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Fabrication of short and thin silicon cantilevers for AFM with SOI wafers

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Abstract

Thin and short cantilevers possess both a low force constant and a high resonance frequency, thus are highly desirable for atomic force microscope (AFM) imaging and force measurement. In this work, small silicon (Si) cantilevers integrating with a Si tip were fabricated from silicon-on-oxide (SOI) wafers that were used for reducing the variation of thickness of the cantilevers. Our fabrication process provided SOI chips containing 40 silicon cantilevers integrating with an ultra-sharp Si tip. We showed that the resolution of images obtained with these tips was much higher than those obtained with the commercial tips, while the force constants were much less, that is, more suitable for imaging soft samples. The availability of such SOI chips greatly facilitates large scale modification of the surfaces of the silicon cantilever tips with a monolayer of oligo(ethylene glycol) derivatives that resist the non-specific interactions with proteins, rendering them most suitable for imaging and measurement of biological samples.
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Keywords: Thin cantilevers; SOI wafers; AFM probes

1. Introduction

Recently, short and thin cantilevers have been used for atomic force microscope (AFM) imaging and force measurement [1,2]. Such cantilevers have a high resonance frequency and a low force constant. The high resonance frequency allows for fast imaging [2,3], which is highly desirable for monitoring the reactions, interactions, and conformational changes of biomolecules. The low force constant of the cantilever greatly minimizes the deformation of soft samples such as biomolecules. In addition, it significantly increases the sensitivity of force measurement which has been widely used for studying the inter- and intra-molecular interactions between macromolecules [3]. Furthermore, it has been demonstrated that small cantilevers also reduced the thermal noise [1]. All these unique advantages associated with small cantilevers have motivated the development of processes for the fabrication of such cantilevers and instrumentation for using them.

Currently, AFM cantilevers are predominately fabricated from silicon and silicon nitride (SiN). Several reports for the fabrication of small cantilevers without tips using both materials appeared [4–6]. Among the few reports for the fabrication of small cantilevers with tips, most of them used low stress SiN as the material for the cantilevers because the thickness of SiN cantilevers can be controlled by chemical vapor deposition (CVD) and SiN is not etched in the etchants for silicon or silicon oxide [7]. The SiN tips can be fabricated together with SiN cantilevers or carbon tips can be deposited on the SiN cantilevers by electron beam deposition [8]. Although silicon cantilever tips are more difficult to fabricate compared to SiN cantilever tips, there are several advantages for the use of silicon tips and cantilevers: (1) Si tips can be easily sharpened through thermal oxidation, (2) comparing with carbon tips deposited by electron beam deposition, the Si tips that are integrated with Si cantilevers are easier to be fabricated in large scale, (3) Si tips can be modified with protein-resistant monolayers for application of such tips for imaging biological samples [9–11], (4) the single crystal Si cantilevers have a higher *Q* factor than the amorphous SiN cantilevers grown by CVD [12], and (5) at an appropriate thickness, the Si cantilevers thinner than 500 nm have as high

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as 70% reflectivity to red laser that is a popular light source in commercial SPM heads, but the corresponding SiN cantilevers only have up to 40% reflectivity. Moreover, if blue-violet laser is used in SPM heads, the reflectivity in thin Si cantilevers almost has no variation with thickness because the strong absorption of blue light nearly completely eliminates the thin film interference for Si. In contrast, SiN almost has no absorption to visible light.

Despite the advantages, few reports on the fabrication of thin Si cantilevers with Si tips and only one report on the fabrication of Si tips on SiN cantilevers appeared [13]. This situation reflects the difficulties of fabrication of thin Si cantilever tips. The commercial Si cantilever tips are mostly prepared by backside etching of 300–500 μm thick Si wafers. Due to the deviation of thickness over the whole wafer, and the difficulties in controlling the etching process, it is extremely difficult to prepare cantilevers thinner than 1 μm in a wafer scale by this process. Herein, we present a method for fabrication of a large number of Si cantilever tips using SOI wafers. Our approach allows for the fabrication of cantilevers with a few microns width, down to 100 nm in thickness, and around 10 μm in length. The excellent performance of cantilever tips made of SiN with a similar size has been demonstrated [2]. However, to take advantage of such micron-sized cantilevers requires specially designed AFM heads that remain at the prototyping stage and are available in only a few research groups. In this work, we focus on the preparation of Si-based cantilever tips with a dimension suitable for current commercial AFM instruments.

