Experimental mechanical stress characterization of MEMS by using of confocal laser scanning microscope with a Raman spectroscopy interface

M. Yamaguchi*, S. Ueno*, I. Miura** and W. Erikawa***

* Technical Research Institute Japan Society for the promotion of machine industry,
1- 1- 12, Hachiman- cho, Higashi- Kurume , Tokyo, JAPNA, yamaguchi@tri.jspmi.or.jp
** Renishaw kk, Tokyo, JAPAN ichiro.miura@renishaw.com
*** Lasertec Corporation, Yokohama, JAPAN, w_erikawa@Lasertec.co.jp

ABSTRACT

In this research, confocal laser scanning microscopes (CLS) interface for micro-Raman spectroscopy system has been developed. The potential of this system for characterization MEMS device is demonstrated by measuring Si membrane of a pressure sensor. Mechanical stress is obtained by a shift of Raman peak, and profile of deflection is measured by CLS at same time. The relationship mechanical stress and defection in a small scale MEMS is clearly shown.

Keywords: Raman spectroscopy, confocal laser scanning microscopy, MEMS, reliability

1 INTRODUCTION

The use of micro-electro-mechanical system (MEMS) is becoming popular in many application. To predict fracture, buckling of structure, etc., knowledge of the mechanical stress properties within MEMS devices is very important, because stress increase may cause dislocations, film cracking, and degradation of gate oxide qualty. Analytical or numerical models are often used. The experimental characterization of the mechanical stress properties, either stand alone, or as a verifying tool for analytical/numerical approach, is equally important, but there are not many techniques available that are capable of measuring the stress locally on surface as small as that of a typical MEMS device.

Several methods have been used to characterize stress and strain in semiconductor devices. The most important are X-ray diffraction, transmission electron microscopy (TEM), and micro-Raman spectroscopy. All of these methods have advantage and disadvantages. X-ray diffraction techniques is very sensitive but the technique is cumbersome and lacks high spatial resolution. TEM methods reach spatial resolutions of a few nanometers. But the main disadvantages here are the destructive sample preparation, and the measurement time is often in the range of weeks or even months.

Raman spectroscopy allows measurement of stress in crystalline material. It is well known that micro-Raman spectroscopy can be used to characterize stresses with micron spatial resolution. Several researcher have used micro-Raman spectroscopy to measure the mechanical stress in MEMS structure.[1-5]

On the other hand, the shape measurements are also important in MEMS characterization. Measurement of curvature and deflection, for example, yield average strain. Confocal Laser scanning Microscopes (CLM) are very attractive for three-dimensional imaging of microstructures because of its high lateral and axial resolution and its optical sectioning capability. So, for quality preservation in MEMS structure, CLM is best suited. By combining with a micro-Raman spectroscope, not only shape measurement but also mechanical stress analysis in the same observation area on same time can be performed by CLM. In this study, we demonstrate mechanical stress and shape profile measurements using CLM interface for Raman spectroscopy and that this system is reasonable and helpful to the MEMS designer.

We have shown with an example that CLSM with a micro-Raman spectroscopy interface system has much to offer for investigation in MEMS.

2 EXPERIMENTAL

The principle optical layout of CLM with a micro-Raman spectroscopy interface system is shown in Fig. 1. Light source is GaN diode (408 nm) laser for CLM, and spatial resolution is 0.14 μ m The micro-Raman system consists of optically pumped semiconductor laser (Coherent, sapphire, 488 nm), edge filters to remove the scattered excitation light, a single monochromator, and a thermoelectrically cooled charge-coupled device detector. The experiment was carried out in the backscattering configuration. Focal length of spectrometer is 0.25 m and a 1800 l/mm grating was used, so nominal resolution is 0.2 cm^{-1}. The laser power was limited to about 0.1 mW to minimize sample heating. The 50 times magnifying objective lens was used and the focused laser spot size was approximately 1 μm in a diameter. The sample can be moved under the microscope with a computer controlled XY-stage. This allows us to monitor the stress at different positions on the surface.

