Deformation analysis in microstructures and micro-devices

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Abstract

The mechanical behaviors of microstructures and micro-devices have drawn the attention from researchers on materials and mechanics in recent years. To understand the rule of these behaviors, the deformation measurement techniques with micro/nanometer sensitivity and spatial resolution are required. In this paper, a micro-marker identification method is developed to measure microstructure deformation. The micro-markers were directly produced on the top surface of microstructures by taking advantage of ion milling of focused ion beam (FIB) system. Based on the analysis of marker images captured by electronic microscope with specific correlation software, the deformation information in microstructures can be easily obtained. The principle of the technique is introduced in detail in the paper. An example experiment was executed to measure the displacement and strain distribution in a MEMS device. Obtained results show that the technique can be well applied to the deformation measurement of the micro/nano-electro-mechanical-systems (MEMS/NEMS).

1. Introduction

Rapid development of microfabrication technologies has produced a wide variety of MEMS/NEMS. Those microstructures may have the in-plane or out-of plane movement/deformation as related to the displacement component parallel or perpendicular to the substrate of the device, respectively. A quantitative analysis of the structure deformation is very important for design and functional control of the microsystems. Increasing attention has been paid recently to deformation behaviors of microfabricated structures in some local areas such as near bond anchors or bending joints, where the strain localization and stress concentration may affect the mechanical–electronic performance of the devices or even cause fracture failure of the components [1]. Thus it is a big challenge to obtain the in-plane deformation distributions within a region of a few microns.

A variety of test structures have been designed for strain or displacement measurement. Sharpe et al. [2] measured strain in poly-silicon films with the interferometric strain/displacement gage. The relative displacement change generated by strain can be detected from the movement of reflective fringes. Guckel and co-workers have utilized beam-buckling method[3] for characterizing compressive and tensile strain, respectively. Li [4] proposed a new method using smart material to measure permanent deformations. To measure a relatively large residual tensile strain in polynimide films, an optical microscope inspection of released-beam deformation was shown to be useful [5].

Meanwhile, many kinds of strain measurement devices have been proposed. Pan and Hsu [6] fabricated a strain sensor comprising of a pair of cantilever beams with different lengths connected by a short tip. A bent-beam structure...
has also been developed for strain measurements [7]. Lin et al. designed a passive micro-strain gauge with a mechanical amplifier [8]. A very fine resolution of \(10^{-5}\) strain readouts can be achieved for a micro-strain gauge with a 500 \(\mu\)m long indicator beam. Tjhung and Li proposed the interferometric strain/slope rosette method applied to nanometer-scale measurement [9].

Recently, focused ion beam (FIB) instruments are becoming prevalent for specimen preparation and inspection in microelectronics and MEMS/NEMS fabrication. This is mainly because FIB system permits microscopic inspection of the sample under consideration before, during, or after the ion-milling process via scanning ion microscopy (SIM) and scanning electron microscopy (SEM). The direct write capability of FIB milling allows nanometer-scale fabrication of specimen grids on the specific region without the requirement of an etch mask. On the basis of the capability of FIB milling, a FIB moiré method was proposed by Xie and Li [10,11]. In their works, the specimen grating was directly fabricated on the MEMS structure surface. A moiré pattern will be shown under specific SIM magnification due to the interference between the specimen grating and the beam raster scan. The FIB moiré method can be used to measure full field in-plane displacement of MEMS/NEMS with high sensitivity. In the measurement of the FIB moiré method, the model gratings must locate in a large area on the specimen surface. According to the available techniques with the FIB milling, it is very difficult to form a grating with a uniform pitch by repeating fabrication and joining small areas grating in a large area, while the FIB milling can be conveniently utilized to fabricate the deformation carrier for the marker or speckle pattern method.

The direct write capability of FIB milling also allows nanometer-scale fabrication of marker or speckle on the specific region without the requirement of an etch mask. In this paper, a micron-marker identification method using FIB and image correlation method is proposed to measure in-plane deformation of a micro-cantilever beam end of a MEMS device. Based on the advantages of the FIB system in nano-machining, sub-micron-markers were directly etched on surfaces of MEMS device.