2. Design

The thin film interference effects can impact the optical monitoring of the microcantilever's motion because the intensity of reflection could be weakened by these effects. A layer of metal can be deposited on the back of the cantilever to eliminate the interference and provide a high reflectivity. However, the undesirable effect of the temperature sensitive "bimaterial" strips can become large for thin cantilevers if the thickness of metal layer is comparable to that of the cantilever. In fact, the interference dose not always has a negative effect. With the proper thickness, the reflective light can be strengthened by the interference. A computer simulation of thin film effect is used for calculating the reflection, based upon a matrix formulation of reflection and transmission at interface of dielectric material [14]. In the calculation, at the interface the energy is conserved. The simulation results of reflectivity from Si and SiN cantilevers in red and blue lights are shown in Fig. 1, respectively. The optical parameters of Si and SiN are obtained from Refs. [15–17]. The result of the simulation shows that a high reflectivity can be obtained if the thickness of the cantilevers can be accurately controlled to a proper range. For example, Si cantilevers with a thickness of 110–160 nm have more than 70% reflectivity in red light (wavelength 670 nm). With a certain thickness, SiN cantilevers also possess the reflectivity larger than 40% in red light or blue light (wavelength 400 nm). Here Si cantilevers with a thickness larger than 10 nm show another advantage: they always have a reflectivity around 50% in blue light because the strong absorption of blue light in Si eliminates the effect of thin film interference and higher refraction index of Si in blue light leads to stronger reflection than in red light. With the increasing of the reliability of blue and violet lasers recently, these lasers are expected to be used in future AFM systems.

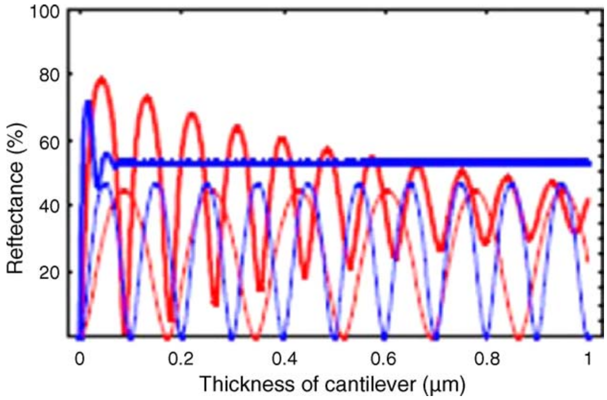

Fig. 1. The reflectance of cantilever for different materials (thick curve: Si and thin curve: SiN) and different color lights (red curve: 670 nm red laser, blue curve: 400 nm blue laser). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of the article.)

The cantilevers with a high resonance frequency and low force constant are highly desirable for imaging biological samples. Unfortunately, commercial Si AFM cantilever are not satisfactory in this regard. For example, two typical silicon probes are available: the long cantilevers with a typical size of 300 μm × 35 μm × 1 μm providing force constant of ∼0.03 N/m and resonant frequency of ∼10 kHz, and the relatively short cantilevers with a typical size of 90 μm × 35 μm × 1 μm providing force constant of ∼1.7 N/m and resonant frequency of ∼150 kHz. The first type is often used for imaging in contact mode or force measurement. For imaging soft samples, tapping mode that eliminates the lateral force often causing deformation of the soft sample is preferred over contact mode. However, the low resonance frequency of these cantilevers limits the rate of imaging. For force measurement these large cantilevers inherently display relatively high thermal noise that greatly lowers the sensitivity of the force measurement. For the second type, the high force constant likely causes deformation of soft samples and increases the thermal noise. In this work, silicon cantilever tips are designed to possess a high frequency and low force constant as well as to be compatible with commercial AFM instruments.

For compatibility with the size of laser beam in common AFM head, we decided to keep the width of cantilevers to be the same as most commercial probes (35 μm), and the length (70 μm) of the cantilevers to be twice of the width. For a rectangular cantilever, the eigenfrequency, f_0, is given by [18]

$$f_0 = 0.162\frac{t}{l^2}\sqrt{\frac{E}{\rho}}, \tag{1}$$

where t is the thickness, l the length of the cantilever, E the Young's modulus of the material and ρ is the density of mass of the material. The spring constant of a cantilever is $k = 0.25Ewt^3/l^3$, where w is the width of the cantilever. Therefore, for a 450 nm thick cantilever with a width of 35 μm and