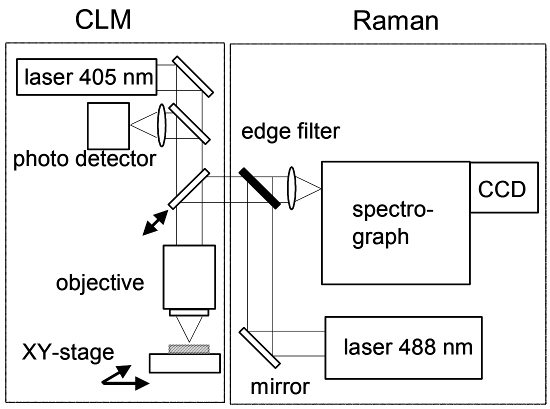

Figure 1: Schematic diagram of the CLM with micro-Raman spectroscopy interface.

Figure 2 shows a typical Raman spectrum of crystaline silicon. When the sample is unstressed (no applied strain), a reference spectrum is measured. When the device is placed in a stressed state, the Raman spectrum displays a shift in a frequency with respect to the reference spectrum. This frequency shift is a result of the induced stress. Ganesan et al. was one of the first to show the effects of strain on diamond structured crystals.[6] In the absence of strain, the first order Stokes Raman spectrum of diamond-type materials exhibits a single peak which corresponds to the q = 0 triple degenerate optical phonons. The Raman wave-number of the (stress free) silicon is about 521 cm^{-1}. In order to determine this frequency, the peak is fitted with a Lorenz function.

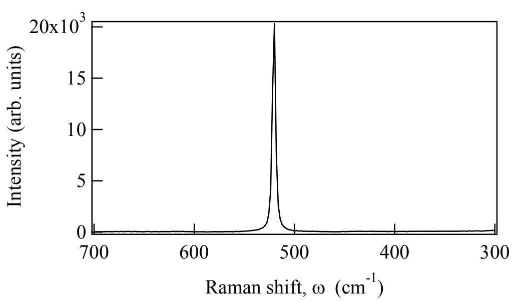

Figure 2: Raman spectrum of crystalline silicon.

To show the potential of this system for the characterization of MEMS device, a crystalline silicon pressure sensor with membranes structure (MKT TAISEI Co. LTD. MS30) was measured. Figure 3 shows a photograph of the pressure sensor. The membrane area and thickness were about 2 × 2 mm and 20 μm, respectively. A measurements were performed on the top side of membrane under various pressure, as indicated in Fig. 3. Si membrane structure is bended by pressure from bottom side. Measurements were performed on the top side of the membrane.

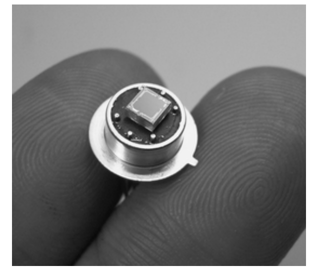

Figure 2. Photograph of a pressure sensor.

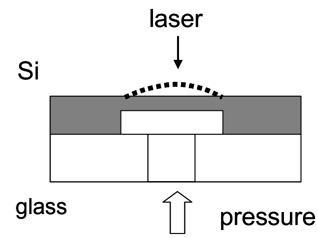

Figure 3: Picture of a pressure sensor. Si membrane structure is bended by pressure from bottom side. Measurements were performed on the top side of the membrane.

3 RESULT AND DISCUSSION

CLM image of pressure sensor are given in Fig. 4. The profile of deflected membrane is shown in Fig. 5.

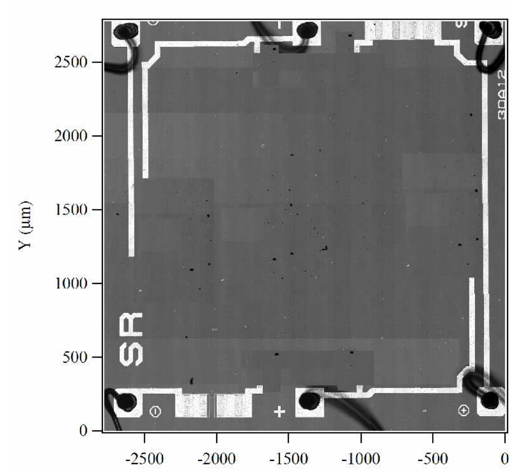

Figure 4: CLM image of pressure sensor

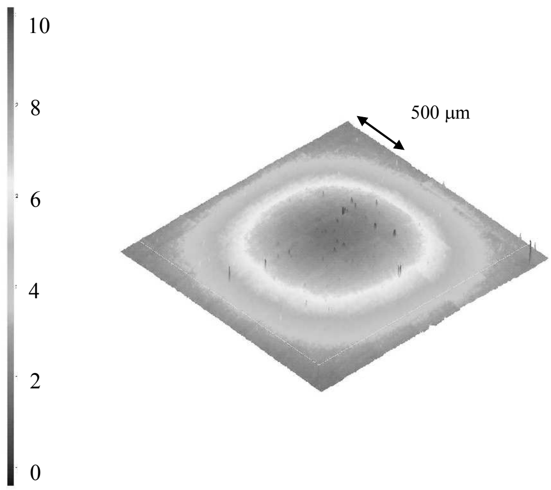

Figure 5: Three dimensional image of deflection.

