European Journal of Mechanics A/Solids 49 (2015) 510–517

Contents lists available at ScienceDirect

European Journal of Mechanics A/Solids

journal homepage: www.elsevier.com/locate/ejmsol

Anisotropic elastic properties of chiral sculptured thin films at micro-scale evaluated by resonance frequency spectra

H. Fang [a, b, *], K. Matsumoto [a], T. Sumigawa [a], T. Kitamura [a]

[a] Department of Mechanical Engineering and Science, Kyoto University, Yoshidahommachi, Sakyo-ku, Kyoto, 606-8501, Japan
[b] Institute of System Engineering, China Academy of Engineering Physics, Mianyang, 621900, China

ARTICLE INFO

Article history:
Received 19 May 2013
Accepted 26 September 2014
Available online 5 October 2014

Keywords:
Mechanical anisotropy
Vibration testing
Micro-scale

ABSTRACT

Chiral sculptured thin films (STFs) are nano-engineered to meet the requirements of a variety of applications such as micro filters, sensors, and waveguides due to their unique frequency characteristics which cannot be achieved by conventional solid materials. For the design, it is necessary to understand the elastic properties of STFs. To facilitate this, we developed an advanced micro-scale vibration testing process. In the testing, specially designed micro-specimens with surface areas of tens by tens of microns are excited using a piezoelectric (PZT) actuator and the resonance frequencies are detected by a laser device in the vertical or lateral directions successfully. The anisotropy elastic modulus of STFs composed of helical nano-springs are identified on the basis of vibration testing. The thin film shows strong characteristic anisotropy that the solid one hardly can attain. The micro-scale testing technique can be extended to other materials and microstructures.

1. Introduction

Chiral sculptured thin films (STFs) are compose of numerous parallel nano-scale spring-units that have helicoid, zigzag, pillar, and other shapes (Suzuki and Taga, 2001). Accordingly, for engineering purposes, a micro-size STF is a unidirectional and anisotropic module that can be used in vibration, wave, and acoustic micro-devices at low (less than 1 MHz) and high (more than 100 MHz) frequencies, which depend on material, geometric characteristics of unit element and structural features of the entire film. A multi-section STF can be conceived of as a micro dynamic component that can be integrated with electronic circuitry on a microchip (Lakhtakia, 2002a, 2002b). Dynamic oblique deposition (DOD), in which the deposition angle and the in-plane direction of a substrate are changed during deposition, enables us to fabricate STFs. This method utilizes the atomic self-shadowing effect during physical vapor deposition due to deposition with a highly oblique angle. Spring shape can be precisely controlled by adjusting the incidence angle of vapor flux and substrate rotation (Robbie et al., 1995; Robbie and Brett, 1997).

Determining the anisotropic elastic properties of micro-size STFs through dynamic methods is challenging and remains a subject of scientific and technological interest in the micro-scale components, i.e., from a scientific point of view, they allow extension of dynamic techniques and models to other materials/microstructures, while the derived properties are also important for device designs, particularly to address compliance issues. The development of dynamic techniques to determine the anisotropic elastic properties enables an understanding of the role of microstructural features and linkages to processing conditions (Tan et al., 2010). Some dynamic studies use fixed-free or free–free resonance bar techniques, and composite oscillator techniques (Gregori et al., 2007). These methodologies determine the weighted value of elastic moduli in a given direction or set of directions. However, singular or averaged values for elastic moduli are inadequate for describing the direction-dependent behavior of anisotropic systems. For measuring elastic constants of anisotropic thin films, researchers have developed a number of methods based on the resonance ultrasound spectroscopy (RUS) technique (Nakamura et al., 2004), which can determine independent elastic constants from the mechanical resonance frequencies. However, this technique is limited by the geometric characteristics of the specimens, which make it hard to detect the oscillation amplitude from micro-specimens with surfaces measuring tens by tens of micro meters. Little vibration testing has been done on the small anisotropic components due to the difficulties associated with

* Corresponding author. Department of Mechanical Engineering and Science, Kyoto University, Yoshidahommachi, Sakyo-ku, Kyoto, 606-8501, Japan. Tel.: +81 757535192; fax: +81 757535256.
E-mail address: fanghui@caep.ac.cn (H. Fang).

http://dx.doi.org/10.1016/j.euromechsol.2014.09.011
0997-7538/

exciting the specimen and detecting oscillation at the micron-scale. Nevertheless, STFs would be used as micro-components, which means that specimens for estimating elastic properties should be micro-ones.

