Thin Solid Films 565 (2014) 267–270

Contents lists available at ScienceDirect

Thin Solid Films

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

Mechanical properties of atomic force microscopy probes with deposited thin films

L. Sirghi *, Daniela Ciumac, V. Tiron

Department of Physics, Alexandru Ioan Cuza University, Blvd. Carol I, 11, 700506 Iasi, Romania

ARTICLE INFO

Article history:
Received 13 May 2014
Accepted 11 June 2014
Available online 19 June 2014

Keywords:
Atomic force microscopy probes
Diamond like carbon thin film
Fluorocarbon thin film
High power impulse magnetron sputtering deposition
Film elasticity modulus
Film mass density

ABSTRACT

Deposition of thin films on atomic force microscopy (AFM) probes is a common technique that is used to either improve the light reflectance of the back side of the probe cantilevers or to modify the surface properties of the probe tips. However, this technique also affects the force constant and resonance frequency of the AFM cantilevers. The present work investigates theoretically this effect in the approximation of very thin films. The cantilever force constant changes due to the contribution of bending moment of the elastic force in the deposited film, while the resonant frequency changes due to the film contributions to the bending force and inertia of the cantilever. It is found that the relative variations of cantilever force constant and resonance frequency depend on the film to cantilever thickness, density and elasticity modulus ratios. This theoretical prediction is confirmed by the experimental investigations on mechanical properties of silicon cantilevers covered by diamond like carbon (DLC) and fluorocarbon thin films obtained by high power impulse magnetron sputtering depositions. Moreover, the effect of film depositions on the cantilever mechanical properties is used to determine the elasticity modulus and mass density of the deposited thin films.

1. Introduction

The rapid development of various atomic force microscopy (AFM) techniques in the last decades has led to an increased interest in AFM probe surface modification in order to obtain a better control of probe–sample interaction forces. The AFM techniques used in surface topography imaging [1], indentation [2] and lithography [3] require probes with hard, low wearing, low adhesion and low friction surfaces [4]. Other AFM techniques as chemical force microscopy [5], molecular recognition force microscopy [6], magnetic force microscopy [7], electrical force microscopy [8], and Kelvin probe microscopy [9] require special AFM probes with well defined chemical and physical properties. Many of such highly specialized AFM probes are obtained by surface modification of commercially available silicon or silicon nitride probes. Highly doped silicon or silicon nitride AFM probes are easily micro fabricated and mass produced at a relatively low cost [10], but their surface properties are not well controlled. Coating of commercially available silicon AFM probes with very thin films obtained by various techniques, which are ranging from plasma assisted depositions [11] to self assembled monolayer depositions [12], is a common method used for AFM probe surface modification. Moreover, coating of the backside of the probe cantilevers with a thin film of gold or aluminum is usually used by AFM probe manufacturers to improve the cantilever light reflectance. However, coating of the AFM probes with thin films affects not only the probe surface properties, but also the mechanical properties of probe cantilevers. While many of the experimental studies have focused on the control of probe surface properties, only few reported modifications of probe mechanical properties as a result of thin film deposition [13]. The effect of thin film depositions on the cantilever resonance frequency has been used by Bowen et al. [14] to determine the cantilever force constant.

The present work investigates the effect of thin film deposition on AFM probes on the mechanical properties of their micro cantilevers. The effect of thin film deposition on the cantilever force constant is evaluated theoretically in the approximation of very thin films (thickness of the deposited film is much smaller than the thickness of the cantilever). In this approximation the shift of neutral bending plane of the cantilever as result of the deposited film is neglected. The cantilever force constant changes due to the contribution of bending moment of the elastic force in the deposited film that is elastically stretched or compressed along with the film-covered surface of the cantilever. The resonance frequency of the cantilevers with deposited thin films changes due to the film contributions to the bending force and inertia of the cantilevers. It is found that the relative variations of cantilever force constant and resonance frequency depend on the film to cantilever thickness, density and elasticity modulus ratios, and are independent on the lateral dimensions of the cantilevers. These theoretical findings are confirmed by the experimental investigations on mechanical properties of silicon

* Corresponding author.
E-mail address: lsirghi@uaic.ro (L. Sirghi).

http://dx.doi.org/10.1016/j.tsf.2014.06.027
0040-6090/

cantilevers covered by diamond like carbon (DLC) and fluorocarbon thin films. Moreover, it is shown that the theoretical predictions can be used to determine the elasticity modulus and mass density of the deposited thin films.

