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Optical thin-film interference effects in microcantilevers

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We report direct observation of thin-film interference effects in microcantilevers, an effect that can impact the optical monitoring of the microcantilever motion. When microcantilevers are illuminated with different wavelengths of light the amount of absorption and the wavelengths of maxima in the absorption depend upon the thickness of the layers, the materials used in the layers, and the direction of illumination. Wavelengths of maximum absorption are observed as microcantilever deflections due to heat-induced bending of the bimaterial structure of the microcantilever. Results are presented for different multilayer configurations and illumination directions. These results are then compared with theoretical calculations based on multilayer thin-film analysis. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1638616]

I. INTRODUCTION

The search for improved sensors for security and medical diagnostic equipment has lead to smaller, less expensive, and more sensitive chemical and biological sensors being developed. Some of the most promising sensors are based upon microelectromechanical systems (MEMS). A microcantilever sensor is an example of a MEMS device that has both high sensitivity and large dynamical range.

Microcantilevers were originally designed for measuring surface topographies in atomic force microscopes (AFMs) in the late 1980s,[1] and are now being used as mechanical sensors.[2,3] These MEMS sensors are capable of detecting Hg, ions, biologically significant molecules, explosives, and other materials.[4–8] Compounds are detected by monitoring changes in the resonant frequency induced by adsorbate mass loading, or by quasistatic deflection (bending) of the microcantilever as material is adsorbed onto the surface thereby producing surface stress. Adsorption changes the mass and surface free energy of the microcantilever.

Selective sensors come in two distinct configurations. The first and most prevalent type uses specific chemical or biological coatings[6,9] to adsorb target materials. Selectivity in the sensors is determined by the properties of the coating. The second type of sensor uses coatingless techniques[10] and the selectivity is provided by the properties of the materials that make up the microcantilever and by external devices. In an attempt to improve the selectivity and decrease the need for coatings, a form of optical spectroscopy is provided by the latter sensor configuration. Much of the previous research in optical excitation of microcantilevers has focused on the far-infrared region of the spectrum[11,12] or on studies at a specific wavelength for use as optical detectors[13,14] or as substrates for testing materials.[10,11]

In optical excitation of microcantilevers many different mechanisms contribute to the deflection. Mechanisms of deflection due to illumination include photoinduced charges, thermal stress, surface stresses induced in organic or chemical coatings, and surface charging. Some of these effects compete in each layer of the material. Microcantilevers discussed here consist of a multilayered structure of metal and semiconductor material in which the response of these materials to photon excitation varies with wavelength. For example, in the semiconductor layer photo-generated charge carriers will exert a stress as well as causing thermal expansion due to the associated absorption and transfer of energy. In pure silicon it has been shown that the expansion due to thermal and electronic signals can compete and move in opposite directions when the excitation energy is above the band-gap energy of the material,[15] while in metals thermal expansion is the dominant factor.

Another important factor in deflection is the multilayer thin-film design of microcantilever sensors. It makes them susceptible to thin-film interference effects when exposed to light. As light interacts with the different layers of material the energy that is not transmitted or reflected is absorbed and converted into heat. This causes the microcantilevers to bend due to the bimaterial effect, in which one material expands more than another. The thin-film reaction demonstrates how the optical activation of microcantilevers could be improved through the use of specific thicknesses of layered materials.

Despite the well-known properties of materials utilized, the precise thermal and stress effects of light–microcantilever interactions are not fully understood at present. As their use in optical systems increases, a better understanding of the microcantilever's interaction with light needs to be developed. With an improved understanding of the light–microcantilever interaction a detailed model for improved sensors can be designed.

II. EXPERIMENT

A. Setup

In this experiment microcantilevers are illuminated with different wavelengths of light and the deflection corresponding to each wavelength is monitored and recorded. The microcantilever is then modified by chemical etching to remove