In this paper, we report on the development of advanced Frequency-Sweep Vibration technique based on Laser Doppler, which can excite and measure the vibration of STFs comprised of helical nano-springs with thickness 1.0 μm. In our study, we prepared two specimens with surface areas of 30 × 30 μm^2 and 15 × 15 μm^2, respectively. Additional mass would be put in a certain place of the specimens, which would change the resonance frequency of specimens and be a significant marker for laser focusing. With this method, we detect the resonance frequency at the vertical and lateral directions, which make it possible to successfully measure the elastic constants of the STFs.

2. STFs composed of helical nano-springs

Fig. 1 shows a field emission scanning electron microscope (FE-SEM) (Hitachi, S-5500) image of a STF that consists of tantalum oxide (Ta_2O_5) helical nano-springs. The nano-springs are grown on the Si substrate via the DOD technique using electron beam (EB) evaporation. The incidence angle, defined as that between the incident flux and the normal to the substrate, is set at 87°, and the substrate is rotated during the deposition so that the number of turns n is four. Nano-springs, which have an almost identical shape within the film, are isolated from each other as shown in Fig. 1. The diameter of the spring wire d gradually increases from bottom to top, which is a characteristic feature often observed in nano-spring manufactured via DOD. The average size of nano-springs is listed in Table 1. Here, N_s is the number of nano-springs contained in a unit area, which is evaluated by removing the cap layer and observing from the top. The springs uniformly distributes. Here, h_s, r, and d represent the scale of spring as illustrated in Table 1. The average values are given in the table based on SEM pictures of several tens of springs. During the mechanical analysis, these values are used because the target of this paper is to evaluate the average elastic modulus of the film. A Ta_2O_5 cap layer with a thickness of $h_c = 1030$ nm is deposited by EB evaporation after the nano-springs are grown. Thus, the STF of nano-springs is sandwiched between the Ta_2O_5 cap and Si base layers. Because of the in-plane symmetry of the film, the *stiffness matrix* of the film is in the form (Lakhtakia, 2000)

$$\boldsymbol{C} = \begin{bmatrix} c_{xxxx} & c_{xxyy} & c_{xxzz} & 0 & 0 & 0 \\ c_{yyxx} & c_{yyyy} & c_{yyzz} & 0 & 0 & 0 \\ c_{zzxx} & c_{zzyy} & c_{zzzz} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{xyxy} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{yzyz} & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{xzxz} \end{bmatrix}, \quad \text{where } \boldsymbol{\sigma} = \boldsymbol{C\varepsilon} \qquad (1)$$

Here, $\boldsymbol{\sigma}$ and $\boldsymbol{\varepsilon}$ are the stress and strain, respectively, and $\boldsymbol{C}$ is the *stiffness matrix*. A key structural feature is in-plane discreteness. *As shown in Fig. 1a, the space between adjacent springs has a width of ~10^{-7}* m. In the vibration testing, the displacement amplitude of the weight on the top of specimen is very small (<10^{-10} *m in bending test as shown in Fig. 11)*. So, there is almost no contact between two