2. Experimental methods

2.1. Sample preparation

A micro-device used in this investigation is shown in Fig. 1. The micro-device fabricated by a deep reactive ion etching (DRIE) technique. The micro-device consists of a mass plate and two groups of comb electrodes aligned on both sides, suspended by a cantilever beam bonded to substrate by anchors. The beam’s width, height and length are 10, 70 and 110 \(\mu\)m, respectively. In this work, we use the micro-device as an actuator by applying a voltage to the finger combs to drive the mass-plate into a rigid in-plane translation and rotation, which in turn generates mechanical deformation in the suspended beam.

There is the strain and stress concentration area near the beam end, in which the beam is easy to be fractured [12,13]. In order to well investigate the micro deformation in this local region, a through semicircular notch near the end of the beam with a depth of 5 \(\mu\)m was fabricated during the micro-device fabrication.

2.2. Micro-marker fabrication

Nanomachining was carried out to fabricate micro-makers on the micro-cantilever beam using an FIB system (the type is FEI DB235). The FIB system uses a scanning Gallium (Ga) ion beam for milling and imaging with a spot size ranging from 8 to 500 nm. During milling, an optimal ion beam current varies from 100 to 600 pA and optimal ion column high voltage varies from 10 to 30 kV. In this paper, well-resolved micro-marker arrays were obtained for a beam current of 300 pA with the nominal spot size of 35 nm. The schematic diagram of micro-marker fabrication pattern selected in this experiment is shown in Fig. 2. The line width, length and depth of fabricated marker are 100, 500 and 100 nm, respectively. The micro-marker array is realized by repeating this pattern across the end of the cantilever. According to the reports [14], the experimental efficiency can be improved by using the markers with different shape. So the irregular micro-marker array is selected in this paper.

Fig. 3 is the FIB microscope image of micro-markers array fabricated on the cantilever beam end.

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**Fig. 1.** MEMS device.

**Fig. 2.** Schematic diagram of a fabricated micro-marker pattern.

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**Fig. 3.** FIB microscope image of micro-markers array fabricated on the cantilever beam end.
2.3. Micro-marker identification method

The principle of the micro-marker identification method is similar to that of the digital image correlation (DIC) method [15]. As an image correlation technique, the marker identification method uses only the surface images where the micro-marker points involved may change their positions during movement/deformation to form varied displacements. The marker image correlation processing searches the displaced marker points in a pair of these pictures by matching marker spots between them [16]. To obtain the in-plane displacement components \( u \) and \( v \) in the \( x \) - and \( y \) -directions for a pair of such images, a pixel subset with \( m \times n \) pixels is used as a searching subregion, in which a micro-marker is selected as a center. To eliminate the influence of image background, a normalized cross-correlation coefficient \( C(u,v) \) of the grey intensity is commonly used to define the correlation degree as

\[
C(u',v') = \frac{\sum_{i=1}^{m} \sum_{j=1}^{n} [f(x_i,y_j) - \bar{f}][g(x'_i,y'_j) - \bar{g}]}{\sqrt{\sum_{i=1}^{m} \sum_{j=1}^{n} [f(x_i,y_j) - \bar{f}]^2} \sqrt{\sum_{i=1}^{m} \sum_{j=1}^{n} [g(x'_i,y'_j) - \bar{g}]^2}}
\]

where \( f(x_i,y_j) \) is the grey level at point \( F(x_i,y_j) \) in one of the images serving as the reference frame and \( g(x'_i,y'_j) \) is that at point \( G(x'_i,y'_j) \) in another image as the deformed frame, and \( \bar{f} \) and \( \bar{g} \) are the mean grey scale values of the pixels involved in the subsets, respectively, and the searching parameters \( u' \) and \( v' \) are the components of the vector linking the subset centers. The correlation coefficient \( C(u,v) \) is computed against the parameters \( u' \) and \( v' \) and the matching spots are obtained when the correlation coefficient \( C(u,v) \) reaches the maximum, then \( u' = u \equiv x'_i - x_i \), and \( v' = v \equiv y'_i - y_i \), respectively. The displacement resolution of the micro-marker identification method can be extended to 0.05 pixels by interpolating the correlation map to fractional locations of the pixels. Here the linear interpolation, the polynomial spline approximation and other interpolations may be utilized. A detailed analysis of the systematic errors due to different interpolations was made recently by Schrier et al. [17].