The measurement results of deflection and Raman frequency shift on center line of membrane is given in fig. 6. Fig. 6 (A) shows profile of deflection measured by CLSM as shown in Fig 5. Figure. 6 (B) shows the change of Raman frequency from zero stress value, Δω, as a function of the position on the center line. A positive shift (Δω> 0) indicates compressive stress, while a negative shift (Δω>0) indicates tensile stress. Tensile stress in the center of the membrane and compressive stress near the edge are clearly found. The relation between stress and Raman frequency is in general rather complex. Raman frequency depends on all strain tensor coefficients and on material constants. However, in some case, the relation becomes simply liner relation. For example, for biaxial stress ($\sigma_{xx} + \sigma_{yy}$) in the Si(100) plane, which can often be assumed to be the case in MEMS, their relation become [7]

$$\sigma_{xx} + \sigma_{yy} \approx -434 \times \Delta\omega \quad [\mathrm{cm}^{-1}]. \ (1) .$$

According to eqn (1), the maximum compressive stress at the edge and tensile stress at the center of the membrane are 120 MPa and 110 MPa, respectively.

Figure 7 shows deflection profiles with various pressure. The deflection of membrane increase with an increasing pressure.

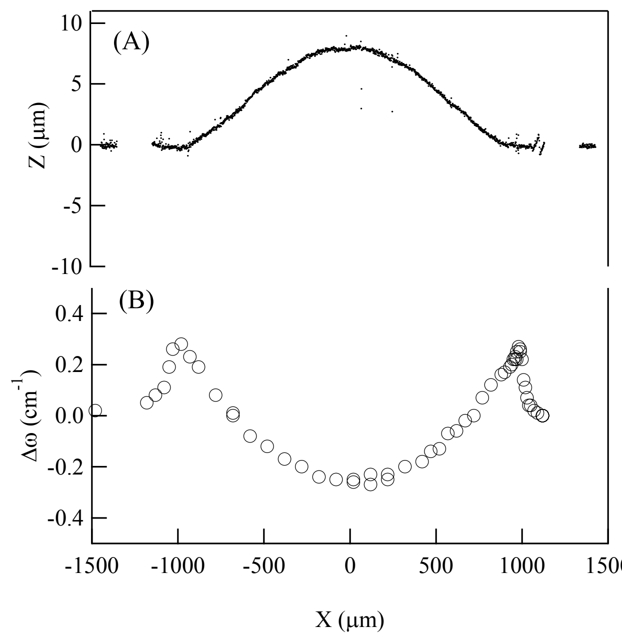

Figure 6: (A): Deflection profile measured by CLSM. (B) : Shift of Raman frequency from zero stress value, Δω, as a function of the position on the center line.

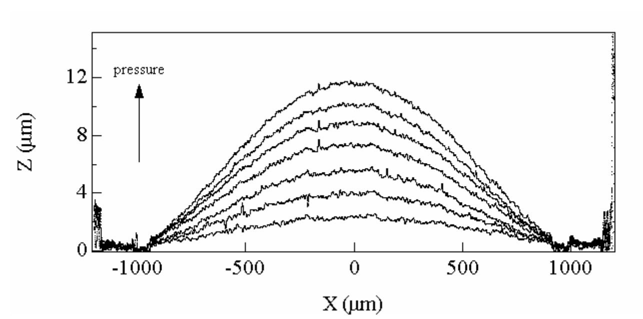

Figure 7: Deflection profile at center line with various pressure.

Figure 8 is enlarged defection profile and Δω around the edge of membrane on center line (pressure in (a) > pressure in (b)). The deflection in (a) is larger than that in (b). It is clearly showed that the deflection and Δω corresponding to pressure increase with an increasing pressure.