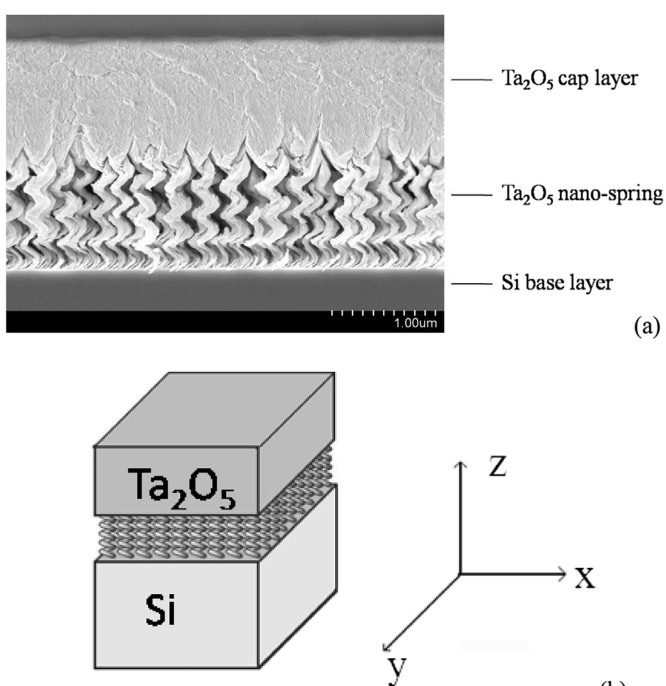

Fig. 1. STFs that consist of Ta_2O_5 helical nano-springs formed by dynamic oblique deposition technique: (a) SEM image, and (b) schematic illustration of the thin film with the associated co-ordinate system.

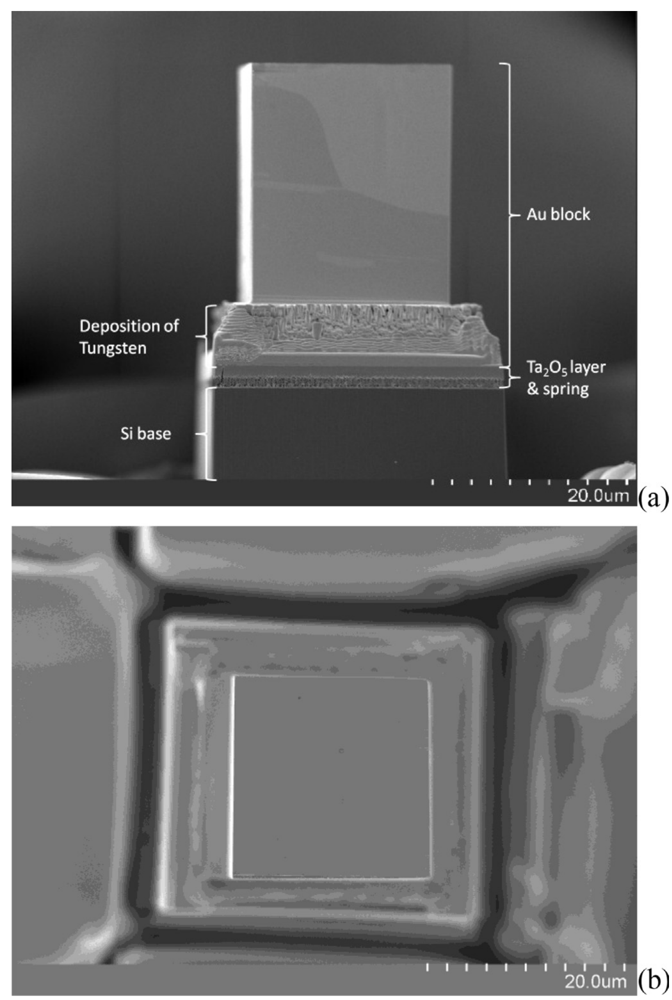

Fig. 2. Specimen A for evaluating the elastic properties of the STFs, Specimen configuration; specimen is a brick consisting of a Au block (top view surface measuring 20 × 20 μm^2), a Ta_2O_5cap layer (top view surface measuring 30 × 30 μm^2), a nano-springs layer, and a Si base layer; brick is fabricated from multilayered thin films by FIB. (a) side view, (b) top view.