3. Result and discussion

The SEM type used in this experiment is FEI sir-ion400NC with a fine mechanical loading system, which is driven by a small servo electromotor system under the vacuum environment within the SEM. Two fine electrical wires are connected with the servo electromotor system and the electrical power outside the SEM. In this experiment, in order to make the MEMS specimen work, both the servo electromotor system and mechanical loading system are replaced by a plugboard. The cathode and the anode architrave of MEMS specimen tested are inset in the plugboard, which is also connected to the electrical power outside of the SEM through the fine electrical wires. In this way, the MEMS specimen can be driven by DC power outside the SEM. For each step of the voltages applied on the finger combs, a region containing the structure surface of a beam-end with micro-markers was scanned by the scanning electron microscope (SEM). These SEM images of markers are then analyzed by the micro-marker identification process to obtain the deformation fields with sub-micro resolution.

The accuracy of deformation measurement of this technique depends on both the SEM scanning resolution and the micro-marker identification processing sensitivity. The geometric size on the material surface corresponding to a pixel of the SEM image can be evaluated by the scanning range divided by the sampling numbers. Interpolation algorithms can be used in the micro-marker identification processing to obtain the displacement components smaller than 0.1 pixel in the images.

Fig. 4a and b give the SEM images represented by grey scales, at the actuating voltages of \( U_0 = 0 \) V and \( U = 50 \) V, respectively. These grey scale images are directly processed by the micro-marker identification computation to search the in-plane displacements in the beam-end region. We employed 512 pixel \( \times \) 512 pixel sampling points to cover a scan area of 20 \( \mu \)m \( \times \) 20 \( \mu \)m. In this case, each pixel of the SEM image corresponds to a size of about 39.06 nm on the structure surface.

The deformation field of the beam-end caused by the actuation of the voltage change \( \Delta U = 50 \) V are measured from the region ABCD of Fig. 4 and shown in Fig. 5. Fig. 5a and b are the contours of the vertical displacement \( v \) and the horizontal displacement component \( u \), respectively. The vertical displacement increases from left to right as the position away from the fixing anchor, indicating that the beam structure is loaded by a bending moment. At the right of the notch extension line, the maximum vertical displacement is up to 445 nm. While at the left of the notch extension line, near the anchor, the vertical displacement is uniform and its average value is only 261 nm.

The deformation distribution of the beam-end depends not only on the bonding condition of the anchors but also
the structure form of the notch, beam-end and whole beam. At the right of the notch extension line, the horizontal displacement has parallel contours with the sign changing from positive to negative along the $y$-axis, and with an area of null displacement. The deviation of this neutral layer from the beam’s centre-line is mainly due to the effect of the notch structure. Near the tip area of the notch, variation of the gradient of the horizontal displacement field is the maximum.

The strain component $e_x$ is measured by analyzing the derivative of the horizontal displacement field along the $x$-axis and shown in Fig. 6. Subjected to the bending moment on the microstructure, the extensive strain concentration is very significant near the top area of the notch, where MEMS device is more easily to be broken.

4. Conclusion

The in-plane deformation and strain fields on the silicon micromachined structure surface have been evaluated by the micro-markers identification method as the micro-devices are actuated by electrostatic forces. The SEM grey scale images of micro-markers provide better unimodality of correlation coefficients hill, which ensures an accurate determination of the in-plane displacement except in some local areas where either the grey level variations or the displacements are very small.

For the microfabricated structure suspended and driven by the finger combs, the deformation fields obtained by the combination of SEM scanning and micro-markers identification processing provide useful information to reveal the real displacement boundary conditions, the strain/stress components in the microstructures.

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