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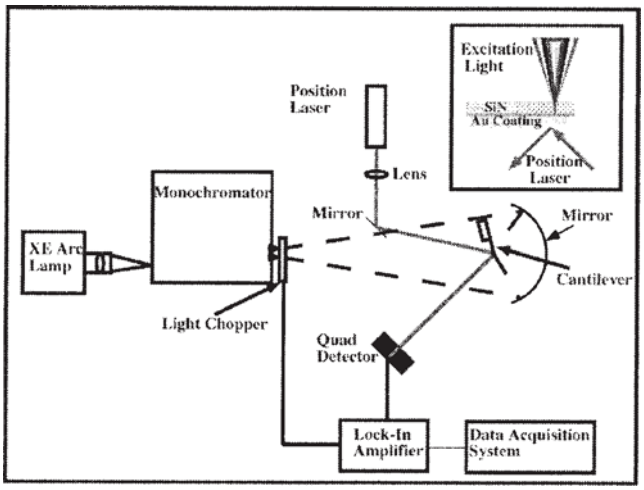

FIG. 1. Experimental setup for the microcantilever illumination.

a metal layer and the absorption spectrum is repeated. The microcantilevers consist of a silicon nitride (SiN)–chromium (Cr)–gold (Au) layered structure in which the thin Cr layer acts as an adhesion surface between the thicker layers of SiN and Au. Changes to the resonance frequency of the microcantilever before and after chemical etching are combined with visual inspection of the surface and color to determine if the metal layers are removed. For each microcantilever configuration the absorption is obtained for illumination from both sides.

To accomplish the above, commercially available 300-μm-long, V-shaped, SiN microcantilevers[16] are illuminated with light from a 300 W Xe arc lamp that is separated into different wavelengths by a monochromator.[17] A block diagram for the experimental setup is shown in Fig. 1.

Mechanical response of the microcantilever is measured for each wavelength of illumination by monitoring the reflected signal of a diode laser with a 635 nm wavelength. The reflected beam is monitored with a position-sensitive detector (PSD) with quadrants labeled A and B for each pair in opposition. It is protected from scattered light by a bandpass filter with a peak transmission centered at the 635 nm wavelength. The differential signal between the quadrants $A-B$ is calculated and divided by the sum signal $A+B$ to convert it into a less-noisy deflection signal. The resulting signal is processed with a lock-in amplifier that compares the chopped illumination "on" state to the illumination "off" state. The difference between the illumination on and off states is then divided by the normalized wavelength-dependent illumination intensity of the monochromator which is measured with a calibrated silicon detector. Also, to monitor for any inconsistencies or possible light contamination of the PSD the sum signal $A+B$ and the raw deflection $A-B$ signal are recorded separately.

B. Experimental results

Experimental results for a microcantilever that is illuminated in the Au–Cr–SiN direction are presented in Fig. 2, while Fig. 3 presents the case for the SiN–Cr–Au direction. The interference effects are seen in the repeating deflection

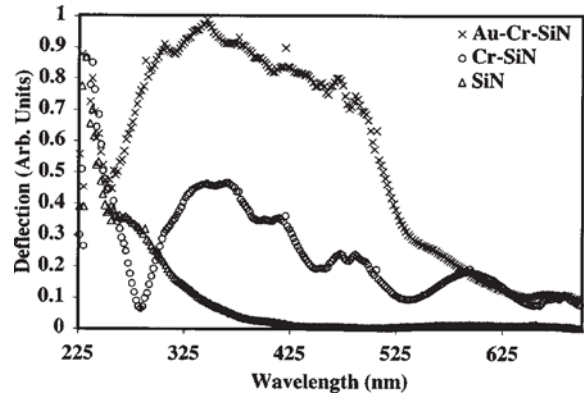

FIG. 2. Experimental data for a microcantilever that is illuminated in the Au–Cr–SiN, Cr–SiN, and SiN directions.

peaks that are present in the SiN–Cr–Au case and that are greatly reduced for the Au–Cr–SiN data. The only difference between these absorption curves is the direction of illumination. As a result, one can see that the deflection is very dependent upon which surface of the microcantilever is illuminated. The graphs also present the results for the microcantilever after the Au and then Cr layers are removed with an acid wash demonstrating differences due to the layer structure and due to illumination directions. In the Cr–SiN case, smaller interference peaks are observed while the SiN–Cr case looks like the SiN only. The SiN case is the same for both graphs and does not vary with direction of illumination.

C. Computational results

A computer simulation[18] of the thin-film effect, based upon a matrix formulation of reflection and transmission of light at dielectric interfaces,[19] incorporates experimentally determined dielectric functions[20] for each layer and allows for an arbitrary number of interfaces to be incorporated. The transmission T and reflection R of light incident normal to the surface of the multilayer system is calculated. Conservation of energy is then used to calculate the absorption $A=1-T-R$.

