After predeposition 20 min of LTO process at 900 ℃ is performed to ease the removal of the BSG. Wafers are subsequently oxidized in wet O_2 ambient at 1100 ℃ for 40 min. The photolithography and the EPW etching process are performed for the fabrication of $p+$ silicon cantilevers. The frontside of the rotating beam structure is protected with SiO_2 not to be etched. The SEM photograph of the fabricated $p+$ silicon cantilevers and the rotating beam structure are shown in Fig. 4.

IV. Measurements and Results

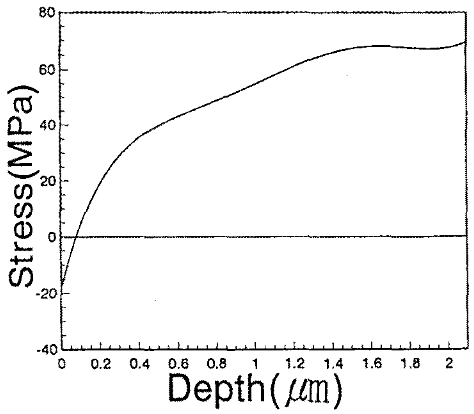


Fig. 5. The estimated stress profile along the depth of p^+ silicon films.

The etch depth of the frontside of cantilevers after EPW etch are measured by α-step. The SEM is used for the cross-sectional measurement of p^+ silicon films before the EPW etch and after EPW etch. The deflection of p^+ silicon cantilevers are measured by means of focusing a calibrated microscope. The measured vertical displacements of cantilevers for various film thickness are shown in Table 1. The plus sign of v_L means that the cantilevers are bent downward. By inspecting the SEM of the rotating beam and comparing it with the result of ABAQUS simulation, the average of the residual stress distribution is estimated to be 50 MPa. Fig. 5 illustrates the calculated stress profile along the depth of the p^+ silicon film. The figure shows that the film is subjected to tensile residual stress except the region near the surface(about 0.1 ㎛), where the stress gradient is steep.

TSUPREM Ⅳ simulation of the p^+ diffusion profile at very high concentration is not as accurate as that at low concentration. The inaccuracy of the simulation causes errors in estimating C_o and a, which generate the error in calculating the etch time. This error does not have a critical effect on the calculation of the stress profile. The etch depth and the thickness of the films are measured by the α-step and the SEM for the calculation of the stress profile.

TABLE Ⅰ. The vertical displacements for various film thickness.

samples	h_m(㎛)	δ_m(㎛)	v_L(㎛)
1	2.1	0	280
2	1.7	0.2	180
3	1.47	0.315	176
4	1.44	0.33	130
5	1.15	0.475	120
6	1.11	0.455	95
7	2.07	0.515	82
8	1.0	0.55	80
9	2.1	0	

The accuracy of the vertical displacement measurement is ± 2 ㎛. The estimation error for the relative stress profile is attributed to the vertical displacement, the etch time and the curve fitting. The estimation error of the average stress is about ± 4 %, which is caused by the measurement error of ± 0.2 ㎛ for the rotating beam structure.

Ⅴ. Conclusions

In this paper, a method to quantitatively estimate the absolute stress profile along the depth of p^+ silicon films. The experimental results for the films fabricated by a special process shows that most of the p^+ silicon film is subjected to the tensile stress, except the region near the frontside, where the stress gradient is steep. This method of a quantitative stress profile estimation is expected to be useful to analyze the relationship between the residual stress and process parameters such as time and temperature.

References

[1] F. Maseeh and S. D. Senturia, "Plastic Deformation of Highly Doped Silicon," Transducers '89 Digest, Vol. 2, Montreux, Switzerland, pp. 861-865, June 1989.

[2] X. Ding and W. H. Ko, "Buckling Behavior of Boron - Doped p^+ Silicon Diaphragms, Transducers '91 Digest, Montreux, Switzerland, pp. 93-96, June 1991.

[3] L. B. Wilner, "Strain and Strain Relief in Highly Doped Silicon," IEEE Solid-State Sensor and Actuator Workshop, Hilton Head Island, U. S. A., pp. 76-77, June 1992.

[4] W. H. Chu and M. Mehregany, "A Study of Residual Stress Distribution Through the Thickness of p^+ Silicon Films," IEEE Trans. Electron Devices, Vol. ED-40, pp. 1245-1250, July 1993.

[5] 양 의 혁, 양 상 식, 지 영 훈, "붕소가 도핑된 실리콘 박막의 잔류응력으로 인한 변형에 관한 실험적 연구," 대한 전기학회 하계학술대회 논문집 A권, pp. 72-75, 1994.

[6] J. F. L. Goosen, B. P. Drieënhuizen, P. J. French, and R. F. Wolffenbuttel, "Stress Measurement Structure for Micromachined Sensors," Transducers '93, Yokohama, Japan, pp. 783-786, June 1993.

[7] H. Seidel, "The Mechanism of Anisotropic Silicon Etching and Its Relevance for Micromachining," Transducers '87 Digest, Tokyo, Japan, pp. 120-125, June 1987.