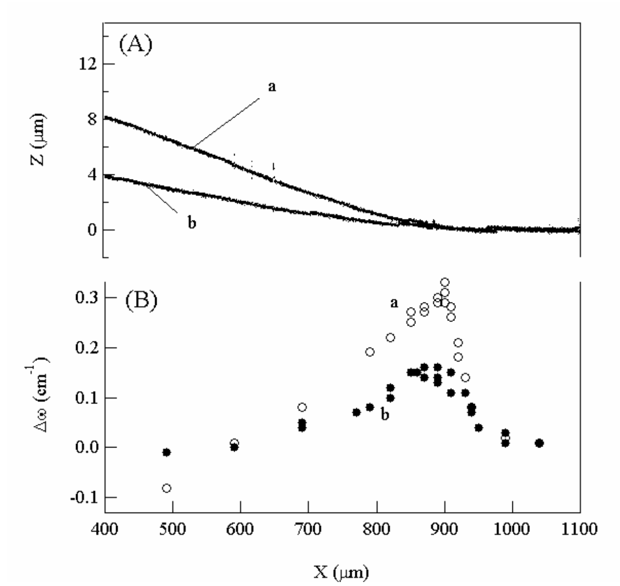

Figure 8: Enlarged defection profile and Δω around the edge of membrane under different pressure (pressure in (a) > pressure in (b))

Figure.9 shows a relation between maximum of deflection in the center of membrane, Z_{max}, and Δω at edge and center. The Δω corresponding to stress increase linearly with an increasing $Z_{max.}$ The present result indicate that the relation between stress and defection can be understood by small deflection theory within the pressure in our experiment,

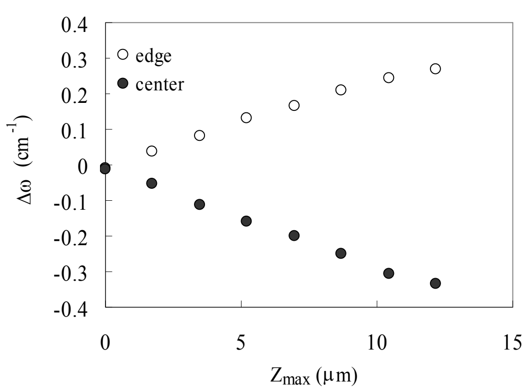

Figure 9: Relationship between tensile stress at edge and largest deflection, Z_{max}, at center of membrane.

4 CONCLUSIONS

The relationship mechanical stress and defection in a small scale MEMS is clearly demonstrated. We can obtain both stress and deflection at same time. It has been shown that CLM with a Raman spectroscopy interface system has much to offer for investigation of mechanical stress in silicon MEMS device.

ACKNOWLDGMENT

The authors are grateful to Mr. Isamu Shimizu of for providing the samples used in this work and helpful discussion.

This research was supported by the funding from the Keirin Association of JAPAN.

REFERENCES

[1] L. Startman, J. Busbee, J. Reber, J.Lott, W. Cowan and N. Vandelli, "Stress measurement in MEMS devices" Technical Proceedings of the 4th Intl. Conf. on Modeling and Simulation of Microsystems, Hilton Head, SC 398-401, 2001

[2] L. A. Starman Jr., J. A. Lott, M. S. Amer, W. D. Cowan and J. D. Busbee, "Stress reduction characterization using Raman spectroscopy measurements on MEMS devices", International Conference on Optical MEMS and their Applications, Busena Terrace, Okinawa, Japan, 24-28 Sept 2001

[3] L. A. Starman Jr., J.A. Lott, M. S. Amer, W. D. Cowna, J. D. Busbee, "Stress characterization of MEMS micro bridges by micro-Raman spectroscopy", Sensors and Actuators A 104 (2003) 107-116

[4] V. T. Srikar, A. K. Swan, M. Selim Unlu, B. B. Goldberg, and S. M. Spearing "Micro-Raman measurement of bending stresses in micromachined silicon flexures," IEEE Journal of Microelectromechanical systems, Vol. 12, No. 6, December 2003, pp. 779-787

[5] W. M. Spengen, I. D. Wolf, R. Knechtel, "Experimental one- and two-dimensional mechanical stress characterization of silicon microsystem using micro-Raman spectroscopy", Proceeding of SPIE vol.4175, (2000) p.132

[6] S. Ganesan, A. Maradudin, J. Oitmaa, "A lattice theory of morphic effects in crystals of the diamond structure", Ann. Phys. 56 (1970) 556-594

[7] I. De Wolf, "Stress Measurements in Si Microelectronics Devices using Raman Spectroscopy", J. Raman Spectrosc., 30, 877-883 (1999)