The absorption is dependent upon the number of layers, the materials of the layers, and on the direction of incidence

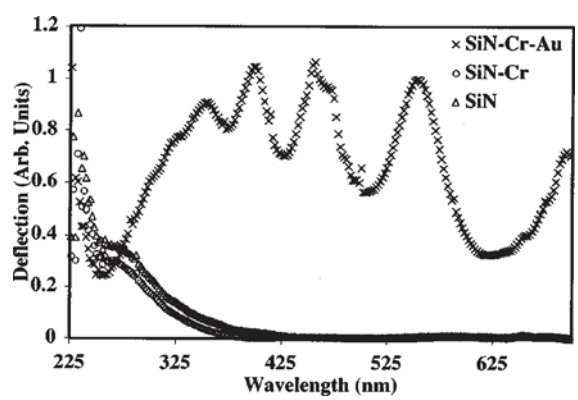

FIG. 3. Experimental data for a microcantilever that is illuminated in the SiN–Cr–Au, SiN–Cr, and SiN directions.

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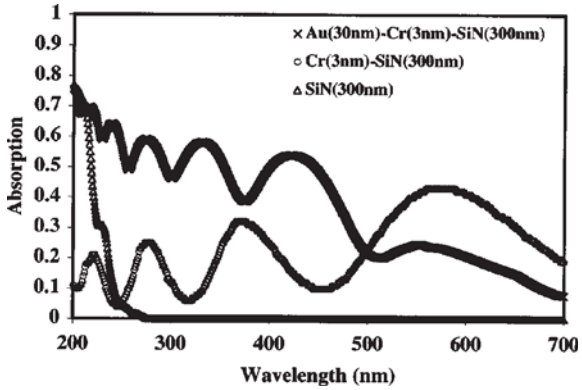

FIG. 4. Theoretical absorption for light incident normal to the Au–Cr–SiN, Cr–SiN, and SiN layered systems.

for the light. For all of the theoretical curves shown in this article, the light is incident normal to the surface. The small cutout in Fig. 1 shows the layered structure of an illumination setup for the experiment.

Figures 4 and 5 show the absorption curves for light incident from the Au and SiN side of a multilayer system, respectively. For all cases the gold layer is 30 nm thick, the Cr layer is 3 nm thick, and the SiN layer is 300 nm thick. The material dimensions correspond to the approximate thickness used in the microcantilevers for the experiment.

In Fig. 4, absorption for light incident on the gold side of the Au–Cr–SiN interface is presented. The interference effect is present in the multiple peak structure observed in Fig. 4. Absorption curves for light incident on the Cr side of the Cr–SiN systems as well as SiN alone are also shown in Fig. 4. These curves demonstrate how the absorption varies with changes to the number of layers and material present. Figure 5 shows the case for light incident normal to the SiN side of the SiN–Cr–Au, SiN–Cr, and SiN interface systems. Differences in the absorption are present between Figs. 4 and 5 that are dependent upon the direction of illumination and the existing material layers.

The absorption characteristics of the systems are also dependent upon the thickness of the materials used in the layers. Figure 6 demonstrates the theoretical change between a 50- and 30-nm-thick layers of Au in the Au–Cr–SiN system. The light is incident normal to the Au surface in both

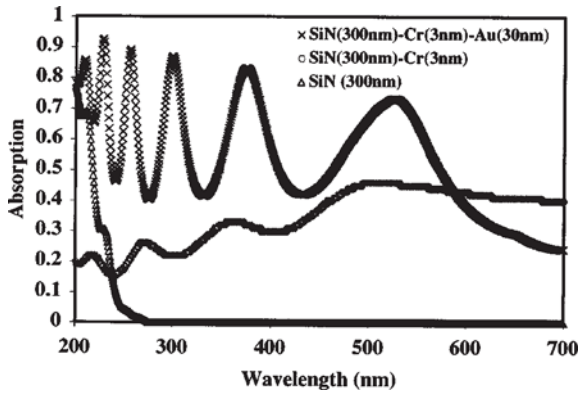

FIG. 5. Theoretical absorption for light incident normal to the SiN side of the SiN–Cr–Au, SiN–Cr, and SiN layered systems.