2. Theoretical model

Into the following, a mathematical expression of contribution of the film elasticity to the cantilever force constant is derived in the approximation of very thin films ($t_1 \ll t$). The sketch in Fig. 1 illustrates the deflection of an AFM cantilever of thickness, t, with a deposited thin film of thickness, t_1, under the effect of a normal loading force, F_z, applied at the free end of the cantilever. Within the approximation of very thin films $t_1 \ll t$ the shift of the neutral plane of the cantilever due to the deposited film is neglected. Therefore, bending of the cantilever causes a relative elongation or constriction ($\Delta l/l$, where l is the cantilever length) of the deposited thin film

$$\frac{\Delta\ l}{l} = \frac{t}{2R} \tag{1}$$

where R is the bending radius of the cantilever (Fig. 1). This relative elongation of the film determines an elastic force (F_1) in the film, which according to the Hook's law is

$$F_1 = E_1 \cdot \frac{\Delta l}{l} \cdot S_1 \tag{2}$$

where $S_1 = w \cdot t_1$ is the cross-section area of the film (w being the cantilever width) and E_1, the elasticity Young modulus of the film. Then the elastic force in the bended film is

$$F_1 = E_1 \cdot \frac{w \cdot t \cdot t_1}{2R}. \tag{3}$$

This force determines the film contribution to the bending moment of the cantilever, $M_1 = F_1 \cdot t/2$, as

$$M_1 = E_1 \cdot \frac{w \cdot t^2 \cdot t_1}{4R}. \tag{4}$$

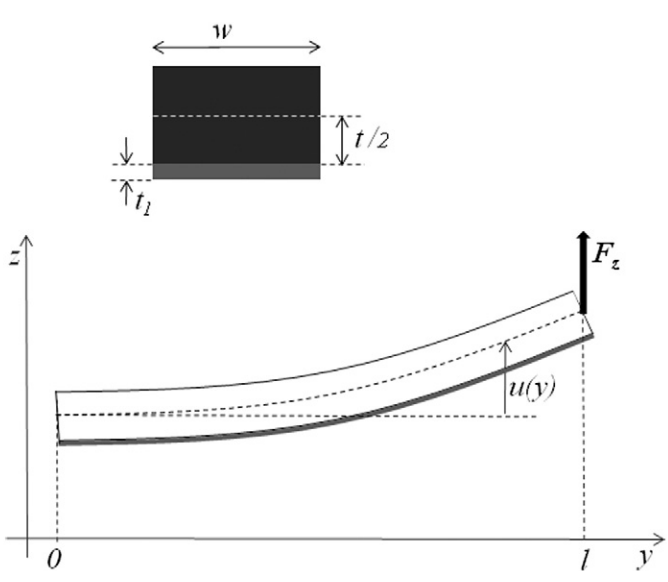

Fig. 1. Sketch of the cantilever geometry during its deflection under a normal force, F_z, applied at its free end. The inset shows a sketch of the cross section of the cantilever with the deposited film, where w is the cantilever width, t, the cantilever thickness and t_1, the film thickness.

Therefore, the bending moment of the AFM cantilever after thin film deposition (M') is the sum of the bending moment of the bear cantilever (M) and the bending moment of the film (M_1)

$$M' = M + M_1. \tag{5}$$

The bending moment of the bear cantilever is:

$$M = \frac{E\ J_z}{R} \tag{6}$$

where

$$J_z = \frac{w\ t^3}{12} \tag{7}$$

is the second moment of inertia of the cantilever cross-section (Fig. 1) and E, the Young elasticity modulus of the cantilever material.

Thus, the bending force moment of the bare cantilever is

$$M = E \cdot \frac{w \cdot t^3}{12R} \tag{8}$$

and the bending moment of the cantilever covered by the film is:

$$M' = \frac{Ewt^3}{12R} + \frac{E_1 wt^2 \cdot t_1}{4R}. \tag{9}$$

The local curvature radius of the cantilever for small deflections ($dz/dy \ll 1$) is:

$$\frac{1}{R(y)} = \frac{d^2u}{dy^2}. \tag{10}$$

The bending moment generated by the force F_z which is acting at the end of the cantilever, is distributed along the cantilever as

$$M' = F_z \cdot (l - y). \tag{11}$$

Using Eqs. (10) and (11) into Eq. (9) gives the following second order differential equation

$$\left[\frac{Ewt^3}{12} + \frac{E_1 \cdot w \cdot t^2 \cdot t_1}{4}\right] \cdot \frac{d^2u}{dy^2} = F_z \cdot (l - y) \tag{12}$$

which integrated with border conditions $u(0) = 0$ and $du/dy(0) = 0$, gives the solution

$$u(y) = \frac{F_z(3l - y) \cdot y^2}{6\left(\frac{Ewt^3}{12} + \frac{6E_1 \cdot w \cdot t^2 \cdot t_1}{4}\right)}. \tag{13}$$

Eq. (13) for $y = l$ determines the cantilever deflection $\Delta z = u(l)$ as

$$\Delta z = u(l) = \frac{F_z \cdot l^3}{\frac{Ewt^3}{4} + \frac{3E_1 \cdot w \cdot t^2 \cdot t_1}{4}} = \frac{F_z}{k'}. \tag{14}$$

Thus, the cantilever force constant after the film deposition is

$$k' = \frac{Ewt^3}{4l^3} + \frac{3E_1 wt^2 \cdot t_1}{4l^3} = k + k_1 \tag{15}$$

where

$$k = \frac{Ewt^3}{4l^3} \tag{16}$$