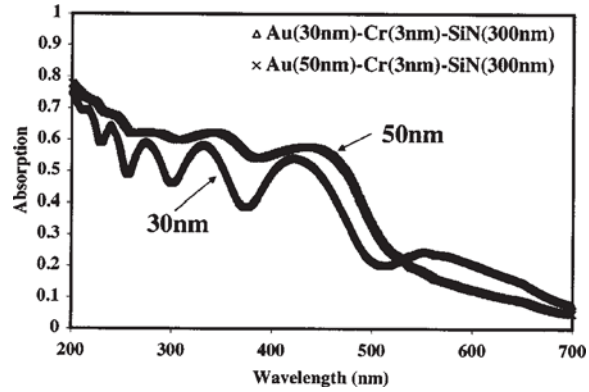

FIG. 6. Comparison of the absorption for 30 and a 50 nm layer gold surfaces of the Au(d)-Cr(3 nm)-SiN(300 nm) system. Illumination was normal to the gold surface. As the gold layer gets thicker the features of the absorption spectrum flatten out.

cases. As the Au layer increases in thickness more of the incident light is reflected and less is absorbed into the system. If the Au thickness is increased significantly, all of the interference effects disappear and the absorption looks like that of a single gold layer.

III. DISCUSSION

The goal of this experiment is to test the influence of optical interference effects upon the absorption process. The interference effects are demonstrated in the experimental results in Figs. 2 and 3 as compared with the theoretical data in Figs. 4 and 5. The results demonstrate maximum deflection points that correspond well to interference patterns observed in the thin-film simulation. It is surmised that some of the light that is not transmitted or reflected is converted into heat that causes the structure to bend due to the bimaterial effect. For this case, photocarrier induced deflection should not be a factor because the illumination wavelength energies are below the band-gap energy of the SiN.

Another feature that is present occurs when the Au side of the cantilever is illuminated so as to reflect much of the light and not allow significant intensity to reach the SiN side of the cantilever. For comparison when the SiN side is illuminated first the light is absorbed and converted to heat and many deflection peaks are observed. The experimental results for the Au–Cr–SiN system closely resemble the simulation for a 50-nm-thick Au foil. These differences affect the use as mechanical sensors and help to determine which side of the lever to illuminate. How thick to make the layers and which side of the cantilever to illuminate become very important questions. Also, the side on which a compound adsorbs will affect the interaction of the light with the microcantilever. If the compound conducts thermal energy to the cantilever effectively, a large deflection may be observed or the compound may act as a reflecting agent and restrict the amount of light that is absorbed onto the cantilever.

For the cases of Cr–SiN the experimental results are not as convincing. In the Cr→SiN direction of illumination, small peaks in the absorption can be observed indicating interference effects. In the SiN–Cr illumination direction the absorption looks like plain SiN. This may be caused by the

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thinness of the Cr layer or by the domination of the signal by bending in the SiN. The results for this case are inconclusive. Only in the SiN case were we able to show that the experimental and theoretical results compare very well. The absorption results are not affected by the direction of illumination indicating that the Au and Cr layers were removed completely.

This information and simulations could lead to a better design for the sensors. The layered structure could be optimized to maximize or minimize the effect at a specific wavelength. Use of additional layers of material could also permit optimization of the device. Differences in semiconductor properties such as the band-gap energies could be exploited for specific cases. As materials adsorb the chemical reactions may cause changes in the absorption properties that could be viewed as bending signals. A mechanical microspectrometer could be optimized for use across a wide bandwidth of wavelengths of light. A single device with many arms and different layers optimized for specific wavelength regions could be used to create a versatile and small microspectrometer with the ability to obtain spectra of minute quantities of compounds.

As material adheres to the surface the interference effect could come into play, thus changing the layered structure of the detector. Further studies are planned to examine this possibility.

IV. CONCLUSION

Thin-film interference effects are observed as deflections in the microcantilevers. The associated bending should be taken into account when optical illumination of microcantilevers is preformed. Variation of the thickness of a layer or addition/removal of a layer changes the location of the maximum absorbance. Theoretical results show a good correlation with the experimental results. The direction of illumination, for identically layered systems, is very important in determining the location of the absorption maxima. The results demonstrate how the optical activation of microcantilevers can be improved quantitatively through the use of specific thicknesses of layered materials. This understanding should lead to improved microcantilever sensor design.

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